EXPERIMENTAL VERIFICATION OF CREEP ANALYSES FOR PRESTRESSED CONCRETE REACTOR VESSELS

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SUMMARY

Although various analytical methods have been proposed to evaluate the effect of creep on the behavior of prestressed concrete reactor vessels, the validity of them has not necessarily been checked with respect to experimental evidence. The purpose of this study was to make clear which creep analysis is most suitable in view of the comparison with experimental creep data based on the tests of prestressed and reinforced concrete members subjected to long term temperature gradients. The main conclusions within the limit of experiments are as follows:

(1) First, experiments were made to determine the properties of concrete under the environmental conditions similar in a operating PCRV. It was found that in the range of temperature 20-80 ℃ creep of sealed concrete may be assumed to increase in direct proportion to the temperature expressed in Centigrade, and that elastic modulus decreases linearly with increase in temperature.

(2) Experimental investigations were carried out in which prestressed concrete beams, hollow cylinders and a full scale model (outside diameter 3 m, external height 4 m, and wall thickness 0.5 m) were subjected to long term temperature gradients under the similar restraining conditions as in the walls of PCRV.

It was found that influence of high temperature creep of concrete on the deformations and the restraining forces in prestressed concrete members for PCRV can not be neglected even during the first stage of heating up.

As a result of creep in concrete the compressive stresses in bonded reinforcements placed near the hotter faces of prestressed concrete members for PCRV may increase to a few times as large as initial elastic stresses. This emphasises the necessity that when the allowable compressive stresses should be specified, due consideration must be paid.

(3) Various analytical methods such as effective modulus, rate of creep, superposition etc., have been been used to calculate creep strains in prestressed concrete members for PCRV. It was made clear, however, that these methods could not always give a realistic prediction for creep behaviors of concrete members especially in such stage as initial heat-up of PCRV, when concrete undergoes fairly wide variation of temperature.

The authors proposed a new method of creep analysis based on the theory of strain hardening, which assumes that accumulated creep at a given time influences the creep after that. This method was applied to calculate step-by-step the behaviors of uniaxial creep of concrete under variable temperatures and stresses, creep in reinforced concrete specimens and the behaviors of prestressed concrete beams under thermal gradients. The experimental and calculated results agreed fairly well. Further, this method was incorporated in the finite element creep analysis for the prestressed concrete hollow cylinder and the full scale model.

The calculated strain changes with time pursued closely those obtained by experiments.

The above led to the conclusion that from the viewpoint of both accuracy and computation time the strain hardening method proposed by the authors may be judged advantageous for practical usages.

1. Introduction

Prestressed concrete reactor vessels (PCRV) have already been successfully constructed in Europe and America, and considerable experience has probably been obtained with respect to the design and construction of the structure. However, if PCRVs are to be realized in Japan, several problems are left to be solved to evaluate the inherent safety of PCRV and rationalize the design procedure. In particular, PCRVs are exposed to unusual environmental conditions of temperatures, that is, the maximum of 50 - 80°C for a couple of decades, under which conditions conventional concrete structures have been soldom designed. On top of that, since stresses and temperatures in the walls of a PCRV are not constant, the effect of creep becomes different in space and time. Although the validity of various methods of creep analyses should be checked based on the comparison of creep behaviors of prestressed concrete members with those analysed, few such experimental works conducted in the above conditions have so far been published. Hence this constitutes one of the most urgent problems to be solved.

The purpose of this study was to clarify the above mentioned critical problems by means of experiments and to help rationalize the design of a PCRV, which in future will be realized in Japan. In this paper the results of the experimental investigations are completed, placing special emphasis on the effect of creep at high temperatures on the behaviors of prestressed concrete members for PCRV.

A creep analysis based on what is called strain hardening is proposed. The creep behaviors of various model concrete members were compared with those calculated by the method. The agreement were fairly well, and the validity for practical application was confirmed.

2. Basic concrete properties and constants employed in the analysis

Creep behaviors of concrete at high temperatures have been investigated Serafim(1), Wallo(2), England(3), Browne(4), Hansen(5), Hannant(6), Neville(7), Okumura (8), Kawasumi(9), etc. Based on these studies the creep characteristics of sealed concrete at temperatures from 20°C through 80°C may be summarized as follows.

(1) At constant temperatures creep increases linearly with rise in temperatures up to 70°C.

(2) Creep strains at around 70°C are generally 2 ∿ 4 times larger than those at room temperature.

(3) When the test temperature is raised half way during a creep test, the effect of temperature on the increase of creep becomes conspicuous immediately after the rise in temperature.

(4) Creep recovery at high temperature is far less marked as that at room temperature.

With a view to investigating the temperature dependence of creep in concrete the authors made a high temperature creep test on concrete subjected to constant stress and temperature. Table-1 shows the proportion of concrete employed in the test.

The strength of concrete at the time of loading (56 days) was about 450 kg/cm^2 and the stress level was kept at 100 kg/cm^2. Tests were conducted at temperatures of 20°C, 40°C, 70°C and 80°C. The creep strains obtained by the tests, if devided by the product of stress (σ kg/cm^2) and temperature (°C), could be approximately by a straight line with respect to the log scaled time after loading (Fig.-1). Thus, a creep strain ε_{cr} is described as the following equation.

$$\varepsilon_{cr} = B\cdot\sigma\cdot T \log_{10} (t + 1) \qquad \text{eq (1)}$$

where ε_{cr} : creep strain (10^{-6})

σ : stress (kg/cm^2)

T : temperature (°C)

t : time after loading (days)

B : a constant determined by experiments.

The constant B for the particular concrete employed in our investigation was found to be 0.049×10^{-6} $\{^1/(kg/cm^2)°C\}$.

Young's modulus of concrete decreased almost linearly with increase in temperature and could be represented by the equation below.

$$E_T = E_{20} (1.082 - 0.0041T) \qquad \text{eq (2)}$$

where E_T : Young's modulus at T°C

E_{20} : Young's modulus at 20°C

The average thermal expansion coefficient of concrete was measured to be 8.0×10^{-6}/°C. The values adopted in the structural analysis were corrected according to the percentage of axial reinforcements.

3. Outline of strain hardening method

Various analytical methods such as effective modulus, rate of creep, superposition etc., have been used to calculate creep strains in prestressed concrete members for PCRV. It was made clear, however, that these methods could not always give a realistic prediction of creep behaviors of concrete members, especially in such stage as initial heat-up of PCRV, when concrete undergoes fairly wide variation of temperature and relatively slow changes in temperature.

With the above mentioned fact in mind the authors proposed a new method of creep analysis based on the theory of strain hardening, which assumes that accumulated creep at a given time influences the creep after that.

The essence of the method is illustrated in Fig.-2. First, the time is divided into steps, Δt_1, Δt_2 ......, Δt_i, ... Δt_n, in each of which stress and temperature are assumed to be constant. If the suffix of the step under consideration is denoted as "i", then the creep strain at the end of the preceding step may be represented by the following equation, which incooperates the imaginary creep duration time "t_{ix}".

$$\varepsilon cr(i-k) = B \cdot Ti \cdot \sigma i \cdot \mathrm{long}_{10} (t_{ix} + 1) \qquad \text{eq (3)}$$

In the above equation creep strain is assumed to proceed in accordance with the equation (1). Solving the equation (3) with respect to t_{ix}, we can find the unknown value of t_{ix} from the predetermined value of $\varepsilon_{cr(i-1)}$.

$$t_{ix} + 1 = \exp\left\{\frac{2.303\ \varepsilon cr(i-1)}{B \cdot T_i \cdot \sigma i}\right\} \qquad \text{eq (4)}$$

The accumulated creep strain at the end of the i th step can be determined by the following.

$$\varepsilon_{cri} = B \cdot T_i \cdot \sigma_i \cdot \mathrm{long}_{10} (t_{ix} + \Delta t_i + 1) \qquad \text{eq (5)}$$

The above consideration is restricted to uniaxially stressed state problems. The concept, however, may be extended to two or three dimentional problems by introducting creep Poissons's ration ν_{cr}. When the strain hardening method is to be applied to the stress analyses of axisymmetric structures such as PCRV, the imaginary creep duration time must be determined in each of three directions, that is, radial (r), circumferential (θ) and axial (Z) directions. The value can be obtained by solving simultaneous equations, and the solution will be given in a matrix form as below.

$$\begin{Bmatrix} t_{ir,x} + 1 \\ t_{i\theta,x} + 1 \\ t_{iZ,x} + 1 \end{Bmatrix} = \exp\left\{ \frac{2.303}{BT_i} \begin{bmatrix} D \end{bmatrix}^{-1} \begin{Bmatrix} \varepsilon_{cr.r(i-1)} \\ \varepsilon_{cr,\theta(i-1)} \\ \varepsilon_{cr,Z(i-1)} \end{Bmatrix} \right\} \qquad \text{...... eq (5)}$$

$$\begin{bmatrix} D \end{bmatrix} = \begin{bmatrix} \sigma_{ir} & -\nu_{cr}\,\sigma_{i\theta} & -\nu_{cr}\,\sigma_{iz} \\ -\nu_{cr}\,\sigma_{ir} & \sigma_{i\theta} & -\nu_{cr}\,\sigma_{iz} \\ -\nu\sigma_{ir} & -\nu\sigma_{i\theta} & \sigma_{iz} \end{bmatrix} \qquad \text{...... eq (6)}$$

where tir,x, $t_{i\theta,x}$, $t_{iz,x}$; imagenary creep duration time for the i th step in radial, circumferential and axial directions.

σ_{ir}, $\sigma_{i\theta}$, σ_{iz}; stresses during the i th step.$\varepsilon_{cr,r(i-1)}$, $\varepsilon_{cr,\theta(i-1)}$, $\varepsilon_{cr,z(i-1)}$; creep strains at the end of the (i-1) th step.

In this creep analysis the effects of temperature and stress changes are accounted for by adjusting the imagenary creep duration time. From a qualitative point of view this procedure may be considered to reflect realistic characteristics of creep in concrete at high temperatures, which were mentioned in the previous section 2. But as there is no distinct phisical background supporting this theory, experimental study was undertaken, which will be given below.

4. Experimental verification of the strain hardening method

4.1 Uniaxial creep behaviors of concrete under variable temperatures and stresses

First experiments were made on the creep of concrete under variable stresses and temperatures. The specimens employed were ∅15 x 50 cm cylinders, which were sealed by copper plate. They were loaded in a temperature regulated bath. An example of comparison between the experimental creep strains and those calculated by various methods is shown in Fig.-3. As is clear from the Figure, the strain hardening method, together with method of superposition, exhibits a fairly good agreement with the experimental data.

In Fig.-4 a comparison is made for the case in which only the temperature was changed. In this case the method of superposition could not be applied, since the method has no ability to take into consideration only the effect of temperature change. Again a good agreement was obtained between the experimental value and that calculated by strain hardening method.

4.2 Compressive creep in reinformed concrete

When a reinforced concrete member is subjected to sustained axial compressive force, the stress shared by concrete portion gradually shifts to reinforcements as a result of creep in concrete. Therefore, concrete creeps under the condition of diminishing stress. To investigate the creep behaviors of reinforced concrete experiments were conducted in which reinforced concrete cylindrical specimens, the size of which was the same as that described in Section 4.1, were loaded at a stress of 100 kg/cm^2 for a duration of about half a year. Temperatures were kept constant at 20°C and 40°C. The reinforcement ratios adopted were 0, 2.25, 3.43 and 4.50%.

The ratio of creep strain in reinformed concrete specimen to that in plain concrete after a loading of 180 days are plotted in Fig.5, coupled with the curves calculated by the strain hardening method. Also for this case, good agreement were found between the experimental and analytical values.

4.3 Flexural creep behavior of prestressed concrete beams

In addition to the creep of concrete under uniaxial compression, creep and relaxaction behaviors of prestressed concrete beams under sustained temperature gradients were investigated. The beams employed in the tests are illustrated in Fig.-6. Overall length and the cross section of the central portion of the beams were 380 cm and 40 x 12.5 cm, respectively. The beams were supported on roller bearings, allowing for free movement in the longitudianl direction. The length of the central portion of beams subjected to temperature gradient was 220 cm. Uniform prestress of around 70 kg/cm^2 was applied to the beams. Heating programs are shown in Fig.-7. The temperature difference was raised stepwise by 10°C in every 6 hours up to the maximum difference of about 65°C. The maximum temperature difference was sustained for about three months.

Two beams were tested, of which one was flexurally restrained and the time dependent restraining moment was measured (relaxation type). The other was subjected to a constant moment and time dependent deflexion was measured (creep type). Step by step numerical analyses were performed based on the similar assumptions as suggested by England et al.[10] The beam section was divided into 20 equal parts and the creep strains were estimated by the strain hardening method.

A curve of time dependent restraining moment for the first beam is drawn on Fig.-8. It can be seen that considerable relaxation in restraining moment occurs even during the relatively short time of initial heating stage. The restraining moment just after the maximum temperature difference attained was about 40% below the value calculated by an eleatic theory. It can also be observed that forty days of sustained temperature brings the thermal stresses almost to naught, which shows how fast the temperature effect diminishes. At cooling stage behaviors of the beam are essentially elastic and the influence of creep recovery is to be neglected. Accordingly, stress on hotter face, which was compressed at heating stage, becomes tensile at cool down. The agreement is also fair between the experimental and the analytical tendencies.

Fig.-9 shows the time dependent deflection at the center of the beam subjected to sustained moment. The calculated deflection concurs fairly well with the measured.

Judging from the fact that validity of the strain hardening method was confirmed for two extreme cases (relaxation and creep), the applicability of the method to real structures may generally be accepted.

4.4 Creep behaviors of prestressed concrete ring model

In order to further confirm the applicability of the strain hardening method to structural creep analyses in three dimensional condition such that encountered in cylindrical walls of PCRV, a thick walled prestressed concrete ring model was constructed and tested.

The configuration and the technique to give the model thermal gradient are illustrated in Fig.-10. The model was prestressed only circumferentially to a stress of around 50 kg/ cm^2. Strains in concrete were measured by embedded carlson type strain guages. The data related to the model, together with the properties of concrete, are listed in Table-2.

A comparison of measured strains with those calculated is made in Fig.11. The solid curves, which designate the calculated values, seem to agree well with the measured points. The analysis was conducted by means of finite element method, in which creep strains were determined by eq.(5). The acceptability for practical utility of the method was again confirmed by this experiment.

4.5 Creep test of full scale PCRV model

A thermal creep of full scale PCRV model is now under way, by which the validity and the limit of practicability will further be clarified. Here only the dimensions and the cross section of the cylindrical model with top and bottom slabs is to be presented, together with a few data so far obtained (Fig.-12 and Fig.-13). The detailed results and discussions will be published in a separate paper in the near future.

5. Concluding remarks

The authors proposed a new method of creep analysis based on the theory of strain hardening, which assumes that accumulated creep at a given time influences the creep after that.

This method was applied to calculate step-by-step the behaviors of uniaxial creep of concrete under variable temperatures and stresses, creep in reinformed concrete specimens and the behaviors of prestressed concrete beams under thermal gradients. The experimental and calculated results agreed fairly well. Further, this method was incorporated in the finite element creep analysis for the prestressed concrete hollow cylinder and the full scale model. The calculated strain changes with time pursued closely those obtained by experiments.

The above led to the conclusion that from the viewpoint of both accuracy and computation time strain hardening method proposed by the authors may be judged advantageous for practical use.

Table-1. Concrete mix. proporation employed in the experiments

Water cement ratio %	Fine aggregate as volume percent of total aggregate	kg/m^3					
		Water	Cement	Fine aggregate	Coarse aggregate		Pozzolith
					10∿20mm	5∿10mm	
35.4	37.8	170	480	621	547	547	4.80

Slump 8 ±/cm, Air content 2.5 ± 0.5%.

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Table-2. Data related to prestressed ring model

(1) Dimensions of the model	Outer diameter Inner diameter height	3m 2m 1.5m
(2) Properties of concrete at the age of 28 days	Compressive strength Young's modulus Coefficient of thermal expansion Thermal conductivity Specific heat	425 kg/cm^2 3.39×10^5 kg/cm^2 $11 \times 10^{-6}/°C$ 2.13 Kcal/m°chr 0.308 Kcal/kg°C
(3) Prestressing	Total amount of prestress Diameter of strands Friction due to curvature Layers of strands The age of prestressing System	304 ton 15.2 mm 0.420 18 layers 28 days Fressinet
(4) Method of heating and cooling	Inner steel liner (thickness 2.4 mm) was heated by circulated hot water. Outer surface of concrete was constantly showered by cold water. Thermal test was commenced 28 days after prestressing.	

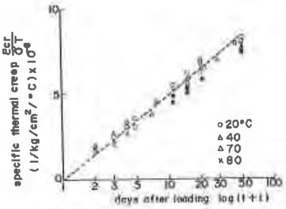


Fig - 1 Relation between days after loading and specific thermal creep

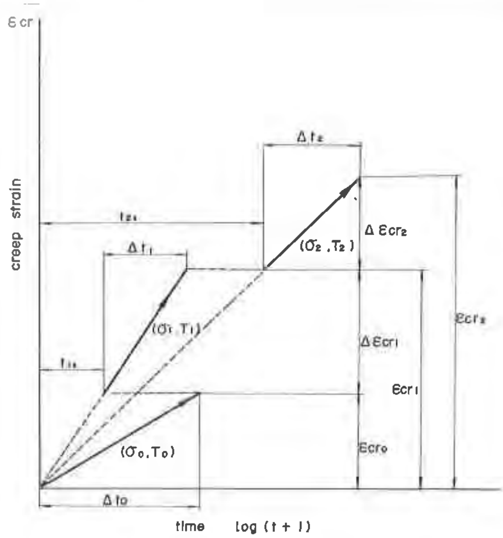


Fig - 2 Concept of strain hardening method

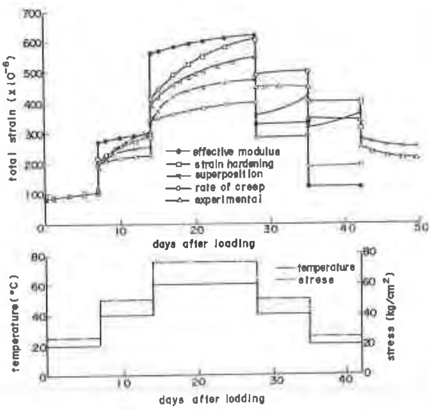


Fig - 3 Creep under variable stresses and temperatures

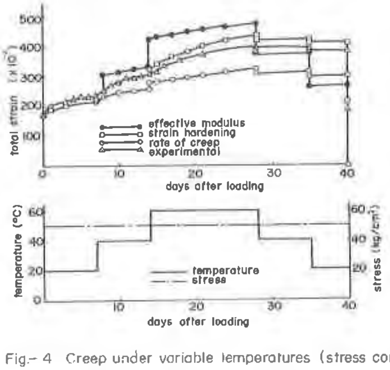
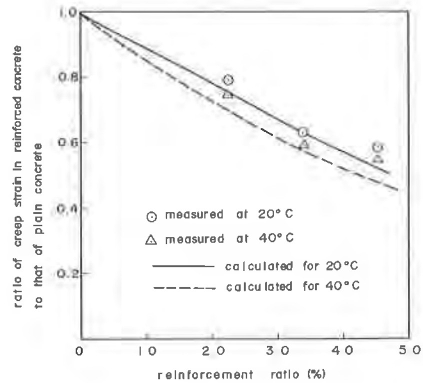
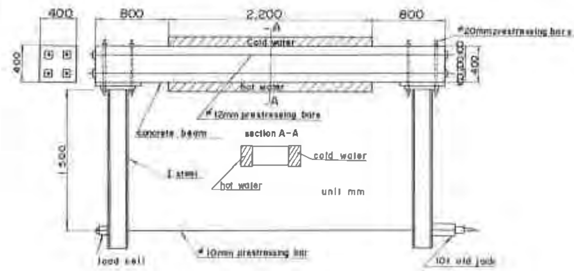


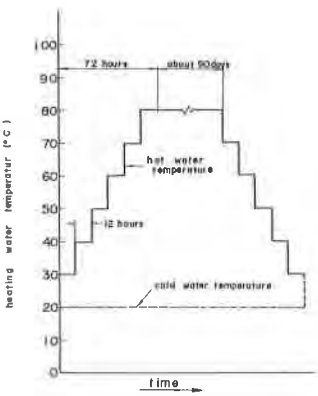
Fig.- 4 Creep under variable temperatures (stress constant)



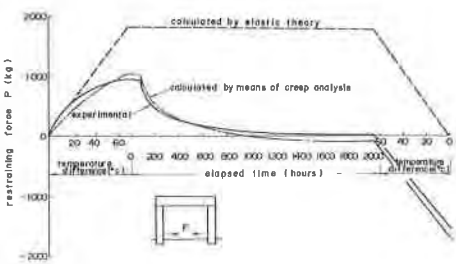
Fig－5 Creep strains in reinforced concrete as a function of reinforcement ratio



Fig－6 Thermal test apparatus for prestressed concret beams



Fig－7 Heating program for prestressed concrete beams



Fig－8 Time dependent restraining force for prestressed concrete beam (relaxation type test)

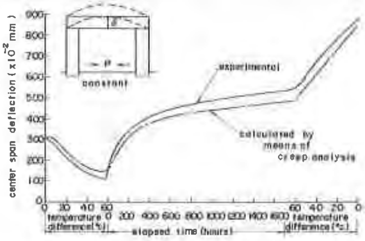


Fig — 9 Time dependent deflection at the center of prestressed concrete beam (creep type test)

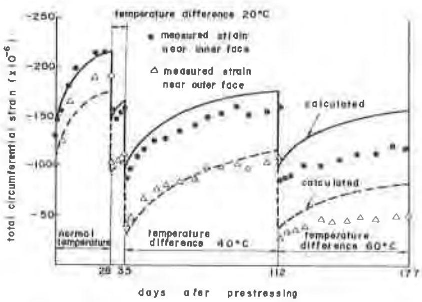
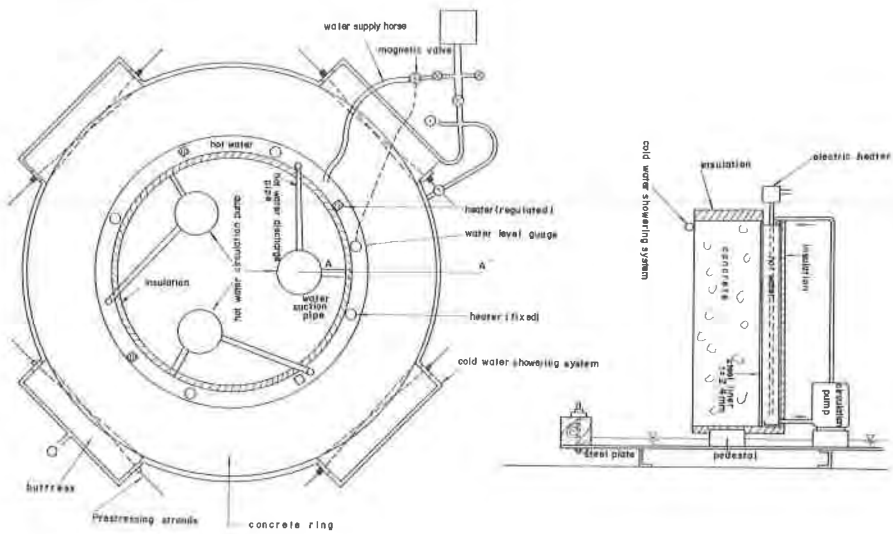


Fig — 11 Comparison of measured and calculated strains in prestressed concrete ring model



Fig—10 Thermal test method for prestressed concrete ring model

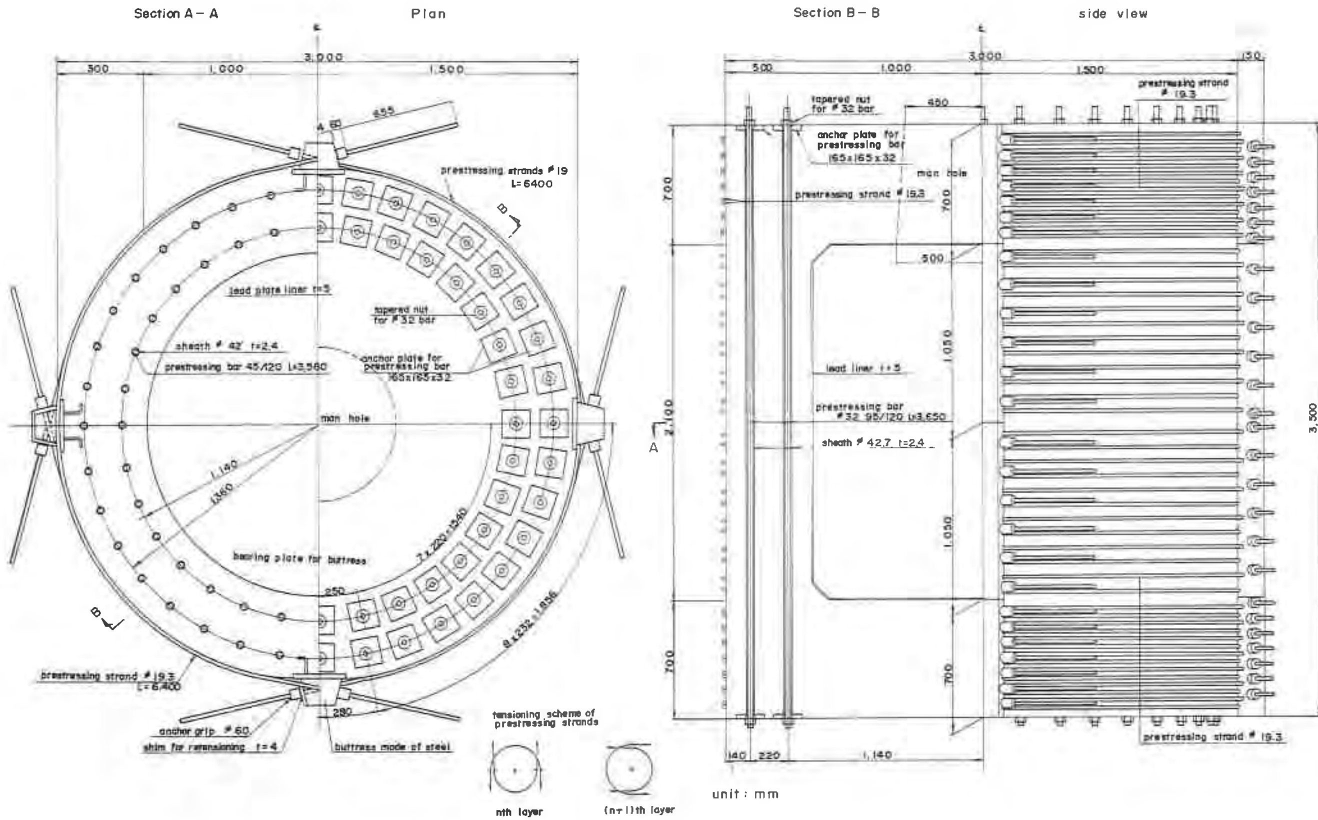


Fig – 12 Full scale model of PCRV for thermal creep test

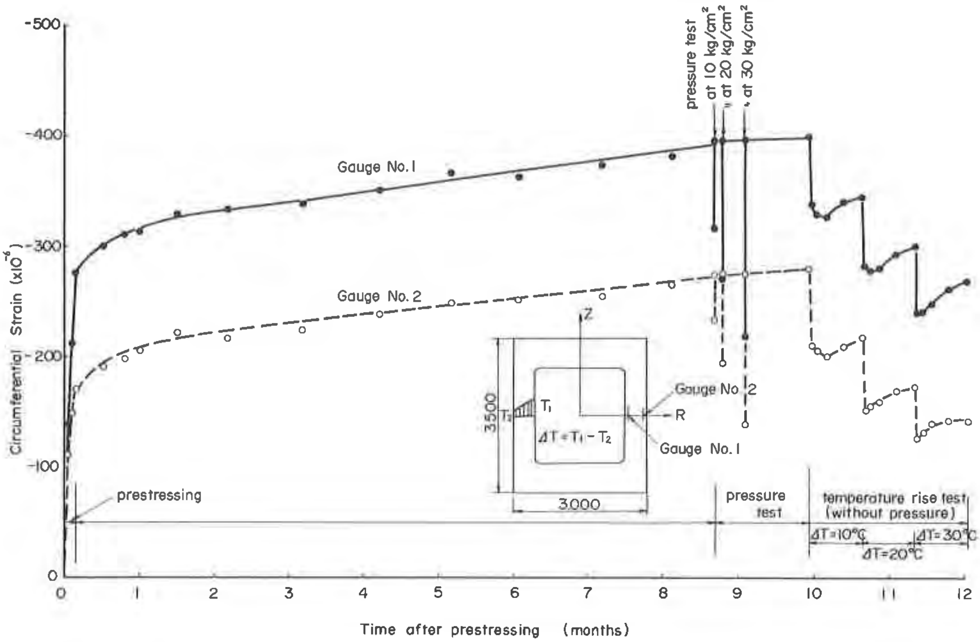


Fig – 13 An example of measured circumferential strains in P C R V