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# STUDY ON A METHOD FOR CONTROLLING THERMAL CRACK BY MEANS OF MODERATE PRESTRESSING

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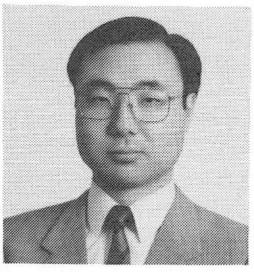
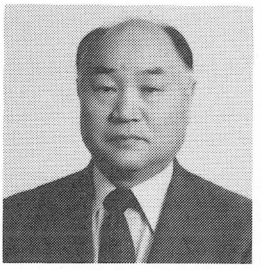
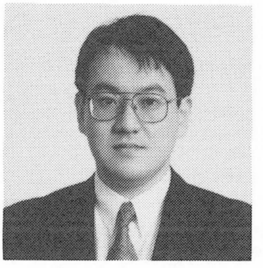
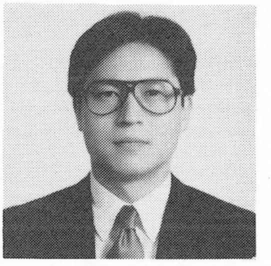

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## SYNOPSIS

With the recent tendency of enlarging structure in size, thermal cracks in massive reinforced concrete structures have become one of the pressing problems of the day. This paper deals with the development of a moderate prestressing method using an expansive admixture for thermal cracking control. In order to evaluate prestressing force of a new prestressing device, several laboratory experiments are carried out, and this new method is proved useful by several field experiments. In addition, the experimental results are compared with some numerical calculations to clarify the applicability of the theoretical method which was newly proposed for predicting the effect of thermal crack control.

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## 1. INTRODUCTION

Thermal cracks in massive reinforced concrete structures, such as nuclear power stations, large-sized piers, liquid natural gas storage tanks and underground concrete structures, have become one of the pressing problems of the day [1],[2]. To maintain durability and watertightness in these structures, the methods to control thermal cracks are essential. The development of control methods may afford the required solution in design [3],[4].

This paper deals with the development of a moderate prestressing method using an expansive admixture for thermal cracking control. This new method is proved useful by several field experiments. In addition, in order to predict the effect of thermal crack control with this method, a new theoretical model is proposed on the basis of both ACI's method [3] and CPM(Compensation Plane Method is called CPM for short) [1].

## 2. OUTLINE OF MODERATE PRESTRESSING METHOD

The typical moderate prestressing device using an expansive admixture for thermal cracking control is shown in Fig.1. This device is composed of five main parts: I .expansive admixture, II .unbonded sheath, III .prestressing steel bar, IV .cylinder and V .anchoring plate, as shown in Fig.1. The expansive admixture reacts with hydration heat of concrete. Prestressing force of the prestressing device is about 50～200kN per bar.

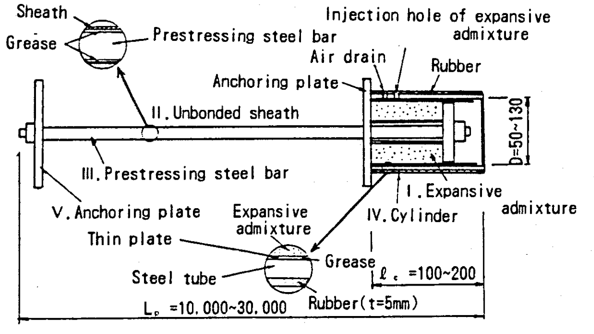



Fig.1 Typical structure of the moderate prestressing device(unit:mm)

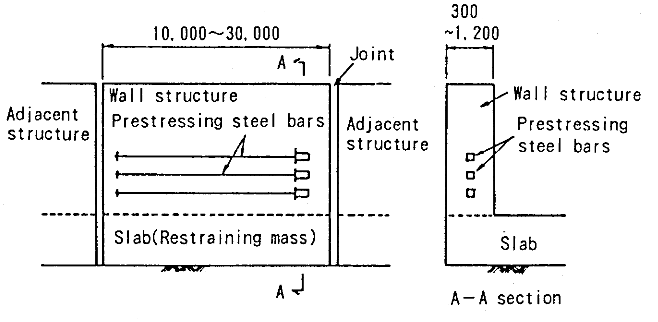



Fig.2 General view of setting the prestressing devices (unit:mm)

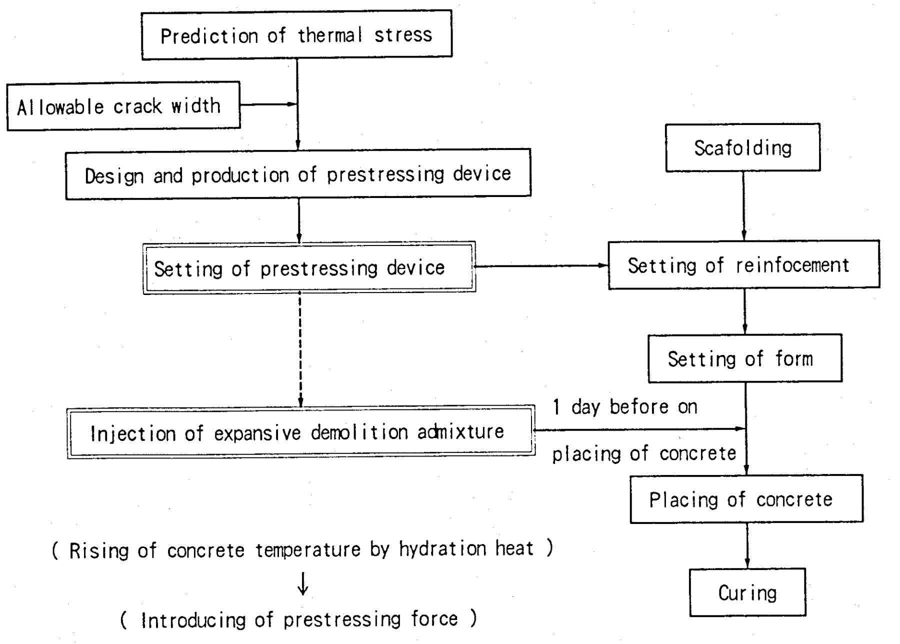



Fig.3 Procedure of construction

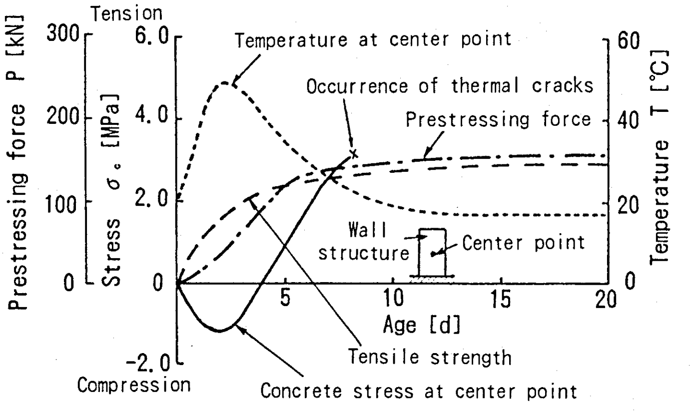



Fig.4 Typical temperature, thermal stress, prestressing force with time in massive wall structure

The prestressing steel bars are embedded in the center of concrete wall structure as shown in Fig.2. Fig.3 illustrates the procedure of construction for setting of these bars.

The typical temperature, thermal stress and prestressing force with time in a massive wall structure are shown in Fig.4. For controlling thermal cracks by means of the moderate prestressing, the initial prestressing is introduced after concrete has hardened, and the majority of final prestressing force will be introduced before cracks by thermal stress will occur.

## 3. EXPERIMENTS FOR PRESTRESSING DEVICES

### 3.1 Experimental Apparatus and Procedure

The experimental prestressing device in this study is schematically shown in Fig.5 [5]. The device consists of three main parts :a cylinder model, a heating system and a recorder. Each part of devices in Fig.5 is as follows: ①cylinder, ②expansive admixture, ③plate, ④prestressing steel bar, ⑤anchoring plate, ⑥nut, ⑦heating cord, ⑧load cell, ⑨displacement gauge, ⑩thermal controller and ⑪automatic recorder . The cylinder is a high-strength steel tube, and a metallic sheet is wrapped inside of it. The expansive admixture reacts with heat generated by an electric heating cord. A position of a nut is at the distance, s=0.95 ～11mm, from the ⑤ anchoring plate. The distance s is equivalent to the elastic displacement for prestressing steel bar of 1.3 ～15m in length. Namely, the distance s is given by $s=(L_p P)/(A_s E_s)$ ($L_p$ :length of prestressing steel bar, P: prestressing force, $A_s$:cross-sectional area of prestressing steel bar, $E_s$ :elastic modulus of prestressing steel bar).

The experimental procedure is by the following steps. First, the cylinder is filled with an expansive admixture(W/C=30%, W:weight of water per unit volume, C:weight of expansive admixture per unit volume). And then, heat around the cylinder is generated by an electric heating cord after 24 hours under normal temperature. Here, the experiment was performed under two different thermal conditions by using a thermal controller:one is under temperature change with elapsed time on assumption of the wall width of about 1.0m(Run-A) and another is under constant temperature(Run-B). The values of temperature, displacement and strain are continuously measured and recorded by the automatic recorder.

In order to clarify through experiments how prestressing force in this method works, the experiments were carried out in sixteen different conditions as shown in Table-1.

Photo-1 shows the experimental apparatus.

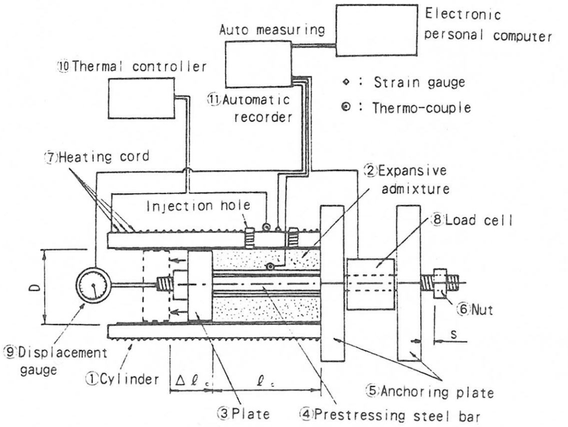



Fig.5 Schematic presentation of experimental apparatus

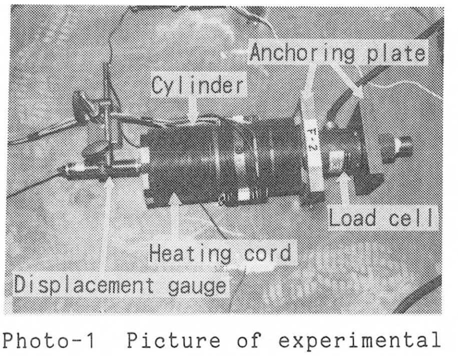



Photo-1 Picture of experimental apparatus

### 3.2 Experimental results and discussions

The prestressing forces in all experiments are listed in Table-1. To examine characteristics of prestressing force, experimental results are described under appropriate conditions.

Fig.6 shows the prestressing force with time, where the diameter of a cylinder and the length of an expansive admixture are fixed and temperature changes from normal to maximums of either 35℃ or 45℃. The time t starts when expansive admixture is injected in the cylinder. The solid lines are under $T_{max}$ =45 ℃(Run-A-3), and the dot-dash-lines are under $T_{max}$ =35 ℃ (Run-A-6). The prestressing forces are being set up in the concrete before the concrete gets the maximum temperature. And then, the prestressing force increases to nearly 70 ~80% of final one in two days. Relationship between final prestressing force and the maximum temperature to the utmost limit obtained by arranging the results of Fig.6 and Table-1 is shown in Fig.7. The increase of prestressing forces is hardly affected by external heating. Fig.8 shows the prestressing force with time, where the temperature change of concrete and the length of expansive admixture are fixed and the diameter of a cylinder is changed. Relationship between final prestressing force and cross-sectional area of expansive admixture obtained by arranging the results of Fig.8 and Table-1 is shown in Fig.9. It is obviously found that the prestressing force depend on the cross-sectional area of an expansive admixture. Fig.10 shows the prestressing force with time, where only the length of the expansive admixture is changed. Relationship between the final prestressing force and the length of an expansive admixture obtained by arranging the results of Fig.10 and Table-1 is shown in Fig.11. It can be considered that there is no effect of the length of the expansive admixture.

Therefore, the final prestressing force P under $L_p$ ≒10 ~15m and $T_{max}$ =35 ~60℃ is obtained as,

$$P \fallingdotseq 0.15A_d \quad \text{(1)}$$

in which P:prestressing force per bar, $A_d$:cross-sectional area of expansive admixture.

Table-1 Experimental conditions and results

| Case (Run-) | A-1 | A-2 | A-3 | A-4 | A-5 | A-6 | A-7 | A-8 | B-1 | B-2 | B-3 | B-4 | B-5 | B-6 | B-7 | B-8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thermal condition | temperature with time in typical massive wall | | | | | | | | constant temperature | | | | | | | |
| Cross-sectional area of expansive admixture $A_d$ [cm²] | 124.9 | 41.3 | 80.8 | 41.3 | 80.8 | 80.8 | 80.8 | 14.4 | 52.57 | 52.57 | 52.57 | 36.17 | 36.17 | 36.17 | 52.57 | 52.57 |
| Length of expansive admixture $\ell_e$ [mm] | 150 | 150 | 150 | 150 | 200 | 150 | 150 | 150 | 100 | 150 | 200 | 100 | 150 | 200 | 150 | 150 |
| Maximum temperature to the utmost limit $T_{max}$ [℃] | 45 | 45 | 45 | 45 | 45 | 35 | 45 | 45 | 50 | 50 | 50 | 50 | 50 | 50 | 40 | 60 |
| Elastic displacement s [mm] | 11 | 5.5 | 11 | 11 | 11 | 11 | 11 | 0.95 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Plate displacement $\Delta\ell_e$ [mm] | 19.9 | 5.5 | 12.7 | 11.1 | 11.7 | 11.4 | 12.8 | 1.9 | 10.1 | 10.7 | 10.4 | 10.1 | 10.2 | 10.5 | 10.6 | 10.7 |
| Prestressing force per bar after 1 week P [kN] | 176.4 | 72.5 | 124.5 | 56.8 | 145.0 | 103.9<br>118.6* | 167.6 | 26.5 | 86.2 | 103.9 | 110.7 | 46.1 | 54.9 | 55.9 | 100.9 | 213.6 |

* : after 3 weeks

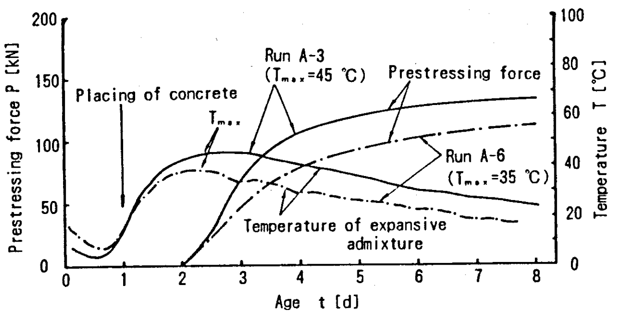



Fig-6 Prestressing force with time P for different temperature with time T

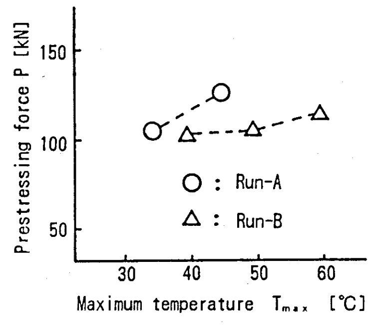



Fig-7 Relationship between maximum prestressing force P and maximum temperature to the utmost limit $T_{max}$

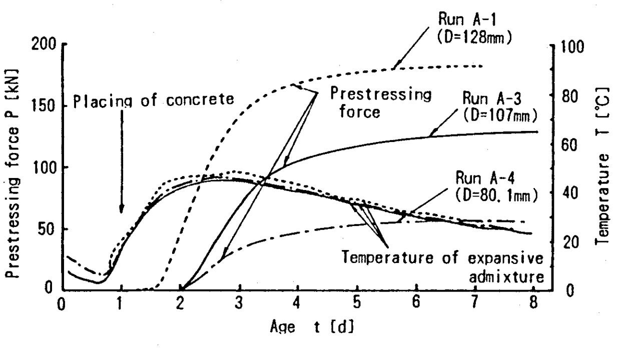



Fig-8 Prestressing force with time P for different inside diameter of cylinder D

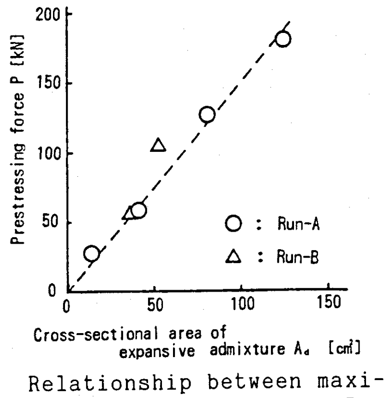



Fig-9 Relationship between maximum prestressing force P and cross-sectional area of expansive admixture $A_d$

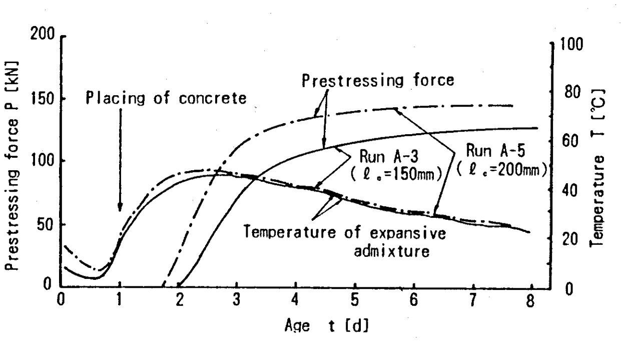



Fig-10 Prestressing force with time P for different length of expansive admixture $\ell_c$

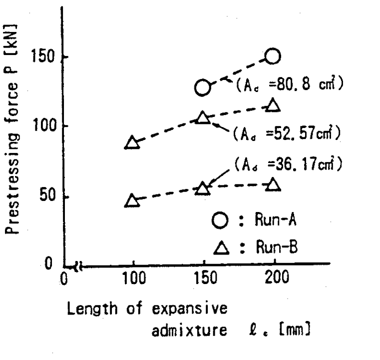



Fig-11 Relationship between maximum prestressing force P and length of expansive admixture $\ell_c$

## 4. ACTUAL PROOF EXPERIMENTS

The moderate prestressing method has been proved useful by the field demonstrations performed in four facilities. This paragraph deals with the experimental results in wall structures of the pumping station(A) [5],[6]. The demonstration results of three other facilities are briefly shown in Table-3 of paragraph 5 of this paper.

### 4.1 Outline of Field Demonstrations

The general view of the pumping station(A) is illustrated in Fig.12. This method was carried out in No. I screen wall in Fig.12. No. II and No. III walls are the same form as No. I wall. In order to compare thermal behavior of No. I wall with that of No. II wall, the same measurement was carried out in both No. I and No. II walls. The expansive admixture had been injected into the cylinder on June 11, 1984. Fresh concrete for No. I and No. II walls had been placed from six to nine in the morning on June 12, and that for No. III wall had been done by noon on the same day. The initial temperature of concrete was at 25 ℃. The cement used in this concrete were ordinary portland cement. The mix proportion of the concrete is shown in Table-2.

Fig.13 shows the view of No. I wall equipped with the prestressing steel bars. The size of wall is 1m in width, 15m in length, 3.9 ～4.73m in height. Fresh concrete was placed on the hardened concrete slab. The space of reinforcing bars was 300mm, and concrete cover for the embedded bars was 100mm. The maximum values of temperature to the utmost limit, tensile stress of concrete, crack width obtained from CPM in the wall structure are $T_{max}$ =46 ℃, $\sigma_c$ =2.69 MPa, $w_{max}$ =0.12mm, respectively.
It is assumed that the width of thermal cracks by the moderate prestressing is zero in design. Six numbers of the prestressing steel bars were arranged with separation distance 300mm in the center of the wall. Prestressing force per bar and cross-sectional area of expansive admixture should satisfy the conditions of $P \geqq 107$kN and $A_d \geqq 73.3$cm², which were determined by the evaluative method of the paragraph 5 mentioned later and Eq. (1) respectively. Therefore, the size of prestressing device becomes D=107mm, $L_p$ =1440mm, $\ell_c$ =150mm, and the diameter of prestressing steel bar is $\phi$ =28mm in Fig.1.

Photo-2 illustrates the view equipped with the prestressing steel bars.

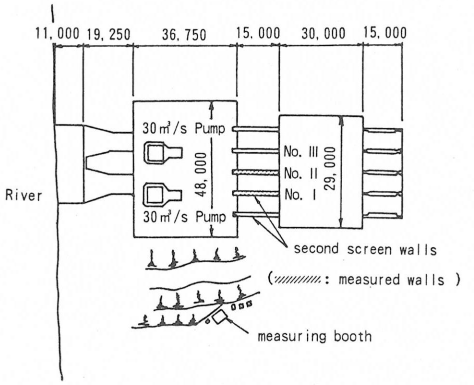



Fig.12 General view of the pumping station(A)(unit:mm)

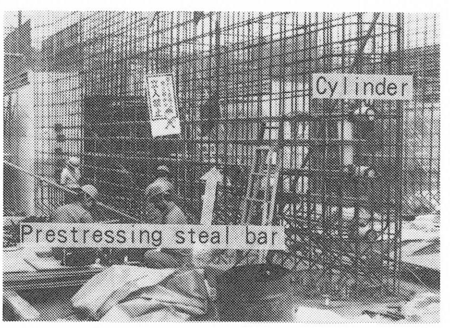



Photo-2 Picture of view equipped the prestressing steel bars

Table-2 Mix proportion of concrete

| nominal strength (MPa) | $G_{max}$ (mm) | slump (cm) | air (%) | W/C (%) | s/a (%) | unit weight (N/m³) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | W | C | S | G | AE |
| 20.6 | 25 | 8 | 4 | 59.8 | 43.0 | 1558 | 2607 | 7879 | 10702 | 0.843 |

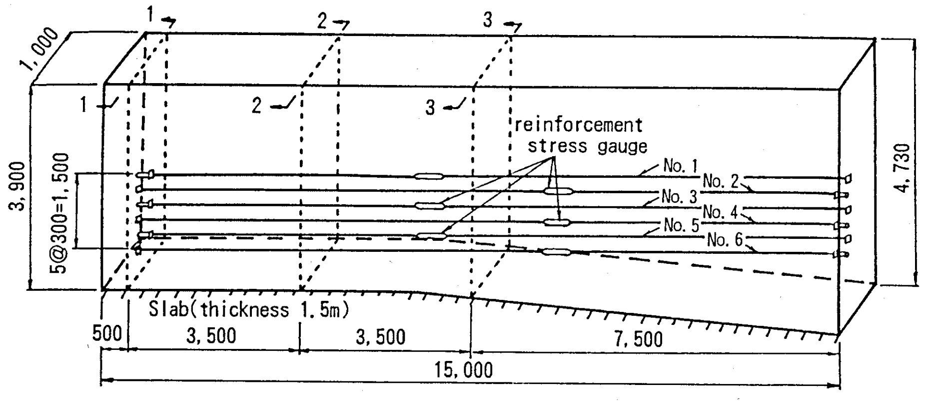



Fig.13 View equipped with the prestressing device in No. I wall(unit:mm)

## 4.2 Items and Procedure of Measurements

Fig.14 shows location of measurement instruments installed into No. I and No.II walls. Temperature, concrete strain, concrete stress and coefficient of linear thermal expansion are measured by thermo-couple, mold gauge, effective stress gauge, non-stress gauge, respectively. The measurement of the prestressing force is taken by reinforcing bar gauge. Compressive strength tests of concrete were carried out by cylindrical test pieces cured under the environment of this site. The width and length of thermal cracks are measured by a crack loupe and a tape measure, respectively.

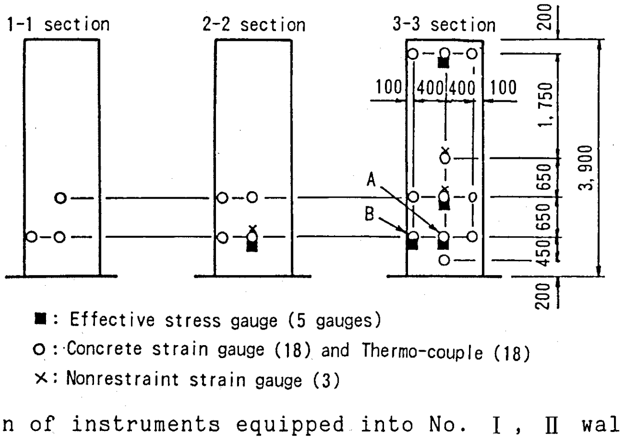



Fig.14 Location of instruments equipped into No. I , II wall (unit:mm)

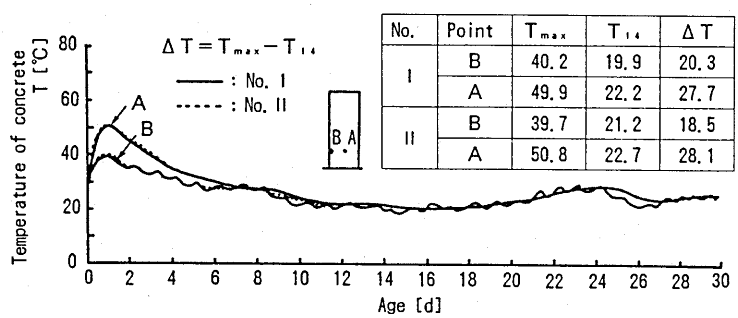
## 4.3 Results and Discussion of Field Experiments

In order to prove the effect of this new method for control of thermal cracks, some of typical results in the field demonstrations are shown in Figs.15 ~19.

Fig.15 shows the temperature with time at the center point A and the surface point B of No. I and No. II walls. Temperature of concrete reached to the maximum temperature to the utmost limit after 22 hours, and decreased to about 20 ℃ at the age of 2 weeks. The temperature with time of No. I wall is similar to that of No. II .

Fig.16 gives the prestressing force per bar with time in No. I wall. The reaction of expansive admixture is commenced after about 9 hours of the concrete placement. The prestressing force is introduced to about 98kN per bar at the age of 2 days, since then, it increases only slightly with time. The average of three prestressing force P=105kN per bar agree well with results obtained from Eq.(1) at the time of occurrence of thermal cracks (age 12 days).

Figs.17 and 18 show the stress and strain with elapsed time at the center point A and at the surface point B, respectively, in No. II and No. III walls. The maximum value of compressive stress and restraining strain appear at the time of maximum temperature to the utmost limit. Tensile stress and strain of the center point A are larger than those of surface point B. The concrete stress of No. II wall(nonprestressed concrete) decreased suddenly, and its concrete strain increased suddenly early in the morning of the age of 12 days. At this time, it is possible to consider that the thermal cracks occurred in No. II wall.




| No. | Point | $T_{max}$ | $T_{14}$ | $\Delta T$ |
|---|---|---|---|---|
| I | B | 40.2 | 19.9 | 20.3 |
| | A | 49.9 | 22.2 | 27.7 |
| II | B | 39.7 | 21.2 | 18.5 |
| | A | 50.8 | 22.7 | 28.1 |

Fig.15 Temperature of concrete with time

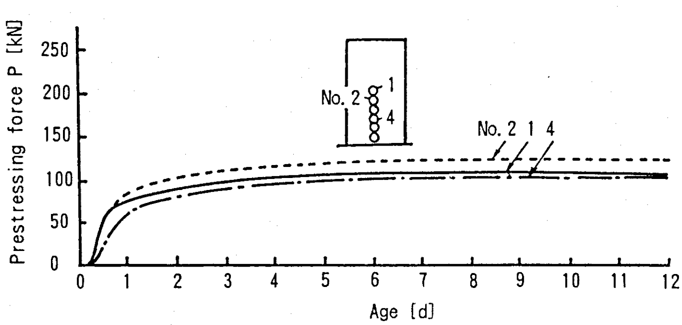



Fig.16 Prestressing force with time

Fig.19 illustrates the state of occurrence of thermal cracks in No. Ⅰ, Ⅱ and Ⅲ walls. Fig.19 (a) shows the thermal cracks at the age of 14 days. It is found that thermal cracks with about 0.1mm in width occurred in nonprestressed No.Ⅱ, Ⅲ walls. On the other hands, the existence of thermal cracks was not observed in No.Ⅰ wall in which moderate prestressing was introduced. These results agree with the results shown in Fig.18. Fig.19 (b) shows thermal cracks at the age of 49 days. Thermal cracks of width 0.1 ～0.18mm occurred in No.Ⅰ wall. While thermal cracks in No. Ⅱ, Ⅲ walls increased from 0.1mm to 0.4～0.5mm.

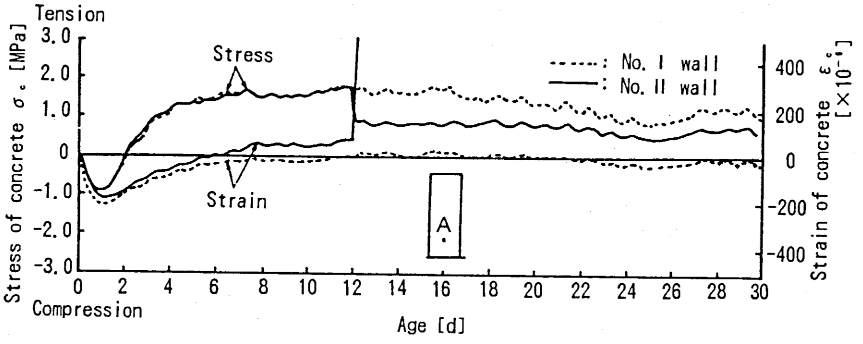



Fig.17 Stress and strain of concrete with time at the center point A

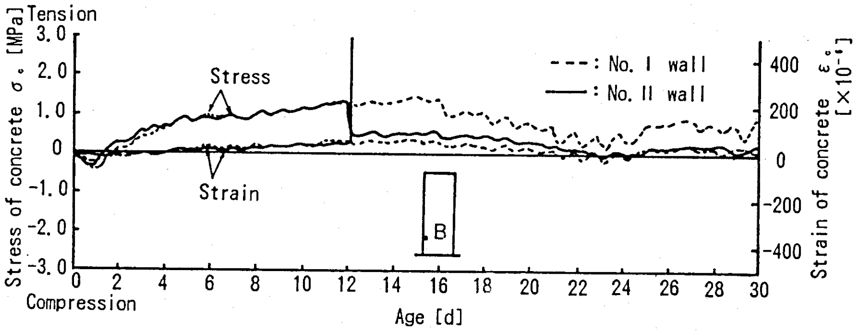



Fig.18 Stress and strain of concrete with time at the surface point B

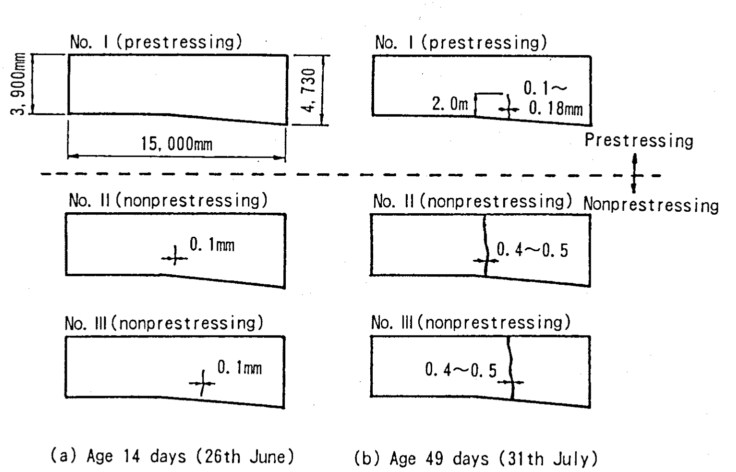



Fig.19 Results investigated the occurrence state of thermal cracks

## 5. DISCUSSION OF CONTROL EFFECT OF THERMAL CRACKS

In order to examine the effect of thermal crack control, this paragraph describes the new theoretical method based on both ACI's method [3] and CPM [1]. And, the field experimental results are compared with some numerical calculations obtained by using this method.

### 5.1 Concrete Stress at the Time of Occurrence of Thermal Cracks

It is necessary to know the distributions of concrete stress at the time of occurrence of thermal cracks for the purpose of its prediction and control. A basic model for predicting the occurrence of thermal cracks is introduced as shown in Fig.20. The concrete wall structure(length of L, width of B, height of h) was built on the hardened concrete slab, and at the same time a moderate prestressing is introduced by the prestressing device proposed in this study.

The distribution of concrete stress $\sigma_t$ (x,y) in the central cross-section of the wall at the age of t is shown as follows:

$$\sigma_t(x,y)=\sigma_{It}(x,y)+\sigma_{Rt}(x,y)-\sigma_{Pt}(x,y)-\sigma_{st} \quad \cdots\cdots\cdots \quad (2)$$

where: $\sigma_{It}(x,y)=\sigma_{It-1}(x,y)+E(t)\{\alpha\Delta T(x,y)-\Delta\bar{\varepsilon}-\Delta\phi(y-h/2)\}$
: internal restraining stress

$\sigma_{Rt}(x,y)=\sigma_{Rt-1}(x,y)+R_{Nt}E(t)\Delta\bar{\varepsilon}+R_{Mt}E(t)\times\Delta\phi(y-h/2)$
: external restraining stress

$\sigma_{Pt}(x,y)=P_t/A+M_{Pt}(y-Y_G)/I$, $A=(E_c A_c+E_f A_f)/E_c$
: restraining stress by moderate prestressing

$\sigma_{st}$ : restraining stress by reinforcement

in which, E(t):elastic modulus of concrete, $\alpha$:coefficient of linear thermal expansion of concrete, $\Delta T$:difference of temperature of concrete, $\Delta\bar{\varepsilon}$, $\Delta\phi$:incremental free axial strain and bending deformation, P:moderate prestressing force, A:equivalent cross-sectional area of wall, $M_P$:moment by moderate prestressing, I:geometrical moment of inertia, H:overall height of structure, h:height of wall, b:thickness of slab, x,y,z:coordinates, $Y_G$:y-coordinate of centroid of overall structure, $E_c$:elastic modulus of wall, $E_f$:elastic modulus of slab, $A_c$:cross-sectional area of wall, $A_f$: cross-sectional area of slab, and suffix t indicates an age of member, however,restraining stress by reinforcement is $\sigma_{st}=0$ because of unsolved phenomenon.

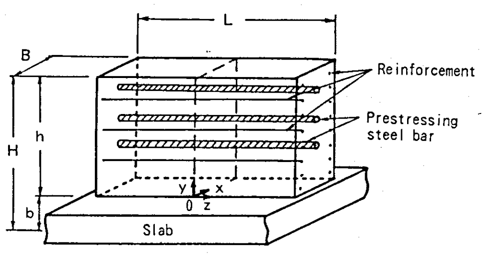



Fig.20 Basic prediction model before the time of occurrence of thermal cracks

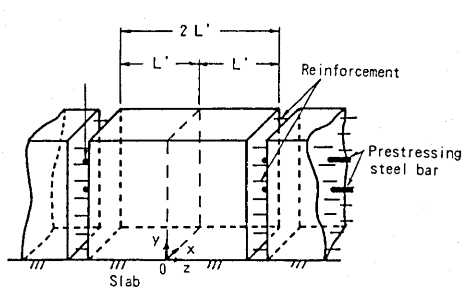



Fig.21 Basic prediction model at the time of occurrence of thermal cracks

## 5.2 Estimation of cracking control effect

In order to examine the cracking control effect by means of the new method just after the time of occurrence of thermal cracks, the estimation method is introduced according to the idea of ACI's method. Here, it is assumed that height of cracks growing is equal to the overall height of wall.

Fig.21 illustrates the basic prediction model at the time of occurrence of thermal cracks with spacing of 2L' in the wall structure shown in Fig.20.

Here, the formula of crack spacing L' proposed by Nagataki et al. [7] can be written as,

$$L' = [(1+K_{RO.U})A_c f_t - 2n\overline{\tau}_s U_s l_{ro}]/B\tau_f \quad \cdots\cdots (3)$$

in which, $K_{RO.U}$:restraining degree in the top of wall when slab is rigid, $f_t$ :tensile strength of concrete, n:number of reinforcement, $\overline{\tau}_f$ , $\overline{\tau}_s$ : average bond stress between wall and slab, between reinforcement and concrete of wall,respectively, $U_s$ :round length of reinforcement, $l_{ro}$ : range of interface between concrete and reinforcement, B : width of wall.

The equilibrium of moment in the state of crack spacing L' is given by,

$$M_{2L'} - M_p(2L'/L) = M_{L'} + M_r \quad \cdots\cdots (4)$$

where,

$M_{2L'} = \int_{Af} \sigma_{t2L'}(x,y)ydA$ : restraining moment in the state of crack spacing 2L',

$M_{L'} = \int_{Af} \sigma_{tL'}(x,y)ydA$ : restraining moment in the state of crack spacing L'

$M_p = \sum_{j=1}^{m} P_j\, y_{Pj}$ : resistant moment by moderate prestressing,

$M_r = \sum_{i=1}^{n} A_S\, f_{si}\, y_{si}$ : resistant moment by reinforcement,

$$\sigma_{t2L'}(x,y) = \sigma_{It}(x,y) + \sigma_{Rt2L'}(x,y),$$
$$\sigma_{tL'}(x,y) = \sigma_{It}(x,y) + \sigma_{RtL'}(x,y),$$
$$\sigma_{Rt2L'}(x,y) = \sigma_{R(t-1)2L'}(x,y) + R_{Nt2L'}\cdot E(t)\Delta\overline{\varepsilon} + R_{Mt2L'}\cdot E(t)\Delta\phi(y-h/2),$$
$$\sigma_{RtL'}(x,y) = \sigma_{R(t-1)L'}(x,y) + R_{NtL'}\cdot E(t)\Delta\overline{\varepsilon} + R_{MtL'}\cdot E(t)\Delta\phi(y-h/2),$$

in which, $\sigma_t$ :concrete stress obtained from CPM, $A_f$ :area of crack plane, $A_s$ : cross-sectional area of reinforcement, $f_{si}$ : reinforcement stress, $y_{si}$ : y-coordinate of reinforcement i, $P_j$ :prestressing force of prestressing steel bar j, $y_{Pj}$ :y-coordinate of prestressing steel bar j, m:number of prestressing steel bar, n:number of reinforcing bar, $R_{N2L'}$, $R_{NL'}$ :axial restraint coefficients in L=2L',L=L', $R_{M2L'}$ ,$R_{ML'}$ :bending restraint coefficients in L=2L',L=L', and it is assumed that $R_{M2L'} \geqq R_{ML'}$ .

It is assumed that $f_{si}$ is in proportion to average concrete stress $\overline{\sigma}_t(x, y_{si})$ in height $y_{si}$. Therefore, $f_{si}$ can be written by,

$$f_{si} = \beta\,\overline{\sigma}_t(x,y_{si}) \quad \cdots\cdots (5)$$

where, $\beta$ is proportional constant.

Next, the relationship between $f_{si}$ and crack width $w_i$ is given by using the crack width formula of the limit state design method as follows:

$$w_i = k_1[4d_c + 0.7(C_s - \phi_s)](f_{si}/E_r + \varepsilon_p) \qquad (6)$$

in which, $k_1$ : coefficient of bond (=1.3), $d_c$ : covering depth of reinforcement, $C_s$ : space of reinforcement, $\phi_s$ :diameter of reinforcement, $E_r$ :elastic modulus of reinforcement, $\varepsilon_p$ :constant value (= $150\times 10^{-6}$).
As a result, width of cracks $w_i$ can be estimated by Eqs.(3)～(6).

## 5.3 Results and Discussions

To examine the availability of the moderate prestressing method and the applicability of the evaluation method in this study, the theoretical results are compared with the field experimental results in both the prestressed walls and the nonprestressed ones.

The experimental results are summarized in Table-3 [5],[6],[8]. The dimensions of the structures in Case-1 ～3 are 0.45～1.0m in width of walls and 15.0 ～42.35m in length, and temperature risen by hydration heat of concrete was by 14.9 ～25.8℃. The thermal cracks finally occurred in all the walls in Case-1 ～3. On the other hand, the results of Case-4 were shown in order to refer to a long time character of prestressing force and resistibility for an external force. Prestressing force introduced by the prestressing device was in the range of about 69～118kN per bar in the experiments. It is found that the design prestressing forces obtained from Eq.(1) are in good agreement with the experimental results. The maximum experimental tensile stress $\sigma_{tmax}$ just before the occurrence of thermal cracks approximately coincides with theoretical results obtained from CPM. Furthermore, the cracks spacing L', which are obtained by Nagataki's formula [7] under the condition of $K_{P0,U}$ =0.38(Case1), 0.75(Case2), 0.73(Case3), $\overline{\tau}_f$ =0.98, $\overline{\tau}_s$ =980MPa, $\ell_0$=30cm, agree with the experimental results. In addition, thermal crack index obtained from the experiments is in the range of 0.86～1.27, and the probability of thermal crack occurrence is of the order of 10 ～70% [9],[10].

Next, the maximum crack widths $w_{max}$ obtained from Eqs.(2)～(6) just after the occurrence of thermal cracks agree well with the experimental results in both the prestressed walls and the nonprestressed ones. But, in Case-1, when the thermal crack of 0.18mm width occurred finally in the prestressed wall, the crack widths in the nonprestressed walls also increased from 0.1mm to 0.5mm with elapsed time. It is considered that the increase of their crack width is due to the effects of drying shrinkage, creep, relaxation, atmospheric temperature change, season change and solar radiation [11]. However, their effects for changes in crack widths are not known in detail.

As a result, the crack width and length are decreased to about 60 ～100% and 19 ～50% respectively by using the new moderate prestressing method.

Next, in order to clarify the effect of thermal crack control with this method, relationships between number m of prestressing steel bars and reinforcement stress $f_s$, crack width $w$, steel bar ratio p (including both reinforcement and prestressing steel bar, or only reinforcement)in a typical wall model are shown in Fig.22. The wall model is 1.0m in width, 4.0m in height. The analyses of their relationships are carried out by Eqs.

(2)～(6) on the assumption that twenty-six reinforcing bars of D19mm are set with bar spacing of 300mm, prestressing force P introduced by the new prestressing device is 98kN per bar, and the difference of average concrete stress $\Delta\sigma_{t(2L'-L')}$ on analyzing $M_{2L'} - M_{L'}$ of Eq. (4) is assumed 49,

Table-3 Outline and results of field experiments

| Items \ Case | | | Case-1 : Screen wall in A pump facilities | Case-2 : Experimental wall | Case-3 : Water tank wall | Case-4 : Pit wall |
|---|---|---|---|---|---|---|
| Size of wall structure (width×length×height) [m] | | | 1.0×15.0×3.9 | 0.7×18.0×1.8 | 0.45×42.35×4.4 | 0.2×2.0×2.5 |
| Thickness of slab [m] | | | 1.5 | 0.8 | 0.6 | 0.5 |
| Size of cylinder : diameter D . length $\ell_c$ [mm] | | | 107 . 150 | 107 . 150 | 79.9 . 150 | 75.9 . 100 |
| Volume of expansive demolition admixture [ml] | | | 1134 | 1134 | 615.9 | 361.7 |
| Position of distribution bars [mm] | | | D19@300 | D13@300 | D16. D22@150 | D13@300 |
| Diameter. number. position of prestressing bar [mm] | | | φ28 . 6@300 | φ28 . 5@300 | φ22. 1000. 1900. 2600 | φ22 . 700. 1600 |
| Area of reinforcement [%]:nonprestressed. prestressed | | | 0.19 . 0.29 | 0.12 . 0.36 | 0.86 . 0.92 | 0.45 . 0.61 |
| Concrete | Cement<br>W/C [%] . C [N/m³] | | normal portland<br>59.8 . 2607 | normal portland<br>55.0 . 3528 | blast-furnace slag B<br>56.0 . 3116 | normal portland<br>55.0 . 3136 |
| Initial tempereture of concrete [℃] | | | 25.0 | 27.0 | 23.3 | 10.0 |
| Compressive strength at the age of 4 weeks $f_{c28}$[MPa] | | | 24.9 | 25.1 | 23.9 | 20.5 |
| Maximum tempereture to the utmost limit $T_{max}$ [℃] (age) | | | 50.8<br>(22h) | 50.8<br>(22h) | 50.8<br>(22h) | 50.8<br>(22h) |
| Prestressing force per bar P [kN] | | theoretical<br>experimental | 107.8<br>104.9 | 107.8<br>98.0 ～ 117.6 | 68.6<br>66.6 | 68.6<br>78.4 (90d) |
| Tensile strength before the occurence time of thermal cracks $f_t$ [MPa] | | | 2.35 | 2.05 | 1.41 | ―――― |
| Maximum concrete stress before the occurence time of thermal cracks $\sigma_c$ [MPa] | prestressed | theoretical (age)<br>experimental(age) | 2.66 (12d)<br>1.86 (12d) | 1.46 (8d)<br>1.67 (8d) | 1.50 (7d)<br>1.18 (7d) | ――――<br>―――― |
| | nonprestressed | theoretical (age)<br>experimental(age) | 2.69 (12d)<br>1.91 (12d) | 1.62 (8d)<br>1.77 (8d) | 1.65 (7d)<br>1.06 (7d) | ――――<br>―――― |
| Index of thermal crack occurence (nonprestressing) | | | 0.88 | 1.27 | 0.86 | ―――― |
| Crack spacing L' in nonprestressed wall [m] | | theoretical<br>experimental | 8.7<br>7.5 | 5.3<br>6.0 | 11.9<br>6.6 ～ 21.4 | ――――<br>―――― |
| Maximum width of thermal cracks $w_{max}$ [mm] | prestressed | theoretical | 0 | 0 | 0 | 0 |
| | $w_P$ | experimental(age) | 0 (14d)<br>0.1～0.18 (49d) | 0 (12d)<br>0 (48d) | 0.05 (11d)<br>0.05～0.08 (38d) | 0 |
| | nonprestressed | theoretical<br>(Nagataki -[7]) | 0.12<br>(0.11) | 0.16<br>(0.14) | 0.06<br>(0.07) | 0 |
| | $w_N$ | experimental(age) | 0.1 (14d)<br>0.4～0.5 (49d) | 0.04～0.08 (12d)<br>0.05～0.2 (48d) | 0.05～0.1 (11d)<br>0.2 (38d) | 0 |
| Final decreasing rate of maximum width of thermal cracks $(w_N - w_P)/w_N$ [%] | | | 64 | 100 | 60 | ―――― |
| Final decreasing rate of length of thermal cracks[%] | | | 50 | 19 | 40 | ―――― |

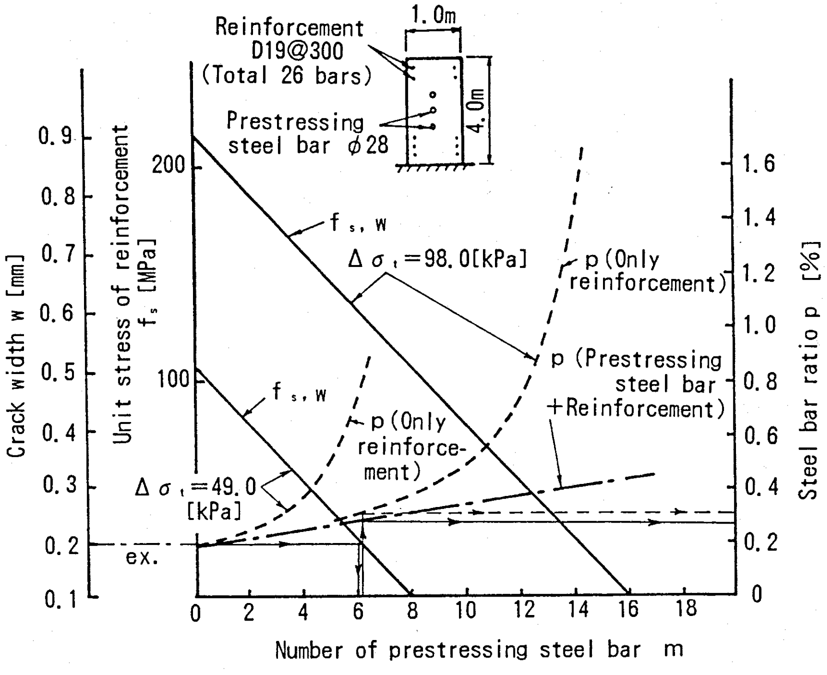



Fig.22 Relationships between number m of prestressing steel bar and reinforcement unit stress $f_s$, crack width w, steel bar ratio p in typical wall model

98kPa. If only reinforcing bars were used to produce the same effects of controlling thermal cracks as does the moderate prestressing device, steel bar ratio p would increase as shown in Fig.22 with broken lines. By introducing moderate prestressing in the wall, crack width decreases in proportion to number m of prestressing steel bars, and steel bar ratio p increases in proportion to it. On the other hand, if only reinforcing bars were used, steel bar ratio p would increase exponentially. As a result, it has been proved that this new method becomes a very useful one for the purpose of controlling the thermal cracks.

## 6 .CONCLUSIONS

A new moderate prestressing method using an expansive admixture for thermal cracking control in massive reinforced concrete structures was developed. This new method was proved useful by several field experiments. In addition, the experimental results were compared with some numerical calculations obtained from the newly proposed theoretical method on the basis of ACI's method and CPM.

The conclusions obtained from this paper can be summarized as follows:

(1) The moderate prestressing method was proved useful to control thermal cracks by several field experiments.
(2) The maximum prestressing force of approximately 196kN per bar can be introduced by the new moderate prestressing method using an expansive admixture.

(3) Relationships between prestressing force and dimension of cylinder and temperature were analyzed by cylindrical model in a laboratory. In particular, prestressing force increases in proportion to cross-sectional area of an expansive admixture.
(4) Crack width and crack length were decreased to about 60 ~100% and 19 ~ 50% respectively by using the moderate prestressing method in the field experiments.
(5) The newly proposed theoretical method is useful to predict width of thermal cracks just after occurrence time of thermal cracks.
(6) Moderate prestressing method was successful for the control of thermal cracks in massive wall structures.

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