CHARACTERISTICS OF CHEMICALLY PRESTRESSED MEMBERS IN FLEXURE AND EFFECTS OF RESTRAINT IN THREE DIRECTIONS

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In this paper, the characteristics of chemically prestressed members in flexure and the effects of restraint in three directions are experimentally investigated. When sufficiently cured at an early age, chemically prestressed members exhibit a large tension stiffening effect and, in the case of flexural members, stiffness near cracking and concrete behavior at the tensile end differ from those of normal concrete. The effects of restraint in three directions are observed in flexural behavior, and found to be notable especially when the section is large. The unusual effects of expansive concrete characteristics on the decrease of crack width are discussed.

Keywords: *expansive concrete, chemical prestress, tension stiffening, curing in early age, fracture energy, multi-directional restraint, crack width*

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1. INTRODUCTION

Adding an expansive agent to concrete can, under appropriate restraining conditions, lead to improved concrete quality characteristics, such as crack resistance. It is known that when such effects of expansion are exhibited, flexural and diagonal cracking loads increase, and crack width is reduced [1]. Expansive strain barely decreases with creep, and this is also a major advantage since expansive strain is introduced gradually during concrete hardening [2].

In "Design and Construction Guide of Expansive Concrete [3]", a scheme is established by which the increased flexural cracking load is evaluated from prestress and the decreased crack width is evaluated from prestrain, which is the strain introduced to the steel as a result of expansion. However, research by the authors has revealed that expansive concrete under restraint shows nonlinear behavior under tensile stress, and that deformability up to cracking is greater than that of normal concrete [4],[5],[6]. It was revealed that the unloading stiffness of expansive concrete gradually decreases as the maximum experienced tensile stress is increased, and that large residual tensile strain remains after unloading. Therefore, the characteristics of restrained concrete affected by expansion during hardening are apparently different from those of normal concrete.

There has been almost no research concerning the behavior of expansive concrete after cracking, and absolutely none has adopted the viewpoint that expansive concrete differs considerably from normal concrete. The authors realize that, besides the increased crack resistance, the greatest advantage of chemically prestressed concrete is the reduced crack width, and that the mechanism of this crack width reduction has not been sufficiently clarified. When no external restraint is provided for expansive concrete, its performance falls. Performance is considerably improved by placing re-bar in one direction [3]. On the other hand, restraint in many directions should lead to great improvement. However, in this regard, only a few results have been published. It has been reported that the diagonal cracking load is further improved under multi-directional restraint [1], and that performance is improved using fibers for restraint [7],[8],[9],[10], but in general the effects of restraint in many directions have not been sufficiently clarified.

Against this background, this research focuses on the behavior of chemically prestressed members after cracking. Further, the effects of restraint in many directions are experimentally examined. Tension Stiffening is examined in a uni-axial tension test, and flexural behavior and the effects of multi-directional restraint are investigated in detail through flexural tests on beams. The objective of the research is to obtain knowledge leading to fuller understanding of the effects of expansive agents, based on a consideration of experimental results and past research results.

2. EXPERIMENTAL PROGRAM

2.1 Tension Stiffening Experiments

Uni-axial tension tests were carried out on chemically prestressed members in order to investigate the tension stiffening behavior expansive concrete. As shown in **Fig.1**, the center of the 100mm x 100mm member section was penetrated by a reinforcing bar, and the length of the specimen was about 2,900mm. Seven specimen types were tested, as shown in **Table 1**. Screwed reinforcing bar was used in the case of D19, and normal deformed

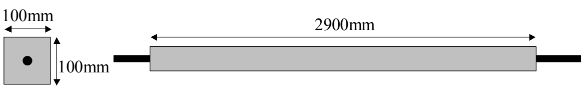

Fig.1 Specimen for Uni-axial Tension Test

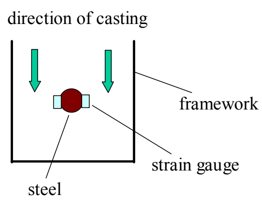

Fig.2 Direction of Concrete Casting

Table 1 Specimens for Uni-axial Tension Test

Name of Specimen	Concrete	Reinforcing bar	Yielding Strength of Reinforcing bar	Reinforcement ratio	Curing Conditon
D19-①	Expansive	D19	345MPa	2.87%	Wet
D19-②	Expansive	D19	345MPa	2.87%	Wet
D22	Expansive	D22	345MPa	3.87%	Wet
D13	Expansive	D13	345MPa	1.27%	Wet
D19-Dry	Expansive	D19	345MPa	2.87%	Drying
N-D19	Normal	D19	345MPa	2.87%	Wet
N-D19-Dry	Normal	D19	345MPa	2.87%	Drying

bar in the case of D22 and D13. The properties of these reinforcing materials are shown in **Table 1**. Expansive concrete was made using ready-mixed concrete with the constituents shown in **Table 2**. The mix proportion was as shown in **Table 3**. The unit content of expansive agent was 70kg, which is quite large as compared to the amount of expansive agent used in shrinkage-compensating concrete. The normal concrete, on the other hand, was made in the experimental workshop. In this case, the cement shown in **Table 2** was used, but the aggregates had different properties from those used in the expansive concrete (density of fine aggregate: 2.55; water absorption ratio: 1.53%; density of coarse aggregate: 2.62; water absorption ratio: 1.2).

A Strain gauge was attached to the reinforcing bar center, and the expansive strain just immediately after casting was measured. As shown in **Fig.2**, taking into account the direction of casting, strain gauges were arranged such that they would be minimally affected by concrete bleeding.

Table 2 Materials for Expansive Concrete

cement	ordinary portland cement (S company)
expansive agent	ettringite type (D company)
fine aggregate	specific gravity = 2.6, water absorption ratio = 1.48%
coarse aggregate	specific gravity = 2.70, water absorption ratio = 0.45%
super plasticizer	polycarboxylate type

Table 3 Mix Proportion of Concrete

Concrete Type	W/(C+E)	Unit Content (kg/m^3)					
		W	C	E	S	G	SP
Expansive Concrete	0.38	175	391	70	737	940	5.07
Normal Concrete	0.38	171	450	0	737	940	5.07

Monotonic loading was implemented under displacement control, and loading was continued beyond the reinforcing bar yield point. This is because the specimens retain sufficient residual displacement and it is easier to observe crack populations and spacing after yield. In order to obtain tension stiffening in terms of the stress-strain relationship of the concrete, the average concrete strain needs to be measured. To make this possible, the specimens were made quite long and, given a large number of cracks in the measuring span. **Equation (1)** was expected to hold good for deriving the average strain. Metal markers were attached to the concrete surface at points at least 500mm from the two ends of each specimen, and the displacement between the markers was measured; this resulted in a displacement-measuring span of about 1,900mm. This 500mm margin from the ends of the specimen was allowed because it has been reported that bond properties deteriorate nearer the ends [11].

Relationships of average stress versus average strain were derived from the experimental results using the following procedure. First, on the assumption that **Equation (1)** holds good, the average strain of the concrete and steel were obtained from the experimental results. Reinforcing bars start yielding at the crack location, and until yielding occurs the reinforcing bars are in the elastic range throughout the specimen. This means the average steel stress can be calculated using **Equation (2)**. Finally, the average concrete stress is obtained using **Equation (3)**. When the reinforcing bar starts yielding at the crack location, the average stress of the steel cannot be calculated using this method. Therefore, in this experiment, it is possible to investigate tension stiffening up to the initiation of reinforcing bar yielding at the crack location.

$$\overline{\varepsilon_{RC}} = \overline{\varepsilon_S} = \overline{\varepsilon_C} \qquad (1)$$

(where, $\overline{\varepsilon_{RC}}$:average strain of RC member; $\overline{\varepsilon_S}$:average strain of steel; and $\overline{\varepsilon_C}$:average strain of concrete)

$$\overline{\sigma_S} = \overline{\varepsilon_S} \times E_S \qquad (2)$$

$$\overline{\sigma_C} = \frac{(T - \overline{\sigma_S} \times A_S)}{A_C} \qquad (3)$$

（where, $\overline{\sigma_S}$:average stress of steel; $\overline{\sigma_C}$:average stress of concrete; E_s: Young’s modulus of steel; T: tensile force on member; A_s: area of steel; and A_c: area of concrete）

Strain gauges were attached as shown in **Fig.3** and strain was measured during loading. Until cracking, it is desirable that three strain measurements should coincide: the average member strain, the strain measured by the gauge attached to the center of the reinforcing bar, and the concrete strain at the center of the member. Additional strain gauges were attached to the surface of the concrete in the region about 500mm from the ends . The concrete surface strain and steel strain showed almost the same behavior until cracking in all specimens. Judging from strain values 500mm from the specimen ends, bond properties between concrete and steel are almost the same as at the center of the specimen. Therefore, it can be concluded that in measurements of displacement in this experiment, the effects of reduced bonding near member ends have been excluded. During loading itself and preparations for loading, moisture was kept out of the specimens by coating the with grease .The specimens were wrapped with polyethylene film.

2.2 Experiments related to Flexural Behavior and Effects of Multi-directional Restraint

Here, an outline of the flexural tests is given. **Fig.4** gives details of the specimens. Three sizes of specimen were used. For each size, a specimen with and without stirrups was tested in order to investigate the effects of restraint in many directions on crack resistance. Tensile and compressive reinforcing bars were arranged symmetrically in order to introduce restraint uniformly over the section. As the cross section increases, some regions lack restraint by the reinforcing bars, and this is considered a “size effect” of expansive concrete by the authors. For all three specimen sizes, the reinforcement ratio was constant at 3.5 %.

The stirrups were square-shaped and arranged to enclose the tensile and compressive reinforcing bars. Stirrup spacing was almost the same as the effective depth of the specimen. In the case of the smallest specimens, 9 stirrups of D10 were arranged with 120mm spacing, and resulting stirrup reinforcement ratio was 0.8%. In the case of the mid-size specimens, two stirrup arrangements were provided. In one arrangement, 7 stirrups of D10 were placed at 240mm spacing and the stirrup reinforcement ratio was 0.4%. In the other arrangement, 9 stirrups of D13 were arranged at 210mm spacing for a ratio of 0.8%. In the case of the large specimen, 6 stirrups of D29 were arranged with 540mm spacing and the stirrup reinforcement ratio was 0.8%. For small and mid-size specimens, two specimens were made for the same condition, therefore 12 specimens were tested in total including large size specimens.

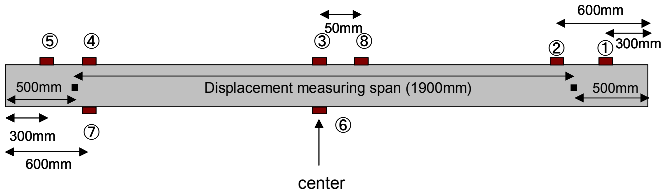

Fig.3 Positions of Strain Gauges on Concrete

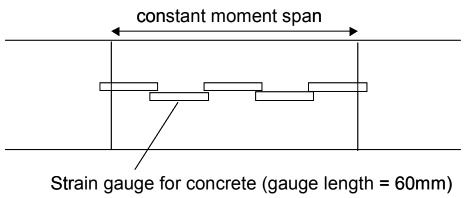

Fig.5 Strain Gauges Attached on the Bottom of Beam Specimens

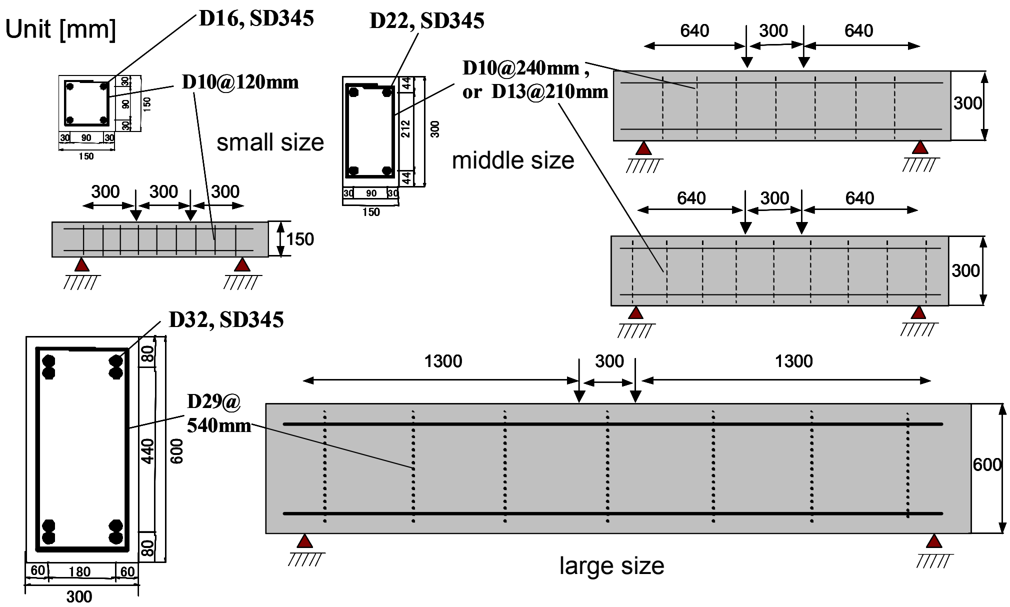

Fig.4 Details of Beam Specimens and Loading System

In the case of the small and mid-size specimens, formwork was removed at the age of 2 days, and ten specimens were cured under wet conditions until flexural testing at the age of about 28days. In the case of the large specimens, formwork was removed at the age of 2 days, and after that, the two specimens were exposed outdoors for about 40days away from the effects of wind. Water was occasionally sprinkled over the large specimens.

The concrete mix proportion was as shown in **Table 3**, and the expansive concrete was the same as that used in the tension stiffening experiment. The loading system is shown in **Fig.4**, and for all specimen sizes, the same moment span of 300mm was. The ratio of shear span to effective depth was 2.5. Furthermore, as shown in **Fig.5**, the bottom of the specimens was covered with overlapping strain gauges each 60mm long so as to cover the whole area of the moment span. The compressive strength of the concrete at loading was 40.3MPa (JIS A 6202). Cylinder specimens were made with metal forms, and compressive tests were conducted just after removing the formwork.

3. TENSION STIFFENING OF CHEMICALLY PRESTRESSED MEMBERS

3.1 Tension Stiffening of Expansive Concrete

In **Fig.6**, the reinforcing bar expansive strain is shown from just after casting until the loading age. Because the cross section is small, the effects of friction against the formwork are relatively large, and these frictional effects restrain deformation in the axial direction. However, after removing the formwork at 2 days, expansive strain developed rapidly free from these effects.

Figure 7 shows the tension stiffening model for normal concrete as proposed by Okamura, et al [12]. This model specifies the relationship of average stress versus average strain for concrete including cracks. The relationship is linear up to the tensile strength, and thereafter a plastic range entered where stress is constant. In the range where strain is more than double the strain at the tensile strength, the average stress versus average

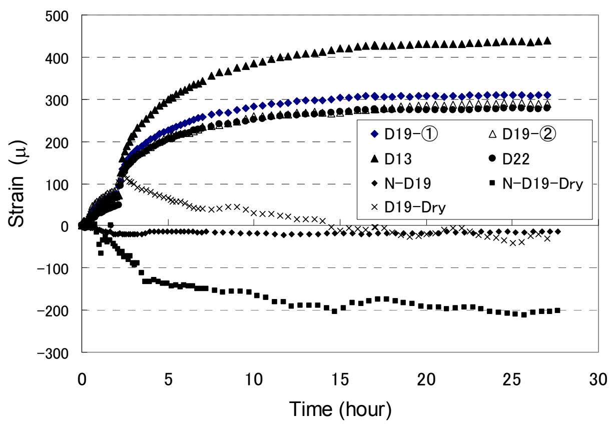

Fig.6 Steel Strain in Uni-axial Tension Specimens just after Casting

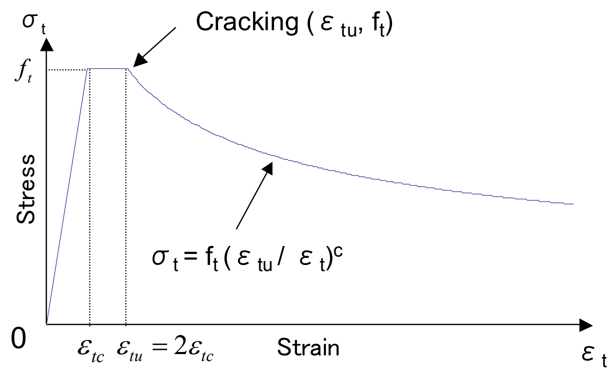

Fig.7 Tension Stiffening Model of Normal Concrete

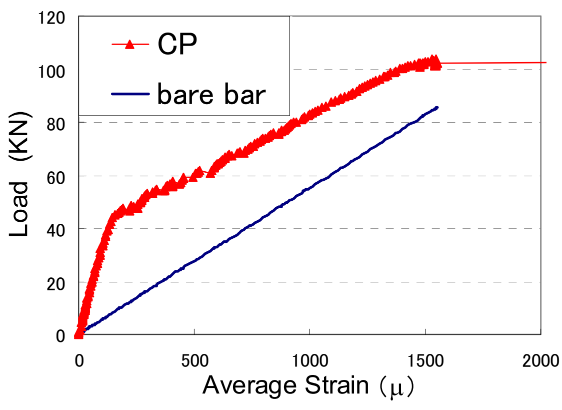

Fig.8 Load-Average Strain Relationship of D19-1 Specimen

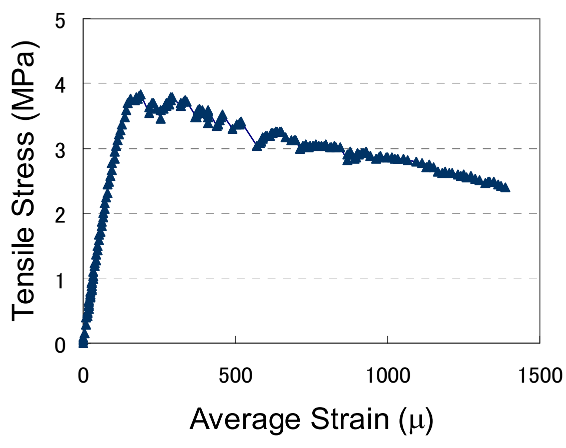

Fig.9 Average Stress-Average Strain Relationship of Concrete of D19-1 Specimen

strain relationship is determined by parameter C, which specifies the softening curve. (In **Fig.7**, σ_t: average stress of concrete; ε_t: average strain of concrete; f_t: tensile strength; ε_{tc}: strain at tensile strength; ε_{tu}: cracking strain; C: parameter determining the softening curve (0.4 for deformed bars and normal concrete))

Figure 8 shows the relationship between load and average strain for D19-1. The relationship between load and strain for the reinforcing bar itself is shown in the same graph. In **Fig.9**, the average stress versus average strain relationship is shown, as calculated using the procedure already described. As noted earlier, the relationship between average stress and average can be obtained up to the point where the reinforcing bar starts to yield at the cracks. **Figure 9** confirms that, in the case of expansive concrete, tension stiffening occurs after cracking.

Figures 10 to **13** show the average stress versus average strain relationships for expansive concrete (wet curing) and tension stiffening model for normal concrete shown in **Fig.7** [12].

From the four experimental results(**Fig.10** to **Fig.13**), the softening behavior after cracking is quite similar for restraining reinforcement ratios from 1.3% to 3.9. **Figure 14** shows the experimental results for normal concrete (wet curing), though made at a different time and with different materials. Compared to normal concrete, stress does not decrease suddenly after cracking in expansive concrete, and plastic behavior is exhibited after cracking. The model for normal concrete shown in **Fig.7** includes a plastic range after cracking. This plastic range is assumed to be present to cover the analysis of seismic walls, where cracking is distributed, and the analysis of beams where curvature, or a strain gradient, exists. From the results of the uni-axial experiment given in **Fig.14**, this kind of apparent plastic range where stress remains constant was not observed. However, in the case of expansive concrete, even in uni-axial tension tests, a plastic range was observed and softening of stress after cracking was very slow. These characteristics, which are peculiar to expansive concrete, are particularly notable under flexure and under multi-directional. These points are examined further in Section 5.

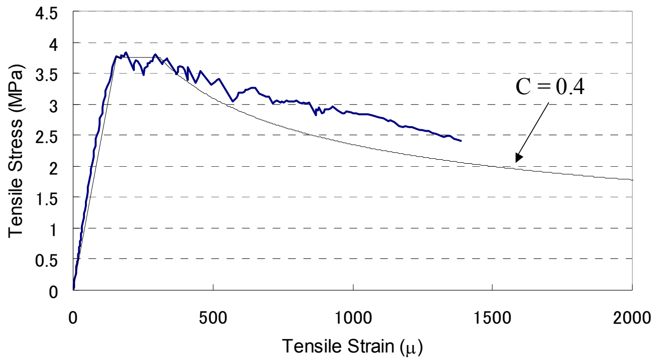

Fig.10 Average Stress–Average Strain Relationship of Concrete of D19-1 Specimen

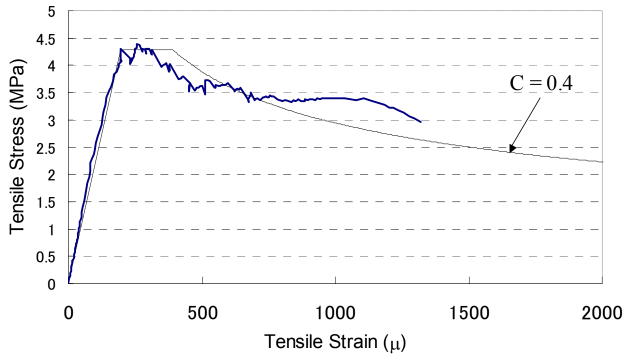

Fig.11 Average Stress–Average Strain Relationship of Concrete of D19-2 Specimen

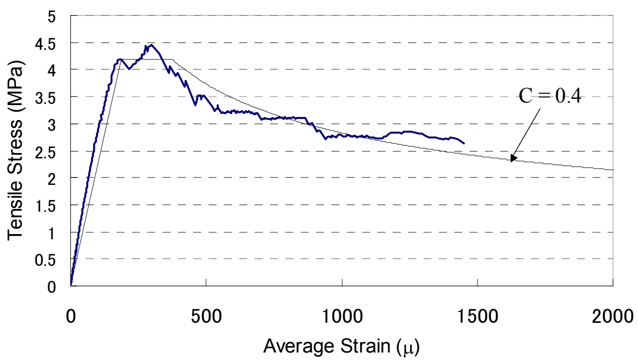

Fig.12 Average Stress – Average Strain Relationship of Concrete of D22 Specimen

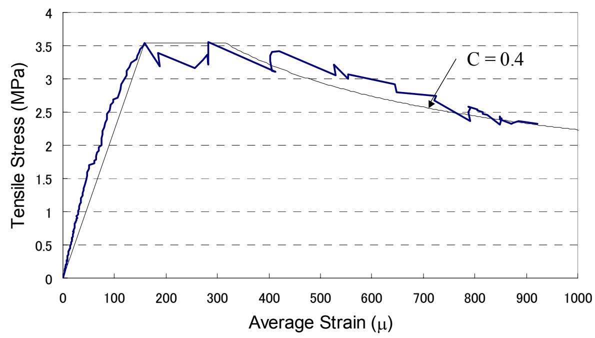

Fig.13 Average Stress – Average Strain Relationship of Concrete of D13 Specimen

Next, the effects of higher tensile strength due to the chemical prestress of expansive concrete are discussed. Before considering expansive concrete, the tension stiffening of general prestressed concrete is briefly considered. As shown in **Fig.15**, when prestress is introduced mechanically, the concrete is subjected to compressive. However, the properties of the concrete do not change after the introduction of prestress, so when the introduced stress is released, the concrete returns to its initial state. The result of this is that the tension stiffening of prestressed concrete and normal concrete is the same, if the origin of graph is set as in **Fig.15** and differences in bonding characteristics are neglected. On the other hand, if the point at which prestress is introduced is set as the origin, the degree of softening becomes large, as shown in **Fig.16**. This is because the energy consumed by concrete after cracking must be the same regardless of the position of the origin. If this kind of treatment is not carried out, the tensile stress carried by concrete after cracking is likely to be overestimated. However, the discussion here is based on the understanding that bonding characteristics do not differ between RC and PC.

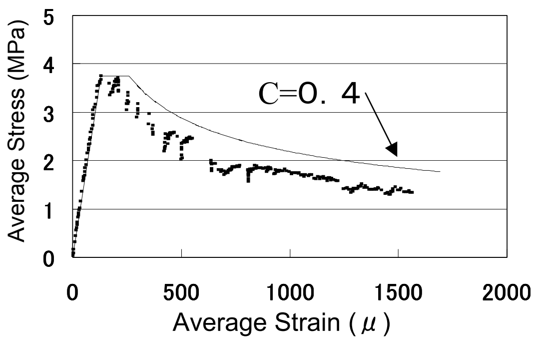

Fig.14 Average Stress–Average Strain Relationship of Concrete of N-D19 Specimen

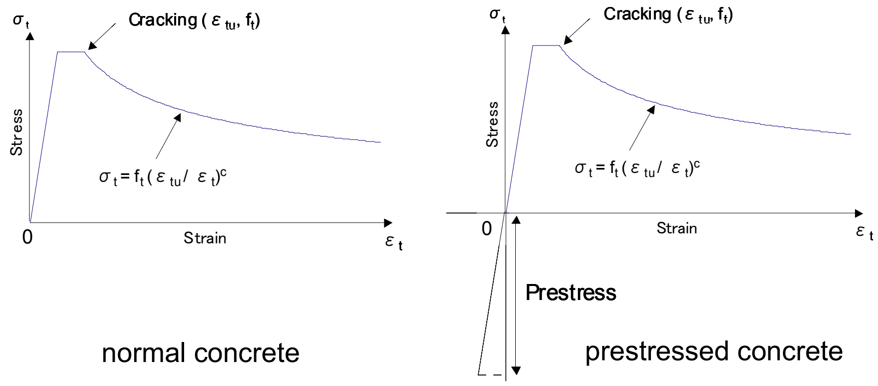

Fig.15 Tension Stiffening of Prestressed Concrete

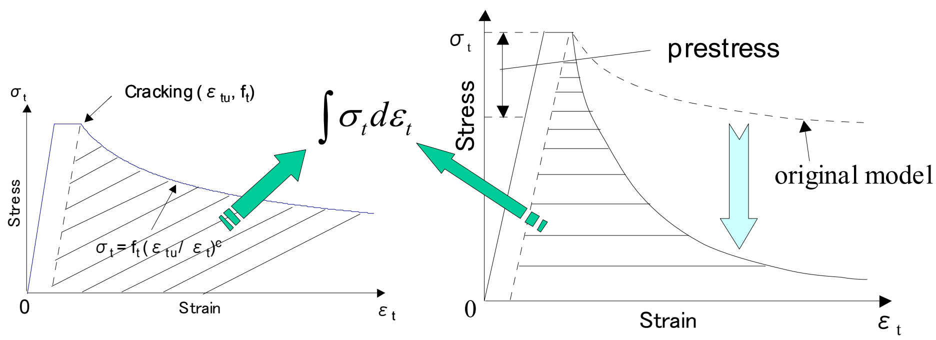

Fig.16 Adjustment of Fracture Energy in Prestressed Concrete

Figure 17 shows the crack patterns for all specimens after loading (until yielding of reinforcing bars). Both for expansive concrete and normal concrete, with insufficient curing and depending on drying at an early age, the observed crack spacing becomes small. When the effects of drying are removed, for specimens with D19, the crack spacing is almost the same for expansive concrete and normal concrete. Consequently, concerning the experimental results obtained in this study, the argument made above with respect to **Fig.16** can be applied.

In **Figs.10** to **13**, the origin is taken to be the point at which chemical prestress is introduced to the concrete. In these graphs, tension stiffening of the expansive concrete is better than predicted by the model for normal concrete. Based on the discussion of tension stiffening in prestressed concrete, the tension stiffening of expansive concrete is clearly larger than that of normal concrete, if the effect of increased tensile strength due to chemical prestress is considered. However, in this experiment, the expansive concrete and normal concrete were cast in different seasons and using different methods, so the difference in tensile strength is smaller.

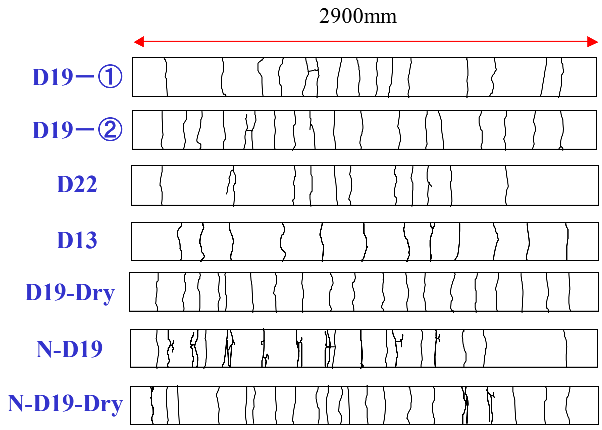

Fig.17 Crack Pattern of Each Specimen

3.2 Effects of Early-age Curing on Tension Stiffening

In **Figs.18** and **19**, the experimental results are given for specimens exposed to drying conditions in the experimental workshop after removing the formwork at 2 days. The inadequate curing leads to considerably reduced tensile strength. The tension stiffening of chemically prestressed members is lower than predicted by the model for normal concrete, indicating that post-cracking characteristics are also affected by curing. Okamura, et al. showed that when expansive concrete is cured suitably until 7 days and if expansive strain develops sufficiently, expansive strain recovers with the supply of water even after expansive strain falls as a result of drying [13]. Considering the experimental results obtained in this study along with these past research results, it can be said that adequate curing at an early age and the development of sufficient expansive strain are important factors in bringing out the full effects of expansive concrete.

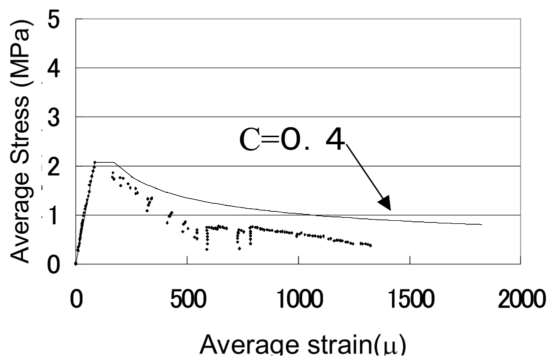

Fig.18 Average Stress–Average Strain Relationship of Concrete of D-19-Dry Specimen

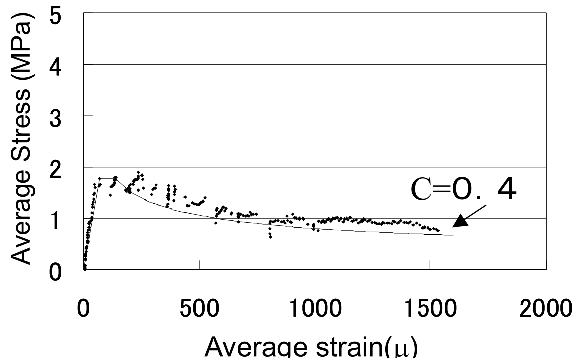

Fig.19 Average Stress–Average Strain Relationship of Concrete of N-D-19-Dry Specimen

4. FLEXURAL BEHAVIORS OF CHEMICALLY PRESTRESSED MEMBERS

4.1 Relationship between Load and Displacement

First, the flexural behavior of chemically prestressed (CP) members is analyzed. **Figure 20** shows the relationship between load and deflection for the mid-size specimen without stirrups. In the case of the CP

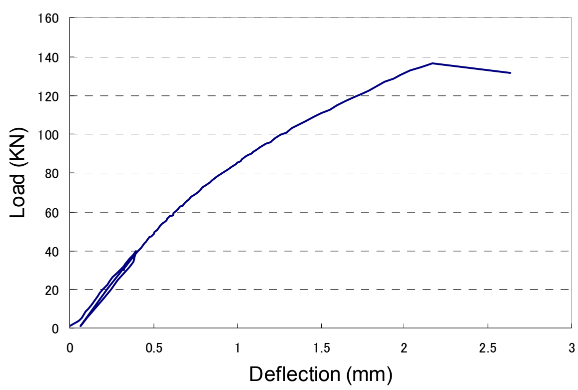

Fig.20 Load–Displacement Relationship of CP Mid-Size Specimen (without stirrup)

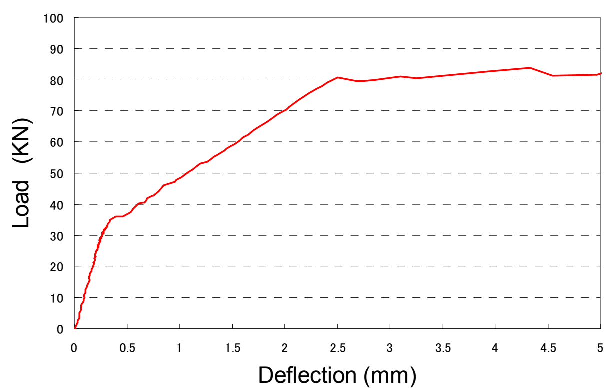

Fig.21 Example of Load–Displacement Relationship of Normal Concrete Specimen

member, it is difficult to identify a load on this curve at which the stiffness of the member suddenly changed. In fact, it was difficult to identify even the cracking load, and in the case of both small and mid-size specimens, it was impossible to hear the sound of the first flexural crack. **Figure 21** shows an example of the relationship between load and displacement for a normal concrete beam. In this figure, at around 35kN, the stiffness suddenly changes. According to the authors' past research [14], the characteristics of normal mortar under compression and those of expansive mortar are not that different under the stress at which flexural cracking occurs. Therefore, it is considered the difference seen in **Figs.20** and **21** derives from the differences in characteristics under flexural tensile stress.

4.2 Behaviors of Concrete at Bottom of Tensile End of Specimen

a) Relationship between Load and Strain at Tensile End

Figure 22 shows the relationships between load and strain for concrete at the tensile end of the CP member featured in **Fig.20**. In the same way, **Fig.23** shows the relationships for the normal concrete specimen featured in **Fig.21**. By comparing **Figs.22** and **23**, it can be seen that the behavior of CP and normal concrete after cracking is considerably different.

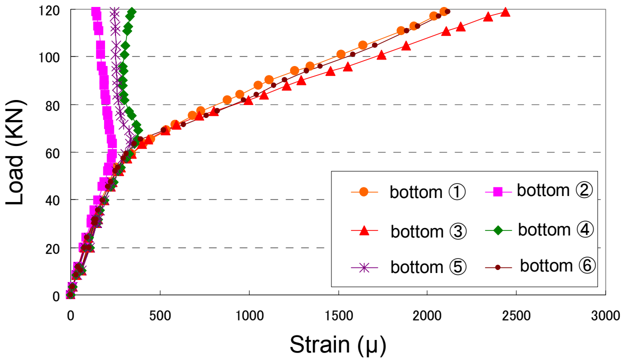

Fig.22 Concrete Strain at Bottom of CP Mid-size Specimen (without stirrup)

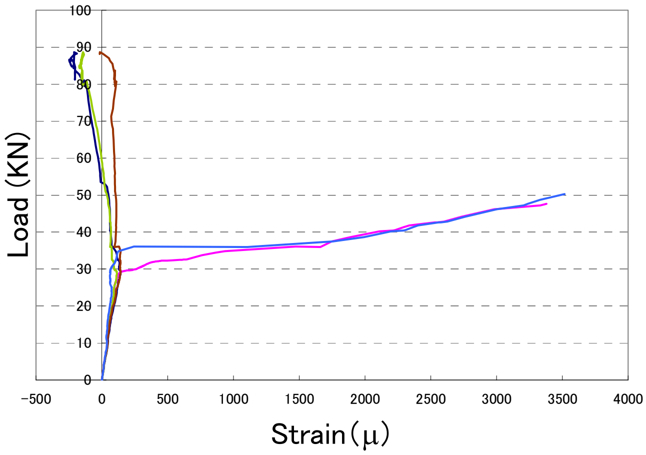

Fig.23 Concrete Strain at the Bottom of Normal Concrete Specimen

b) Behavior of Strain at Tensile End of Normal Concrete Specimen

As seen in **Fig.23**, in the case of normal concrete, a crack occurred at one strain gauge at about 30kN, following which the cracking strain suddenly increased. This sudden increase seems to reflect the sudden development of a crack. At 35kN, another crack occurred, and this crack also opened suddenly. The strain gauges used were 60mm long, so if it is assumed that all deformation is concentrated in the crack opening, a crack of 0.1mm would correspond to a strain of 1667 microns. In the case of normal concrete, cracks widen to about 0.1mm with a slight increase in load, and can be observed with naked eye. In this experiment, the strain gauges were attached using an adhesive agent. As a result, when the deformation suddenly increased, the adhesive gave way and prevented rupture of the gauges. However, adhesion between gauges and concrete was apparently maintained except near the crack, so the displacement calculated from strain is considered to be almost equivalent to the increase in crack width.

Next, concerning gauges where no cracks occurred, tensile strain was released upon cracking and some gauges ultimately indicated compressive strain. Kokubu, et al. reported the same kind of result, and attributed it to the release of drying shrinkage stress at the concrete surface [15]. Thus, in the case of a normal concrete member after cracking, the crack width at the surface suddenly increases and tensile strain is released in surface concrete between the cracks.

c) Strain Behavior at Tensile End of Chemically Prestressed Member

As shown in **Fig.22**, in the case of a CP member, localization of deformation occurred at around 60kN. However, after this localization, the gauge at which cracking occurred exhibited a smaller increase in strain with rising load as compared to normal concrete. If we assume that the deformation over the length of one strain gauge is localized at the crack, a considerably large increase in load is necessary for the strain to reach the 1,600-1,700 microns that correspond to a crack of 0.1mm. Furthermore, looking at gauges where no cracking occurred, no strain was released after localization started and even when the load reached a high level, the tensile strain was maintained. This means that, in a CP member, tensile strain is maintained in the concrete between cracks, while at the same time the rate of crack width increase is remarkably slow.

These two phenomena interact with each other, but here discussion focuses on how concrete tensile strain is maintained between cracks. This phenomenon is thought to result from several characteristics peculiar to expansive concrete. First, as seen in the experimental results related to tension stiffening, there is a prominent transmission of bond stress after cracking, so the tensile strain due to bond stress is large. Secondly, residual tensile strain accumulated up to the point of cracking is large; the authors have already reported that expansive concrete subjected to tensile loading exhibits large residual strain after unloading [4]. A third contribution is relaxation deformation upon the release of prestress, which is opposite in direction to the drying shrinkage stress that occurs in normal concrete. Finally, the re-expansion reported by Okamura, et al.[16] is also thought to contribute; in some cases, expansive concrete exhibits re-expansion when the restraint is released. The extent of this re-expansion effect is not clear during short-term loading, but there does seem to be some effect. Through a combination of these effects, tensile strain is maintained in the concrete between cracks after cracking takes place.

4.3 Effects of Strain Gradient

As **Fig.7** makes clear, the structural behavior of flexural members with a strain gradient or wall members with distributed cracks can be accurately simulated using the tension stiffening model, which incorporates a plastic range after the tensile strength is exceeded. It is also well known that the bending strength of concrete exceeds its tensile strength [17],[18], and this plastic range in the tension stiffening model can be considered a response to this phenomenon. Where there is a strain gradient, in contrast with the uni-axial tensile stress situation, cracks are thought to develop more gradually, and this is confirmed by numerical analysis using the discrete crack model [17],[19].

In the case of CP members, the effects of the strain gradient are thought to be much more remarkable. This is because, when cracking starts (initial localization of deformation takes place) at the tensile end of a CP member, a large compressive strain remains in the paste matrix [4],[5]. As a result, considerable energy is needed to develop cracks, because this strain gradient and compressive strain in the paste matrix adds to the effect of the aggregate. Consequently, it is considered that the range of maintained tensile stress after cracking is extensive and softening becomes very slow, as can be seen in the curve of average stress versus average strain for expansive concrete in **Fig.24**. This conceptual figure refers to the model proposed by Okamura, et al.[12], in which cracking is defined as occurring at the strain corresponding to the end of the plastic range. In this study of expansive concrete, the point where stress reaches the tensile strength is defined as the point at which localization of deformation starts. This definition is necessary because the actual cracking point is difficult to identify in the experimental results.

In **Fig.24**, the tensile stiffness of expansive concrete is smaller than that of normal concrete until the tensile strength is reached. As already reported [4], stiffness at unloading gradually decreases as tensile stress is applied, and this reduction in stiffness increases with increased experienced tensile stress. Furthermore, in the case of expansive concrete, time-dependent deformation occurs rapidly under tensile stress. These phenomena lead to expansive concrete exhibiting lower stiffness than normal concrete up to the tensile strength.

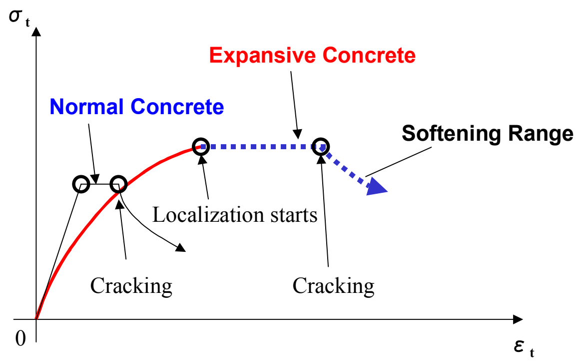

Fig.24 Average Stress–Average Strain Relationship of Expansive Concrete under Flexural Stress (Conceptual)

The authors believe that the characteristics of expansive concrete shown in **Fig.24** lead to the very slow decrease in stiffness shown in **Fig.20**, and consequently to the slow growth of crack width shown in **Fig.22**. In the experiments with thin beam conducted by the authors [4], expansive concrete exhibited extremely large deformability before cracking. This was because the height of the beam was 30mm and the strain gradient was very large, which led to extremely slow cracking progress. Furthermore, in CP members with stirrups, these peculiar characteristics of expansive concrete become more notable, as noted in the next section.

5. EFFECTS OF MULTI-DIRECTIONAL RESTRAINT IN CHEMICALLY PRESTRESSED MEMBERS

Here, the effects of restraining expansion in multiple directions on the flexural behavior of CP members are examined by arranging stirrups in the specimens. The results were different in small/mid-size specimens and large specimens, so these are considered separately below.

5.1 Effects of Multi-directional Restraint in Small/Mid-size Specimens

a) Expansive Strain at Hardening

Figures 25 and **26** show the expansive strain of tensile and compressive reinforcing bars in small and mid-size specimens. In the case of small size specimens, the addition of stirrups results in a slightly lower expansive strain in the axial reinforcement. On the other hand, in the case of mid-size specimens, there is no apparent correlation between the number of stirrups and expansive strain in the axial reinforcing bars. Overall, the addition of had little effect on the development of expansive strain in the axial reinforcing bars of small and mid-size specimens.

b) Strain Behavior at Tensile End of Mid-Size Specimens

Figures 27 and **28** show the behavior of concrete strain at the tensile end of mid-size specimens with stirrups. Overall, these figures are similar to those for specimens without stirrups shown in **Fig.22**. Here the point at which localization of deformation starts is discussed. It can be considered that when stirrups are present, the flexural cracking load is higher than when there are no stirrups due to the multi-directional prestress. However,

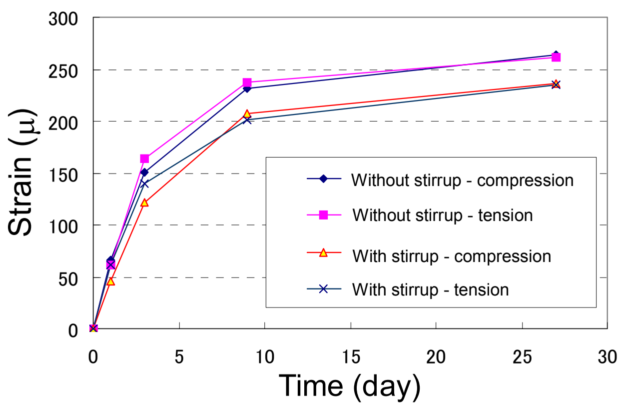

Fig.25 Development of Expansive Strain (Small Specimens)

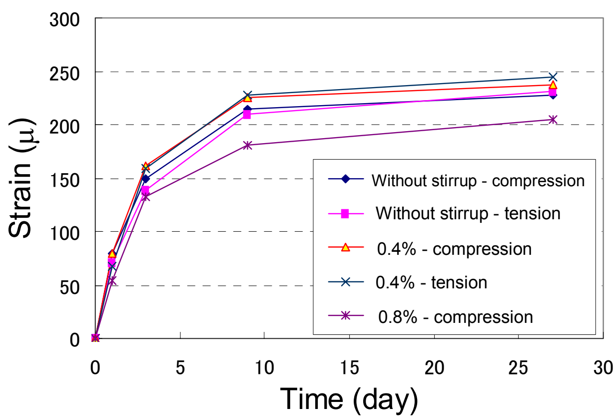

Fig.26 Development of Expansive Strain (Mid-Size Specimens)

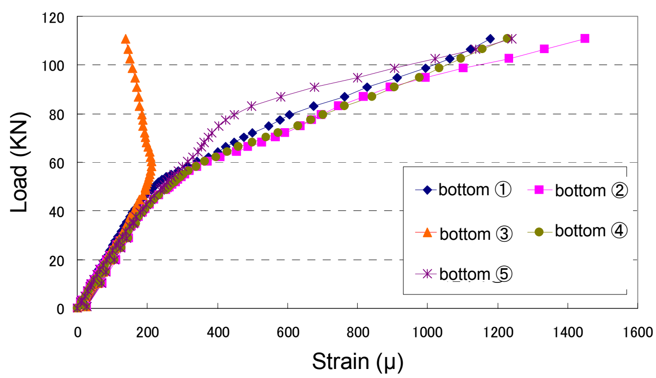

Fig.27 Concrete Strain at Bottom of CP Mid-size Specimen (0.4% stirrup reinforcement)

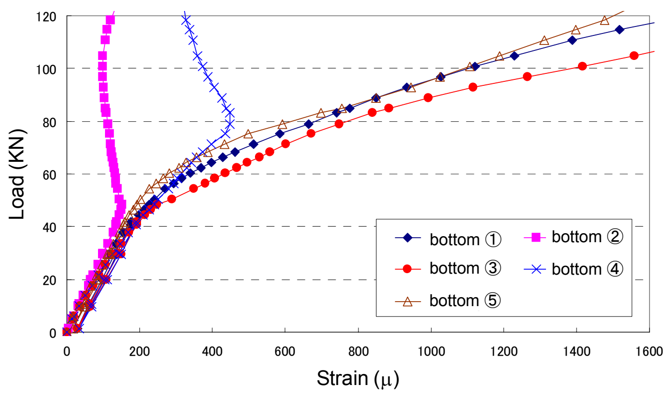

Fig.28 Concrete Strain at Bottom of CP Mid-size Specimen (0.8% stirrup reinforcement)

looking at **Figs.22**, **27**, and **28**, even with the addition of stirrups, there is no change in the load at which localization of deformation starts. (Where this is defined as the point at which the first strain gauge begins to indicate a decrease.) In **Fig.22** with no stirrups, the localization load is 62.4kN, while it is 61.3kN in **Fig.27** with a stirrup ratio of 0.4%, and 48.5kN in **Fig.28** with a stirrup ratio of 0.8%. It is clear that the addition of stirrups does not lead to an increase in the load at which localization starts. Rather, the order of these loads corresponds to the level of expansive strain in the axial reinforcing bars, as shown in **Fig.26**.

In the case of small/mid-size specimens, the restraining effect of reinforcing bars in the section normal to the axis is considered sufficient over the whole sectional area; the restraining effect is greater close to reinforcing bars, and the distance between reinforcing bars is relatively small in small/mid-size specimens. Under these conditions of good restraint, expansive strain in the axial direction is not increased by the use of stirrups. The reinforcement ratio in the axial direction is large and axial restraint sufficient, so expansion in that direction is difficult and there is no significant difference in the load at which localization of deformation starts.

c) Relationship between Load and Displacement of Middle Size Specimens

So, are there no effects of multi-directional restraint using stirrups on the flexural behavior of small/mid-size CP members ? In **Fig.29**, the relationships between load and displacement are shown for mid-size specimens. It is clear that member stiffness is considerably increased when stirrups are used. This can be explained as an increase in the fracture energy of expansive concrete when stirrups are introduced, a phenomenon that cannot happen in the case of normal concrete. In fact, it was confirmed by numerical simulation that in the case of a normal concrete member, when stirrups were introduced, stiffness did not change after flexural cracking until shear cracking began. In the case of small/mid-size CP specimens, the loads at which localization of deformation starts were almost unchanged with the introduction of stirrups, but it is considered that the rate of crack propagation after localization was affected by the existence of the stirrups. This may be because prestress was introduced in the direction of crack propagation due to the multi-directional restraint leading to various distributions of strain in the matrix and increasing the energy necessary for crack propagation. Even with no stirrups, expansion in the direction normal to the axis was considerably restrained as compared to free

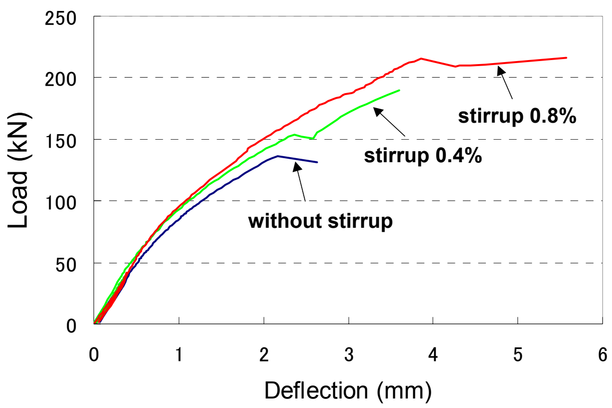

Fig.29 Load–Displacement Relationships for CP Mid-size Specimens

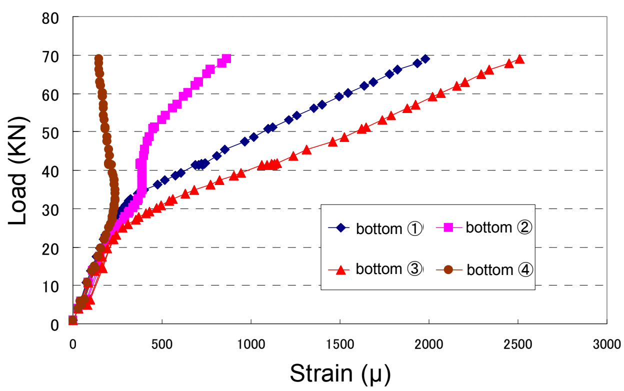

Fig.30 Concrete Strain at Bottom of CP Small Specimen (without stirrups No.1)

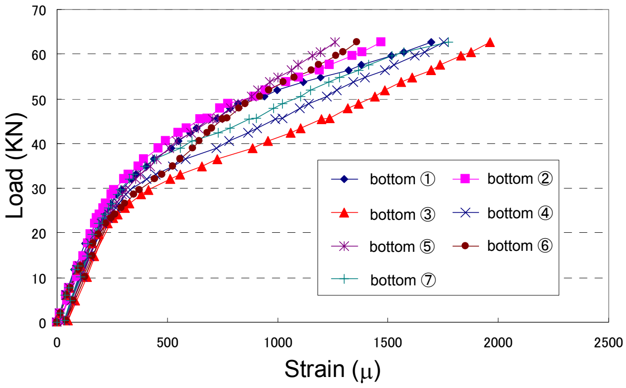

Fig.31 Concrete Strain at Bottom of CP Small Specimen (without stirrups No.2)

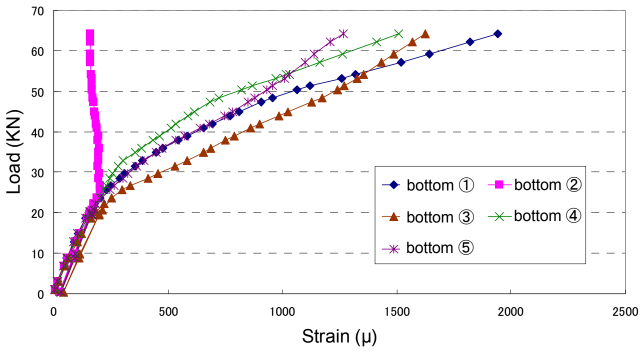

Fig.32 Concrete Strain at Bottom of CP Small Specimen (0.8% stirrup reinforcement)

expansion [23]. However, the stirrups directly introduced prestress in this direction, so propagation of cracks needed much more energy. With cracks being more difficult to propagate, crack width growth at the surface will become slower.

d) Strain Behavior at Tensile End of Small Specimens

The effects of multi-directional restraint introduced by stirrups, as already discussed for mid-size specimens, were also observed in small specimens. Two specimens were made for each condition, and in **Figs.30** and **31**, the behavior of concrete strain at the bottom of small size specimens without stirrups is shown. In **Fig.32**, the behavior with stirrups is shown. The loads at which localization of deformation starts were 33.0kN in **Fig.30** and 26.6kN in **Fig.32**. For these small specimens, it is difficult to evaluate the load at which localization of deformation starts as defined in this study, because even after the strain begins to fall, the change is very small. The load at which the strain measured by each gauge began to be localized was below 30kN, so at least it can be said that the addition of stirrups does not increase the load at which localization of deformation starts. However, with or without stirrups, the strain at the gauge covering the crack increased slowly, and tensile strain at other gauges with no crack was not released suddenly.

In **Fig.31**, characteristics specific to CP members are observed. These results were obtained using seven gauges (gauge length = 60mm) with ends overlapping attached to the constant moment span of 30mm. Cracks occurred at each strain gauge. In the case of small specimens, the strain gradient is steep, so it is deduced that crack propagation requires more energy. As a consequence, localization of deformation is more difficult and cracking is distributed. This is similar to the situation in steel fiber reinforced concrete, in which cracks are distributed as a consequence of the high fracture energy resulting from the bridging effect of fibers.

e) Load-Displacement Relationship for Small Specimens

In **Fig.33**, the relationships between load and displacement are shown for small specimens. The tendency is the same as for mid-size specimens, and the stiffness of a member is considerably greater when stirrups are present. It is inferred that more energy is required to propagate cracks after localization of deformation starts at the tensile end.

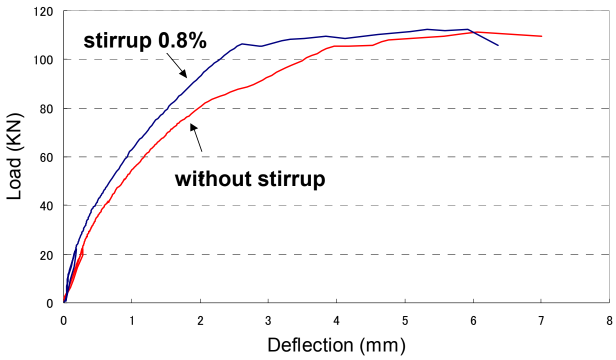

Fig.33 Load–Displacement Relationships of CP Small Specimens

(2) Effects of Multi-directional Restraint in Large Specimens

Expansive strain could not be measured for the large specimen with stirrups, so expansive strains in the axial direction with and without stirrups could not be compared. However, behavior in the axial direction can be evaluated using other data. **Figure 34** shows measurements taken with two strain gauges attached to the center of one of the main reinforcing bars. **Figures 35** and **36** show the concrete strain at the bottom of specimens with and without stirrups.

Unlike small/mid-size specimens, the load at which localization of deformation starts is considerably higher when stirrups are present. The load was 162.3kN for the specimen with stirrups, and 110.3kN without. Thus, with the addition of stirrups to provide restraint in the direction normal to the axis, crack resistance in the axial direction is improved. This effect is observed in the relationship between load and displacement, as shown in **Fig.37** for large specimens. The difference is particularly notable at around 150kN. The tendency for stiffness to change with the introduction of stirrups was observed also in small/mid-size specimens, whereas this change in the load at which localization of deformation starts with the addition of stirrups was specific to the large specimens.

Figure 38 shows a conceptual outline of the effect of stirrups in large specimens. In these large specimens, the spacing between reinforcing bars is greater, so the proportion of the sectional area restrained by the axial reinforcing bars is relatively small. Furthermore, in this experiment, the formwork for large specimens was

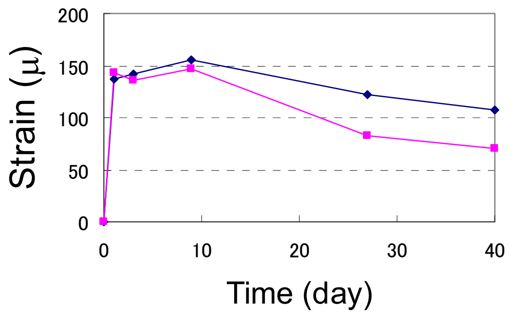

Fig.34 Development of Expansive Strain
(Large Specimen, without stirrups)

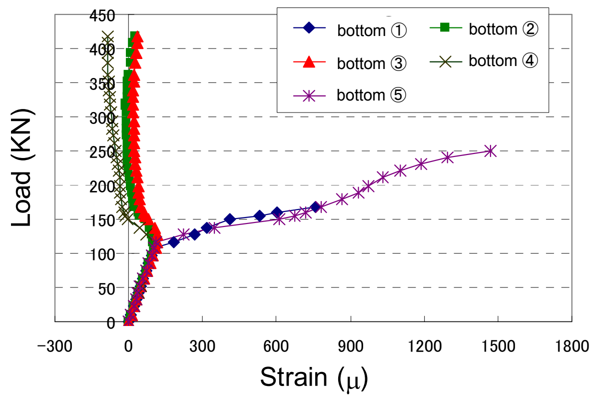

Fig.35 Concrete Strain at Bottom of
CP Large Specimen (without stirrups)

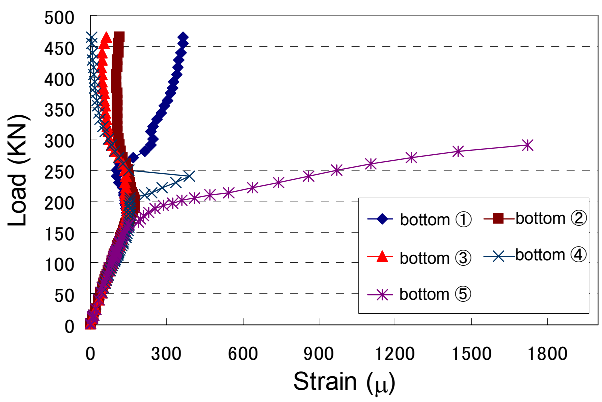

Fig.36 Concrete Strain at Bottom of
CP Large Specimen (0.8% stirrup reinforcement)

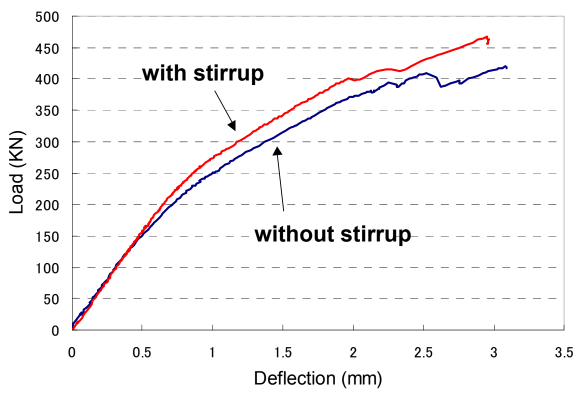

Fig.37 Load–Displacement Relationships of
CP Large Specimens

found to lack sufficient stiffness when casting took place and it had to be strengthened in haste. As a result, the restraint offered by the formwork perpendicular to the axis was inadequate. Consequently, friction between formwork and concrete would have been small, and the area affected by friction would be reduced. Therefore, near the center of the section, expansion would have been almost free. Then, as shown in **Fig.38**, the expansion energy would have pushed out the region restrained by main reinforcing bars. On the contrary, with stirrups present, deformation in the direction normal to the axis is considerably restrained, and the stirrups can be seen as enlarging the area over which restraint by the main reinforcing bars acts effectively. This improves the quality of the concrete in the axial direction, leading to a large increment in the load at which localization of deformation starts.

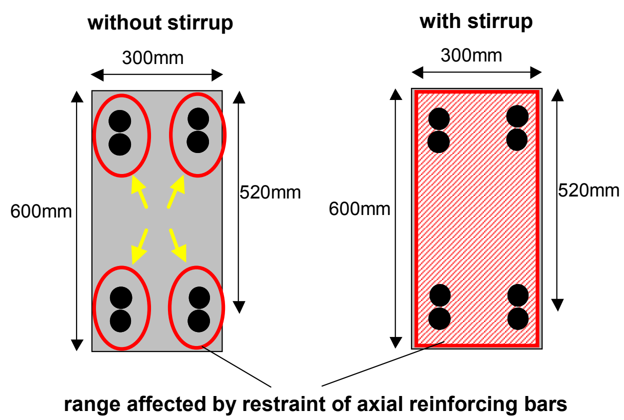

Fig.38 Effects of Stirrups in Large Specimens

This effect of stirrups has previously been reported by Tsuji [20]. According to his research, the addition of stirrups causes the distribution of expansive strain in the section near at the end of the member to become more uniform, and expansive strain in the main reinforcing bars is greater than in the case without stirrups. Further, in the region away from the end of the member, the distribution of expansive strain in the section, originally close to uniform over the length, becomes larger with the addition of stirrups. Tsuji's experiment showed that the addition of stirrups led to effective development of expansive energy in the axial direction.

In this research, the expansive strain in the main reinforcing bars could not be directly compared. However, the authors are convinced that the expansive strain in the main reinforcing bars was larger when stirrups were present.

6. FLEXURAL CRACK WIDTH OF CHEMICALLY PRESTRESSED MEMBERS

Here, the mechanism leading to small crack widths in CP members is considered on the basis of the characteristics of expansive concrete. There has been a great deal of research into crack width in normal concrete, and Kakuta's work [21],[22] is representative of that carried out in Japan. Kakuta examined the crack width of normal concrete theoretically, and the crack width of CP members is discussed here on the basis of that work.

The crack width of normal concrete can be formulated as follows [21]:

$$w = (\overline{\varepsilon_s} - \overline{\varepsilon_c}) \times l \qquad (4)$$

$$\overline{\varepsilon_s} = \frac{\overline{\sigma_s}}{E_s} = \frac{\sigma_s}{E_s} - \frac{\overline{\sigma_t}}{E_s p_e} \qquad (5)$$

$$\overline{\varepsilon_c} = (\overline{\varepsilon_{cp}} + \overline{\varepsilon_{ce}} + \overline{\varepsilon_{\varphi}}) \qquad (6)$$

(where, w: crack width; $\overline{\varepsilon_s}$: average strain of steel between cracks; $\overline{\varepsilon_c}$: average strain of surface concrete between cracks; l: crack spacing; $\overline{\sigma_s}$: average stress of steel between cracks; σ_s: steel stress at crack; $\overline{\sigma_t}$: reduction of steel stress due to bond between cracks divided by the effective section of concrete; E_s: Young's modulus of steel; p_e : effective reinforcement ratio; $\overline{\varepsilon_{cp}}$: tensile plastic residual accumulated before cracking; $\overline{\varepsilon_{ce}}$: elastic strain of surface concrete transferred from steel between cracks; $\overline{\varepsilon_{\varphi}}$:difference in elastic strain between steel and concrete due to creep and shrinkage)

According to these equations, the crack width at the concrete surface is dominated by crack spacing, average steel strain between cracks, and average strain of the surface concrete. The average steel strain is affected by the reduction in steel stress due to bonding between cracks, and the average strain of the surface concrete is affected by tensile plastic residual strain, elastic strain due to cracks between concrete, and creep/shrinkage. The crack width of CP members is now discussed with reference to this background.

First, we look at crack spacing in a CP member. The smaller the crack spacing is, the smaller the crack width becomes. Chemical prestress has the effect of making cracks more difficult to occur, while on the other hand, the cracks tend to be more distributed, as seen in the case of the small specimens investigated in the previous section. The strain gradient and extent of chemical prestress also have some effect. Overall, the mechanism of crack spacing has not yet been clarified sufficiently. Still, even if crack spacing in CP concrete is similar to that in normal concrete, there is a mechanism that causes flexural cracks in CP members to be smaller.

Tension Stiffening is large, so the average steel strain is reduced in **Equation (5)**. Kakuta pointed out that, concerning the average strain in the surface concrete, tensile plastic residual strain and elastic strain due to bonding at the surface are almost negligible [21]. However, in the case of CP members, tensile plastic residual strain is large once cracking has occurred. Furthermore, because Tension Stiffening is large, the elastic strain in the surface concrete due to bond stress can also be considered large. These factors lead to a large maintained tensile strain in the concrete between cracks, as examined in **4.2**. However, the large tensile strain between cracks is considered to include the effect of relaxation deformation due to release of prestress, which is in the opposite direction to drying shrinkage in normal concrete, and also includes the effect of re-expansion after the restraint is released.

According to past research [1],[3], the small crack width observed in CP members is a result of prestrain alone. However, as discussed above, it is actually affected by many factors. Quantitative evaluations of each factor should be the subject of future research.

7. CONCLUSIONS

Uni-axial tension tests and flexural tests of beams were conducted to investigate tension stiffening, flexural behavior, the effects of multi-directional restraint, and crack width in chemically prestressed (CP) members. The following conclusions were reached.

1) Tension stiffening in CP concrete is larger than in normal concrete. In the uni-axial tension test, the relationship between average stress and average strain included a plastic range in which stress was maintained. After cracking, the release of stress was very slow. However, in order to obtain these advantageous characteristics, it was shown to be important to cure the concrete properly at an early age, since this leads to sufficient development of expansive strain.

2) The flexural behavior of CP members is different from that of normal concrete members. Concrete strain at the tensile end differed between CP concrete and normal concrete. In the case of CP members, changes in stiffness as cracking progressed were very slow, and it is difficult to clearly identify the cracking load in the load–displacement curve. Compared to normal concrete, the tensile strain in concrete between cracks was difficult to release after cracking. Furthermore, a greater load was required to increase the crack width whereas the crack width in normal concrete suddenly increases after cracking.

3) The effects of restraining the expansion of CP members in multiple directions by the introduction of stirrups were observed. When the member section was relatively small, the load at which cracking started (the load at which localization of deformation started) was not increased by the introduction of stirrups, while stiffness after cracking increased considerably. The explanation for this increment in stiffness is that the fracture energy of expansive concrete is increased under multi-directional restraint. For members with large sections, the addition of stirrups led to effective development of expansive strain in the axial direction, and this was confirmed by the increased load at which cracking started.

4) The small crack width in CP members was examined. The main factors affecting crack width are the large tension stiffening, large plastic residual tensile strain of concrete between cracks, large fracture energy of concrete, and the release of prestrain at cracks and near cracks. The crack spacing in CP members as compared to that in normal concrete should be investigated further in the future.

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