Proposal of design techniques for concrete structure subjected to effects of high temperature

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ABSTRACT

Design of Fast Breeder Reactor (FBR) buildings in Japan has generally been performed from the view point that in the event of an accident, the structure may be subjected to high temperatures for a long-term period and/or simultaneous high temperatures and earthquake shocks.

This report proposes rational and practical design techniques for reinforced concrete (RC) structures, such as nuclear reactor buildings, which are affected by thermal loads or thermal plus seismic loads. Based on these techniques, evaluation methods for thermal stress, seismic load and seismic stress and strengths of members are recommended.

1 INTRODUCTION

When the RC structures such as FBR buildings are subjected to long-term high temperatures, thermal stresses (i.e. bending moment, membrane tensile force,etc.) are produced in heated members and adjoining members by restraining the thermal expansion of heated members. Subsequently flexural cracking and membrane tensile cracking are generated. In addition, concrete material properties of heated members will vary because of moisture evaporation; reinforcement material properties also vary under high temperature. Consequently, both the rigidity and the ultimate strength of the structure will vary. These characteristics have been clarified through the experimental results.[1] When designing the structure, therefore, it is necessary to consider adequately these variations due to thermal loads.

Under the current circumstances, however, it would not be practical to employ non-linear analysis for large-scale and complicated structures such as FBR buildings. There are various assessment methods currently proposed, but in effect, these methods consist mainly of thermal stress evaluation corresponding to the flexural crackings. It is considered that these methods are not applicable for the design of such structures with predominant in-plane rigidity --- this being an objective of this report.

Considering these situations, this report, therefore, proposes design techniques as follows.

The applicability of these techniques has been confirmed from the results obtained through a series of material tests and structural experiments[1] performed under high temperature conditions of up to 175 ℃.

2 DESIGN TECHNIQUES

The design for RC structures subjected to long-term high temperatures is carried out along with the two different flows as shown in Fig-1.
This figure shows design techniques for the structure subjected to thermal loads and the structure subjected to thermal plus seismic loads.

These techniques are as follows:
(1) In the case of designing under thermal load, since we are dealing with a wall-type structure whose the in-plane rigidity is superior, this method takes into consideration the redistribution of in-plane stress to evaluate thermal stress, based on the reduction of in-plane rigidity due to membrane tensile crackings.

Concerning the material constants of concrete, it is difficult to estimate quantitatively the change in material properties due to moisture evaporation caused by heat, so that this method ignores its effect on thermal stress and uses material constants for normal temperature from the aspect of safety design.
(2) Regarding aseismic design, since seismic load and stress of each member vary from a normal condition to an accidental condition, it is considered to ensure the safety for both conditions. Therefore, seismic loads are determined by comparing the results of response analyses using varying rigidities (from normal conditions to accidental conditions where the rigidity is reduced).

For the reduction of rigidity due to high temperature, this method gives a conservative evaluation to ensure the safety, in consideration of a decrease in Young's modulus for concrete members affected by heat and a reduction of in-plane rigidity due to flexural crackings, and reduction of in-plane rigidity due to membrane crackings caused by thermal stress.
(3) Design of members will be based on the ultimate strength of members, and it is carried out by reducing the strength of members corresponding to the effect of heat imposed on these members.

In addition, the design of members against seismic stress will be carried out without combining thermal stress, since it is confirmed from experiments that the ultimate strength of members will not be affected by thermal stress.

In addition, it is assumed that a linear finite element method is used for thermal stress and seismic stress analysis in these techniques.

3 EVALUATION METHOD

3.1 Evaluation method for thermal stress

The evaluation method for thermal stress is carried out in such a manner that as a first step, the principal stress is calculated for each element through the results of elastic analysis. The area of membrane tensile crackings is approximately determined by comparing principal stress and concrete tensile strength. Then, in-plane force is calculated by linear analysis in which the reduction of in-plane rigidity due to crackings is considered as an anisotropic element. In the second step, bending moment is calculated by considering the reduced flexural rigidity due to flexural crackings, using the in-plane (axial) force obtained from the previous step. We have reported this design method in detail and we have shown that it could simulate non-linear analysis adequately at 7th SMiRT.[2)]

The comparison study between this method and experimental results are shown, herein.

As an example of evaluating in-plane force, maximum strain of reinforcement in the web-wall of a H-wall specimen is shown, in which membrane tensile crackings are produced in part of the web-wall by heating one side of the flange-wall. Distribution of the membrane tensile crackings and the maximum strain of reinforcement in the web-wall are shown in Fig-2. The cracking distribution can be simulated almost accurately by this method and the maximum reinforcement strain is also evaluated adequately. In view of this, the effectiveness of this method is comfirmed.

As an example of evaluating bending moment, reinforcement strain of a cylindrical member specimen, heated inside of a cylinder, is shown in Fig-3. The calculated values are higher in the tension side and lower in the compression side against the measured values, since material constants of normal temperature are used in this method. However, in general, design of sections is carried out for tension reinforcement while compression can be disregarded in practical design.

3.2 Evaluation method for seismic load and stress

Seismic stress subjected to thermal effects is evaluated by using the rigidity, which is determined below, considering the degree of seismic load in Japan. Seismic load is determined by varying rigidity from normal to accidental condition.

(1) Evaluation of reduced in-plane rigidity due to membrane tensile crack

In the area where membrane tensile crackings are produced, a member is assumed as an anisotropic element in the direction of cracking by disregarding the shear transmission along a cracking plane.

(2) Evaluation of reduced in-plane rigidity due to high temperature

It is considered that the effects of reduced rigidity due to flexural crackings are included in the effects of decreases in Young's modulus for concrete members which are heated. In this case, as shown in Fig-4, Young's modulus for concrete is evaluated by using a higher surface temperature.

The decrease of Young's modulus for concrete is evaluated as follows:

- Over 100℃ / 0.6 of normal value (by the lowest value of material tests in the condition of moisture evaporation is allowed)
- 65℃ to 100 ℃ / 1.0~0.6 of normal value with linear distribution (by taking account of the thermal limitation in standards)[3)]

The effects of flexural crackings are also considered by using a higher surface temperature of equivalent linear temperature distribution.

Experimental results compared with calculated results are given below:

The reduced initial rigidity of the heated cylindrical member specimen against horizontal and torsional applying loads as compared with calculated results is indicated in Fig-4. Although a part of the experimental result exceeds the calculated one, this method disregards it because moisture does not evaporate easily in the thick walls of reactor buildings.

For the evaluation of rigidity in the whole structure, the results of I/C model experiments (looped type FBR) as compared with calculated results are indicated in Fig-5. The secant rigidity of experimental value corresponding to the degree of seismic load in Japan (input acceleration nearly 300gal, base shear coef. 0.7 ~ 0.8) is covered with calculated results from the lower boundary.

Also, for the seismic load sharing ratio of each wall in the whole structure, non-linear results[1)] as compared with calculated results of this method are indicated in Table-1. A correspondence exists between the two results in normal conditions, whereas the sharing ratio of this method is more than the non-linear one in the heated IHX wall and less in the cylindrical wall where membrane tensile crackings produced during heating.

In view of this, the IHX wall is safely designed. Moreover, it ensures the design of cylindrical walls for normal conditions, because the sharing ratio in normal conditions greatly exceeds those during heating conditions.

3.3 Evaluation method for strengths of members

The strengths of members are calculated by using the equations which are employed in Japan to evaluate flexure and axial load, out-of-plane shear and in-plane shear strengths, in which decreases of concrete and reinforcement material properties due to high temperature are considered through out the experimental results.

According to the results of material tests, both concrete compressive strength and bond strength show no decrease due to thermal effects. In comparison, splitting tensile strength decreases to about 20% at maximum and Young's modulus also decreases to about 35% at maximum under the condition that moisture evaporation is allowed. The yield point of reinforcement decreases to 9 ~10% at 150℃.

Each equation, notations and applying method are shown in Table-2. The ratios of calculated to measured values are as follows: strength under combinated flexure and axial load 1.16~1.39, out-of-plane shear strength 1.20~ 1.45, and in-plane shear strength 1.06 ~ 1.28 . These show the applicability of this method.

4 CONCLUSION

It was confirmed that the design of a RC structure, such as a reactor building, subjected to long-term high temperature could be performed quite simply by techniques described in this report.

These techniques were applied to the FBR (prototype) building under construction in Japan. They will help greatly to develop demonstration and commercial reactors or design of general structures subjected to high temperatures in the future. When applying these techniques, it is necessary to reconfirm the variation of concrete material properties (Young's modulus, compressive strength, splitting tensile strength) due to thermal load, since they are affected by aggregates or concrete mix proportions.

ACKNOWLEDGEMENTS

This study was performed under the sponsorship of the Power Reactor and Nuclear Fuel Development Corporation (PNC). The authors would like to thank Emeritus Professors H. Umemura (Univ. of Tokyo), M. Wakabayashi (Univ. of Kyoto), Professors B. Kato, H. Aoyama, S. Machida (Univ. of Tokyo), K. Kawase (Niigata Univ.) and Assistant Professor H. Nariai (Tsukuba Univ.) for valuable advice and guidance. Special thanks are in order for Messrs. I. Ohike and K. Hirano of the PNC for their support.

REFERENCES

1) Omatsuzawa, K., Takeda, T., Yamaguchi, T., Yoshioka, K., et al., " Behavior and Ultimate Strength of an Inner Concrete Structure of a Nuclear Reactor Building Subjected to Thermal and Seismic Loads. (J6/2)" , 9th Int. Conf. of SMiRT 1987
2) Seya, Y., Takeda, T., Ohkuma, M., et al., " A Proposal on the Thermal Stress Evaluation for the Reinforced Concrete Structures. (J4/6)" , 7th Int. Conf. of SMiRT 1983
3) ASME Boiler and Pressure Vessel Code, Sec. III , Div. 2, 1983

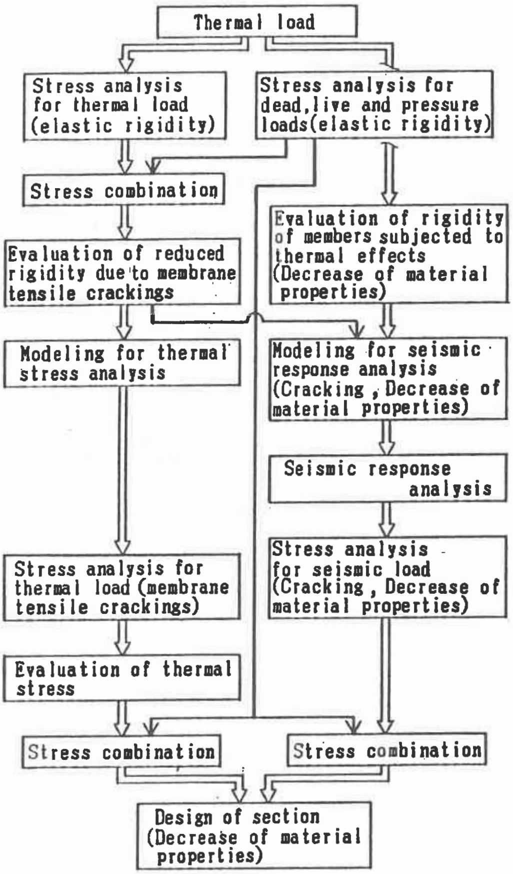


Fig-1 Evaluation flow diagram of RC structures subjected to thermal effects

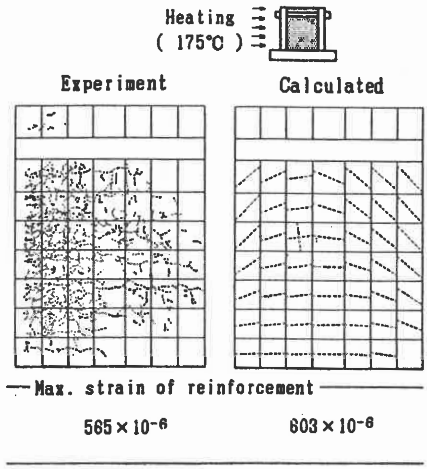


Fig-2 Cracking distribution of web-wall during heating (H-wall:WH3)

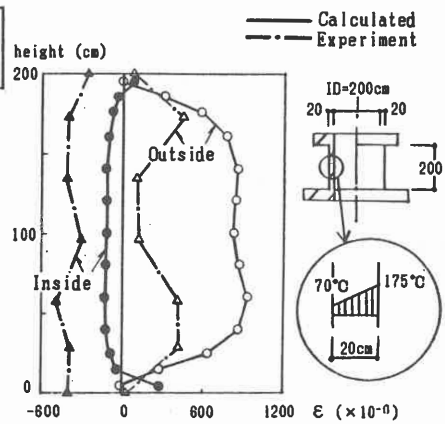
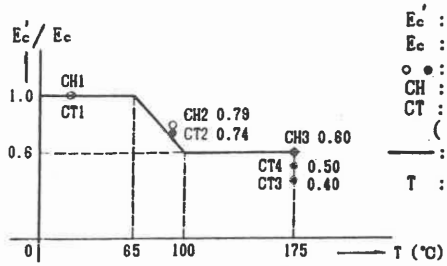
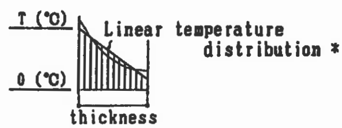


Fig-3 Strain of vertical reinforcement during heating (Cylindrical member : CH3)

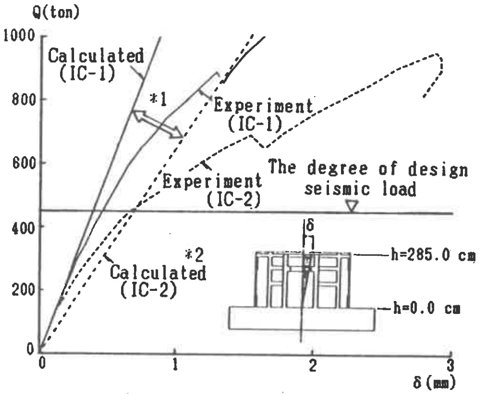


Ec' : Young's modulus of heated concrete
Ec : Young's modulus of non-heated concrete
○ ● : Rigidity ratio against non-heated specimen
CH : In case of applying horizontal load
CT : In case of applying torsional load
(Joint translation angle =1/10000)
—— : Assumed in design
T : The higher surface temperature



* It is modified from the sectional non-linear temperature distribution as sectional forces (axial force , bending moment) are equivalent

Fig-4 Relationship between the Young's modulus of concrete and temperature

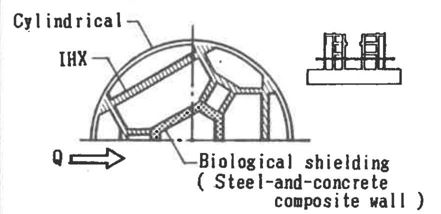


*1 Rigidity range using for seismic load evaluation at an accidental condition
*2 Rigidity using for seismic stress analysis at an accidental condition

Fig-5 Relationship between load and displacement (I/C model)

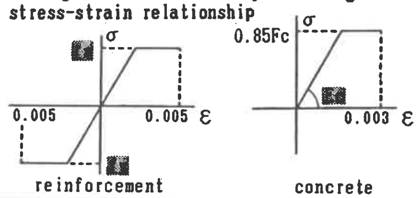
Table-1 Load sharing ratio of each wall against horizontal applying load (Q=450ton:The degree of design seismic load)

wall	Design technique		Non-linear analysis	
	IC-1	IC-2	IC-1	IC-2
Cylindrical	0.17	0.001	0.17	0.12
IHX	0.58	0.62	0.58	0.53
Biological shielding	0.25	0.38	0.25	0.35



IC-1 : Non-heated specimen
IC-2 : Heated specimen

Table-2 Equations for evaluating the strengths of members

The higher surface temperature	~ 65 ℃ (Normal temperature)	65 ℃ ~ 100 ℃	100 ℃ ~ 175 ℃
Strength under combinated flexure and axial load	Strength is calculated by following stress-strain relationship 	1.0 ~ 0.6 Ec fy	0.6 Ec 0.9fy
Out-of-plane shear strength (Qu)	$Q_u = \left\{ \frac{0.053 P_t^{0.23} (F_c + 180)}{M/(Q \cdot d) + 0.12} + 2.7\sqrt{P_w \cdot \sigma_{wy}} + 0.1\sigma_0 \right\} b\, j$ Pt : Ratio of tension reinforcement Pw : Ratio of shear reinforcement M : Bending moment Q : Shear force b : Width of member d : Effective depth of member section j : Internal moment arm σo : Membrane stress intensity (In case of tension , coef.0.1 → 0.2)	Fc + 180 σwy	0.75Fc + 180 0.9 σwy
In-plane shear strength (τu)	$\tau_u = \frac{1}{2}\left\{ (P_{tx} \cdot$ [redacted] $- \sigma_{ox}) + (P_{ty} \cdot$ [redacted] $- \sigma_{oy}) \right\}$ and $\tau_u \leqq 3.5\sqrt{F_c}$ Ptx , Pty : Ratio of shear reinforcement σox , σoy : Membrane stress intensity (In case of compression , σox , σoy=0)	fy	0.9fy

Fc : Specified compressive strength of concrete
fy : Specified yield strength of reinforcement
σwy : Specified out-of-plane shear strength of reinforcement