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# LONG-TERM DEFORMATIONAL BEHAVIOUR OF THICK REINFORCED CONCRETE SLAB LOADED BY OUT OF PLANE FORCE

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## ABSTRACT

The Advanced Thermal Reactor plant is under the design in Japan, in which the reinforced concrete slab supporting a reactor is assumed to be exposed to high temperature and low humidity conditions. The slab deforms plastically over the design period due to creep and drying shrinkage of concrete. To ensure the long term serviceability of the slab, the vertical deformation of the slab in the design period has to be estimated. In the study, the experimental work using 1/5 scale partial models of the slab and the analytical simulations were carried out. Comparing the results of the analysis and the tests, it is confirmed that the analysis suggested here is a suitable procedure to estimate the long term deformation of the slab.

## 1. INTRODUCTION

The Advanced Thermal Reactor(hereafter called "ATR") plant is being designed in Japan. The core of the ATR is supported by the thick reinforced concrete slab with an large opening at the center of the slab. As the weight of the reactor acts as an out-plane force to the slab, the slab deforms plastically over the design period due to creep and drying shrinkage of concrete. To ensure the serviceability of the slab in the design period, the vertical plastic deformation of the slab has to be estimated. In this study, the experiments using 1/5 scale partial models of the slab and the analytical simulations, 2-dimensional FEM program, were carried out and the application of the analysis were discussed.

## 2. TEST PROCEDURES

In the experiments eight models were tested. The following test parameters are were adopted.

(1) Shape and loading condition of the model; Model A and Model B (refer to Fig. 1)
(2)Temperature condition ; 20℃ and 60℃
(3)Surface condition of concrete ; sealed(treated by resin) and unsealed

Shape and steel arrangement are shown in Fig.1. Simulating the actual load condition of the slab, two-point concentrating load was given to the model.

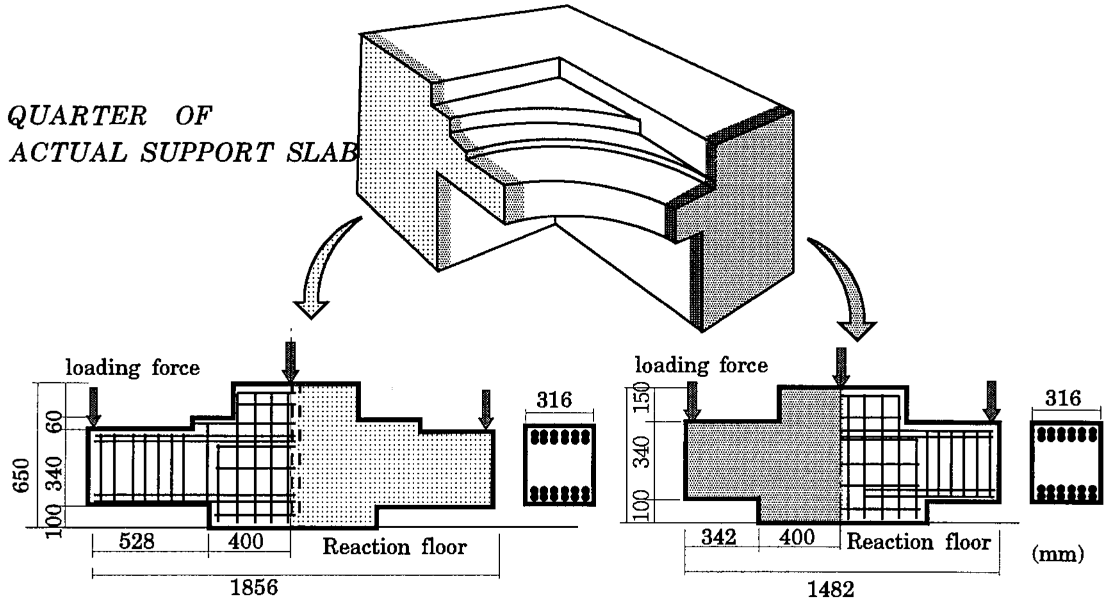
The constant loading force has been kept for 430 days. During the loading test, vertical displacements of the models, loading force and strains in concrete and steels are measured.

The tests will be continued over more 3.5 years. The results so far obtained are discussed here.

Table 1 *LIST OF SPECIMENS*

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Name | ANS | ANUS | AHS | AHUS | BNS | BNUS | BHS | BHUS |
| Temperature | 20℃ | 20℃ | 60℃ | 60℃ | 20℃ | 20℃ | 60℃ | 60℃ |
| Shape Type*) | A | A | A | A | B | B | B | B |
| Coating | resin | no | resin | no | resin | no | resin | no |

*)A series:long-span model, B series short-span model



A series test(long−span model) B series test(short−span model)

Fig.1 *LOADING CONDITION AND DETAILS OF SPECIMENS*

## 3. DESCRIPTION OF THE ANALYSIS

### 3.1 OUTLINE OF ANALYSIS

From a view point of simulating the plastic deformation due to creep and drying shrinkage, the computer program was developed in the study. The program used here was the FEM analysis with two-dimensional quadrilateral 4-nodes isoparametric elements. The interaction between creep and drying shrinkage was ignored in this analysis. The vertical displacements of the models were calculated by summarizing the displacements due to creep and drying shrinkage, which were calculated independently.

### 3.2 CREEP ANALYSIS

The displacement of the model due to creep was calculated by the following procedure. In all elements, creep strains per unit stress and per unit period for any time is calculated based on the property of concrete to be assumed. Summarizing all the strain in whole structure, equivalent external force can be computed. The same calculation is repeated , then the strain and stress of each time step were estimated. In this case, creep strain per unit stress( $\varepsilon_c$) is expressed by following equation.

$$\varepsilon_c=1/E_i+F\bullet ln(t+1)$$

where, $E_i$:initial tangent modulus
$F$ :creep coefficient
$t$ :period after loading

### 3.3 DRYING SHRINKAGE ANALYSIS

The analysis for estimating the displacement of the model due to drying shrinkage takes two process. In the first process, the amount of transferred water or released water in each element were computed by solving a water diffusion equation. In the second process, drying shrinkage strain in each element was calculated by using the relationship between the amount of released water and shrinkage strain of concrete; this relationship has to be obtained in advance.

## 4. COMPARISONS OF RESULTS OF THE ANALYSIS AND THE MATERIAL TESTS

Before performing the analysis of the reinforced concrete slab model, the same analysis was applied to small test specimens, which were prepared for measuring the deformational behavior due to creep and drying shrinkage.

It was confirmed that the analytical procedure was applicable and the mechanical properties of concrete used in the analysis were determined through the pre–analysis. The mechanical properties determined here are shown in Table 2. A typical example of the relationship between strain and the elapsed time(days) after loading is shown in Fig. 2. The figure shows that each strain due to creep and drying shrinkage and the total strain estimated by the analysis have a good agreement with the experimental results.

Table 2 *MECHANICAL PROPERTIES OF CONCRETE USED IN THE ANALYSIS*

| Temp. | Coating condition | Water transfer | | Creep | | Elastic Modulus kgf/cm$^2$ | Poison's Ratio |
|---|---|---|---|---|---|---|---|
| | | diffusion coefficient cm$^3$/day | transfer coefficient cm$^2$/day | $1/E_i$ $\times 10^{-6}$ 1/kgf/cm$^2$ | $F$ creep coef. $10^{-6}$/kgf/cm$^2$ | | |
| 20℃ | resin | 0.0025 | 0.001 | 2.71 | 0.383 | $3.69 \times 10^5$ | 0.167 |
| | no resin | | 0.025 | 2.93 | 0.733 | $3.41 \times 10^5$ | |
| 60℃ | resin | 0.23 | 0.8 | 3.36 | 0.929 | $2.98 \times 10^5$ | |
| | no resin | | 0.03 | 3.76 | 0.970 | $2.66 \times 10^5$ | |
| Water amount in environment 20℃ $9.42 \times 10^{-6}$ g/cm$^3$ 60℃ $10.94 \times 10^{-6}$ g/cm$^3$ | | | | | | | |
| Shrinkage strain per unit stress 20℃ $11500 \times 10^{-6}$ 1／(g/cm$^3$) 60℃ $3980 \times 10^{-6}$ 1／(g/cm$^3$) | | | | | | | |

creep strain per unit stress : $\varepsilon c = 1/Ei + F \cdot ln(t+1)$

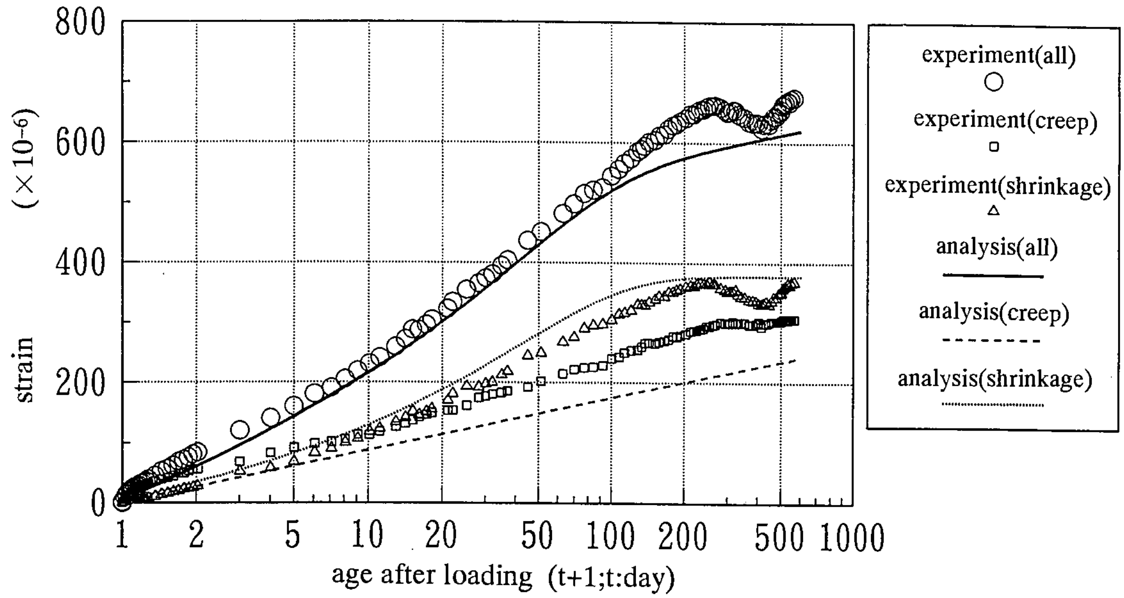


Fig.2 *RESULTS OF MATERIAL TEST AND ANALYSIS (60℃,no–resin)*

## 5. ANALYTICAL SIMULATION OF 1/5 SCALE MODEL TEST

### 5.1 MODELING OF STRUCTURE

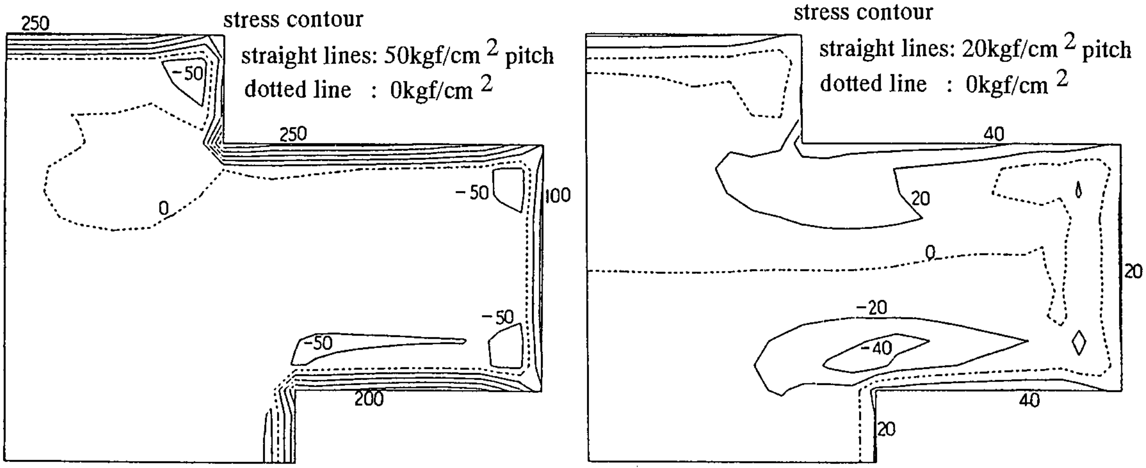
Considering the symmetry of the shape and the loading condition of the test model, a half part of the model were simulated.

### 5.2 STRESS DISTRIBUTION

The typical examples of the stress distribution caused by drying shrinkage of concrete are shown in Fig.3. Fig.3(a) shows the result to be assumed that all the elements have sound rigidity (refer to Table 2 ,elastic modulus).

The excessive tensile stress over 250kg/cm$^2$ are computed at the surface of the slab model. This is because a large drying shrinkage strain is calculated at the surface and because its strain is directly converted to stress; perfectly restrained condition is assumed here. However, in the real condition of the test model, many micro–cracks might occurred near the surface, therefor, the excessive tensile stress never occur.

In order to consider the influence of micro–cracks, the rigidity of the elements at the surface layer is decreased to be 1/10 of sound one. The calculated results using the decreased rigidity , shown in Fig.3(b), shows that the maximum tensile stress of the surface is 40kgf/cm$^2$ and that this consideration on the rigidity of element is pertinent.

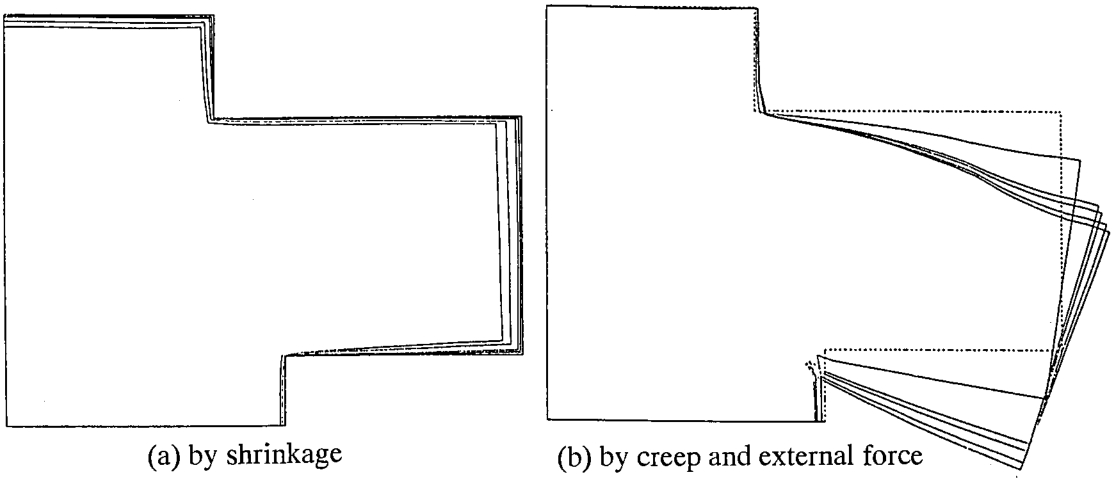


(a)uniform rigidity (b)consider rigidity reduction

Fig.3 *STRESS DISTRIBUTION CAUSED BY DRYING SHRINKAGE*

### 5.3 DEFORMATION BEHAVIOR

The vertical deformation of the slab model caused by the loading force, creep and drying shrinkage are shown in Fig.4. In the analysis on drying shrinkage, since the slab model is assumed to shrink uniformly at the surface; the portion exposed to the open air, the considered nodal point in a element at the upper surface layer moves downward and conversely that at the bottom surface layer moves upward. On the other hand, the vertical deformation due to creep becomes like that of a cantilever beam and shows a slow progress with time. The vertical deformation is calculated by summing the deformations due to creep, drying shrinkage and the loading force.



(a) by shrinkage (b) by creep and external force

Fig.4 *DEFORMATION ON CREEP AND DRYING SHRINKAGE*
(0:dotted line,50,100,300,600 days after loading)

### 5.4 LONG–TERM DISPLACEMENT

The relationship between vertical displacement at the loading point and days after loading is shown in Fig.5, where the experimental results, each calculated results of creep and drying shrinkage and the total one are plotted. The good agreement between the calculated and the experimental results is obtained. However, there is a little difference on the increase tendency of the displacement between the calculation and the experiment. The experimental results shows a curved line, on the other hand, the calculated ones shows almost a straight line. The displacement caused by creep, which occupies the most part of the total deformation, shows almost a straight line because the expression of the relation between creep strain of concrete and the elapsed time, which is proportional to $ln(t+1)$, is adopted in the analysis. Further investigation on the expression of creep behavior of concrete at high temperature condition should be performed.

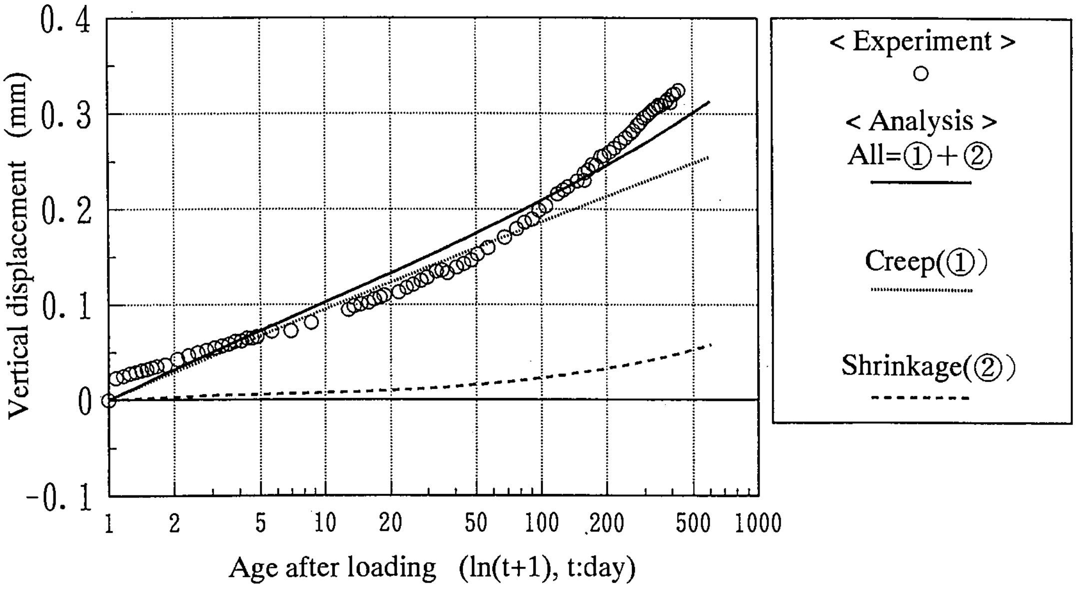


Fig.5 *CHANGE ON STANDING OF DISPLACEMENT AT LOADING POINT(AHUS model)*

Fig.6 shows the comparison of the calculated displacements with the test results, one of which considers the rigidity reduction of the elements at the surface layer and the other does not. The calculated result considering the rigidity reduction agrees with the test results at the ages one year after loading. On the other hand, the calculated result not considering the rigidity reduction gives a good agreement with the test results at the ages from the commencement of loading to 50 days after loading. The rigidity reduction of the elements considers the influence of micro–cracks on the stress development at the surface of the test model. This comparison shows that micro–cracks does not occur considerably for 50 days after loading and that the calculation with the consideration of the rigidity reduction seems to give an over–estimation.

The comparison of the calculated displacements with the tested, which are obtained at the loading point of all specimens at the age of 430 days, is shown in Fig.7. The calculation was performed with and without the consideration of the rigidity reduction. The calculated results considering the rigidity reduction generally have better agreements with the experimental ones as compared with the calculated ones without the consideration of the rigidity reduction and are apt to a little bit under–estimate the experimental ones.

It is confirmed that the FEM analysis suggested in this paper is applicable to the estimation of the long term deformation of the support slab of the ATR.

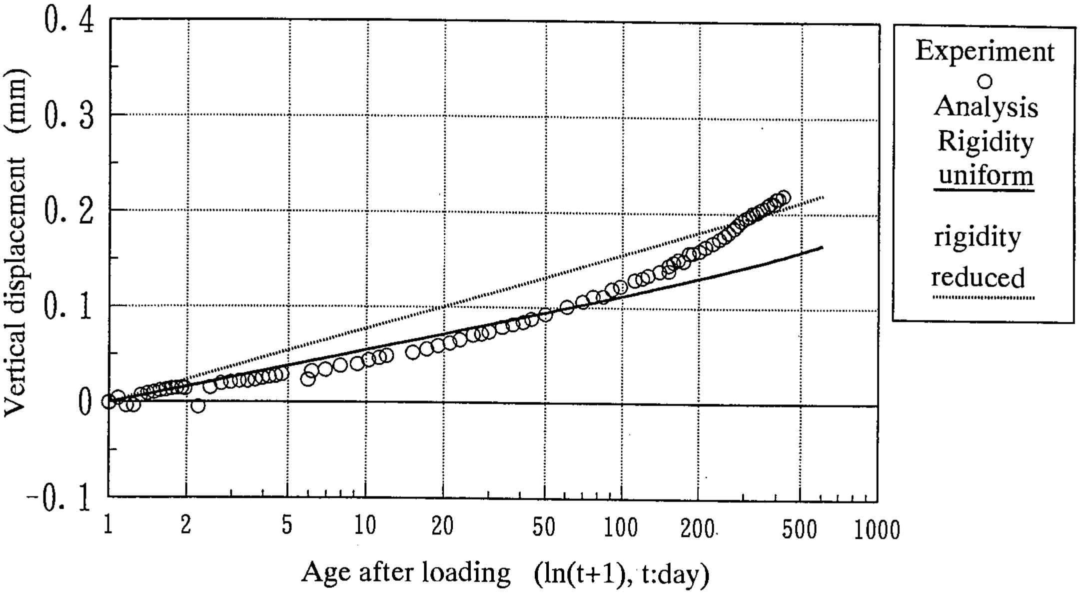


Fig.6 *EFFECT OF RIGIDITY REDUCTION (BHS model)*

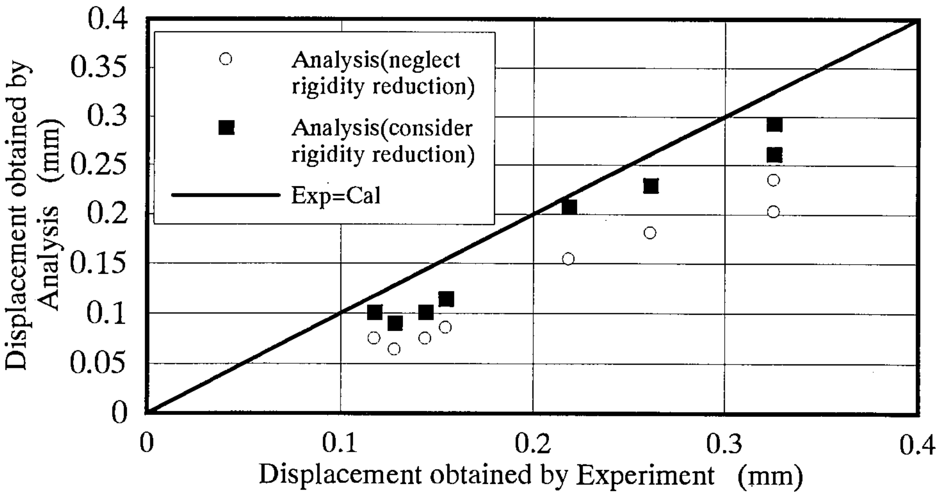


Fig.7 *COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL RESULTS*
(Ultimate displacement at age 430 days after loading)

## 6. CONCLUSIONS

To evaluate the long-term deformational behavior of the support slab of the ATR, 1/5 scale partial model tests were carried out and the application of the analytical simulations using 2-dimensional FEM was investigated. The following conclusions were obtained within the limit of the study.

(1) Mechanical properties used in the creep and the drying shrinkage analyses can be determined.

(2) Non-linearity at the surface layer caused by micro-cracks has to be considered in order to estimate the actual stress condition. The non-linearity can be estimated by considering the rigidity reduction of the elements at the surface of the calculation model.

(3) The FEM analysis suggested in this paper is applicable to the estimation of the long term deformation of the support slab of the ATR.