# Experimental study on the time dependent flexural behavior of prestressed reinforced concrete beams

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## ABSTRACT

For prestressed reinforced concrete structures, cracking is allowed at the serviceability limit, and the crack width should be controlled by deformed reinforcing bars and prestressing forces. There are many research results relating to the flexural crack widths in RC beams; however it is not clear in PRC beams especially the effect of creep and drying shrinkage on their crack width. Experimental study using PRC, RC and PC beams are carried out to investigate it. In this paper deformation and crack widths of PRC beams under the sustained flexural load will be discussed with the data of creep and drying shrinkage of concrete without reinforcement.


## INTRODUCTION

In prestressed reinforced concrete bridges, cracking is allowed at the serviceability limit and the crack width should be controlled by arrangement of de-formed reinforcing bars and prestressing forces. PRC bridges increases in number recently while most prestressed concrete road bridges in Japan were designed to avoid cracking in design load combinations.

In PRC bridges, crack control is important to as-sure durability. However long-term behavior of crack width in PRC beams, especially the effect of creep and drying shrinkage, is not clear.

In this paper, cracking, deformation and crack widths of PRC beams under the sustained flexural load will be discussed with the data of creep and drying shrinkage of concrete without reinforcement.

## EXPERIMENTAL PROCEDURE

Dimensions of test beams are shown in Figure 1 and Table 1. Span length of each beam is 3000mm.

Beam A1 was designed as fully prestressed concrete member; there is no compressive/tensile stress at the concrete surface with deign load in this test, 27.5kN m (1.0Md). Beam B1, B2 and C2 were designed as PRC members and prestressing force of these beams were decreased. Beam D1 and D2 were designed as RC members.

Diameter of re-bars was selected as tensile stress of longitudinal reinforcements in beam B2, C2 and D2 would be approximately 200MPa with 2.0Md bending

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moment.

Prestressing tendons and steel reinforcing bars were in compliance with JIS. Prestressing force was introduced after 10 days from casting. Properties of prestressing tendons, tensile longitudinal reinforcement and concrete are shown in Table 2 and Table 3.

Sustained load test started approximately 28days after casting. Test beams were set upside down on support steel H-beams and flexural load was introduced by four prestressing tendons placed near both ends of beams (Fig. 2). Sustained flexural load was checked and adjusted at least once a month.

Displacement at the mid-span of test beams, strain of prestressing steel, re-bars and concrete were monitored with strain gauges. Deformation of beams was measured with contact strain gauge that

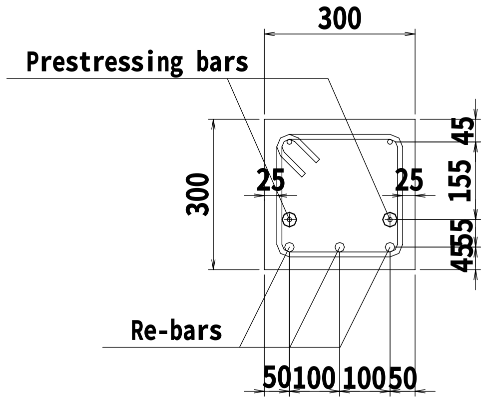


Figure 1. Section of test beams.

Table 1. Test beams.

| Beam | A1 | B1 | – | D1 |
|---|---|---|---|---|
| | | B2 | C2 | D2 |
| Prestressing bars* | 2-17mm | 2-13mm | 2-9.2mm | – |
| Re-bars* | 2-10mm | 3-16mm | 3-19mm | 3-22mm |
| Prestressing force | 272kN | 159kN | 80kN | – |
| k** | 100% | 58% | 29% | 0% |
| Sustained load*** | 1.0Md (A1, B1 and D1) | | | |
| | 2.0Md (B2, C2 and D2) | | | |
| Tension stress | 1.6 | 38.0 | – | 110.8 |
| of Re-bars (MPa) | – | 222.0 | 219.0 | 210.8 |
| Tensile stress | 0.0 | 2.1 | – | 4.8 |
| of concrete surface (MPa) | – | 7.5 | 8.7 | 9.8 |

* Diameter of prestressing bars/re-bars

** $k = M_0 / M_d$, $M_0$ is the bending moment with which there is no stress at concrete surface in tension side.

*** 1.0Md = 27.5kN m in this test. Sustained loads in beam B2, C2 and D2 were adjusted to control maximum tensile stress in tensile longitudinal reinforcement (200MPa).

Table 2. Properties of prestressing bars and rebars.

| Beam Specimen | Diameter | E Modulus | Yield Strength |
|---|---|---|---|
| <Prestressing bars> | | | |
| A1 | 17mm | 200GPa | 1061MPa |
| B1, B2 | 13mm | 201GPa | 1055MPa |
| C2 | 9.2mm | 200GPa | 1262MPa |
| <Re-bars> | | | |
| A1 | 10mm | 187GPa | 369MPa |
| B1, B2 | 16mm | 188GPa | 365MPa |
| C2 | 19mm | 185GPa | 379MPa |
| D1, D2 | 22mm | 186GPa | 386MPa |

Table 3. Properties of concrete

| | |
|---|---|
| Water cement ratio | 49% |
| Compressive strength | 39.7MPa |
| E Modulus | 28.6GPa |
| Tensile strength | 3.22MPa |

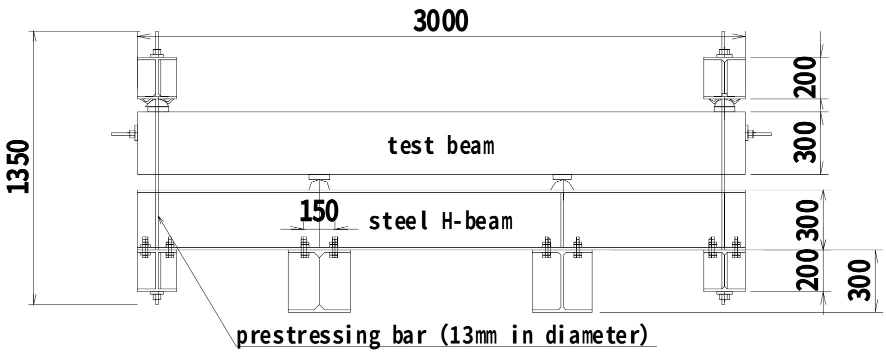

Figure 2. Arrangement for sustained load test (dimensions in mm)

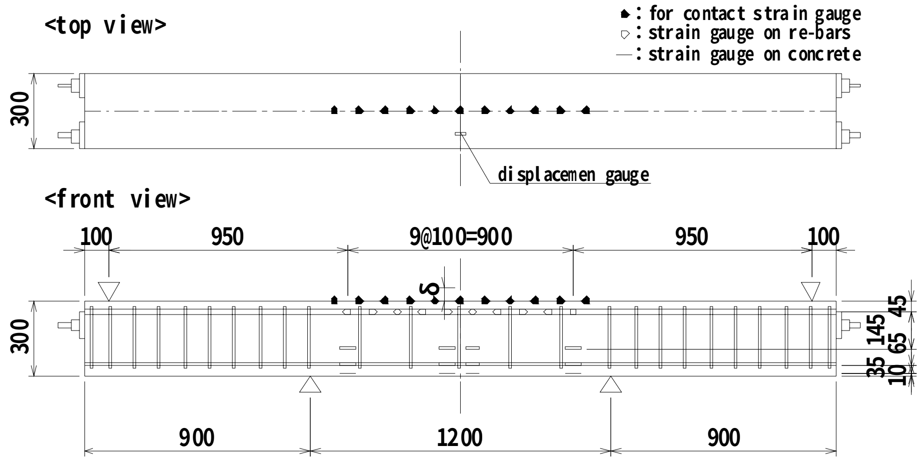

Figure 3. Positions of strain gauges and points for measurement (dimensions in mm).

has 100mm base length and in cracked area measured values are taken as the change of crack width. This measurement was carried out once a month. Positions of strain gauges and points for measurement are shown in Figure 3.

Table 4. Drying shrinkage of concrete

| Days after casting | 28 | 62 | 91 | 227 | 413 |
|---|---|---|---|---|---|
| Strain × $10^{-6}$ | 97 | 156 | 216 | 348 | 402 |

Drying started 4days after casting.

Table 5. Creep coefficient

| Days after introducing prestressing force | 22 | 64 | 201 | 386 |
|---|---|---|---|---|
| coefficient | 0.73 | 1.04 | 1.60 | 1.84 |

Drying shrinkage of concrete was measured at center of 300 × 300 × 1200mm concrete specimen (Table 4). Creep coefficients were measured with 300 × 300 × 3600mm concrete specimens with 483kN prestressing force (Table 5).

## TEST RESULTS

### *Cracking of beams*

Cracking maps after one year loading are shown in Figure 4. Nine or ten cracks were observed on the surface of beam B2, C2, D1 and D2 at the start of sustained load test. The numbers of cracks have not changed through the test. Five cracks were observed on the surface of beam B1 after 60days loading while no crack was observed at the beginning of test. The number of cracks in beam B1 has not changed after cracking was observed.

In beam B2, C2, D1 and D2, average crack spacing in each beam is fit to the calculation result pro-posed in JSCE standard specification that is based on an assumption that tensile stress in concrete is negligible. On the other hand, in beam B1, number of crack is less than that of B2, C2 and D2.

No crack was observed on the surface of beam A1.

*Deflection of beams*

Mid-span deflections of test beams are shown in Figure 5. Deflection of beam B2, C2 and D2 has been increased approximately 0.5mm under sustained flexural load and deflection of beam D1 in-creases approximately 0.4mm.

Beam A1 and B1 have no bending crack at the beginning of sustained load test and deflections of these beams are almost same. However, deflection of beam B1 has increased through the sustained load test while deflection of beam A1 has not been in-creased significantly.

*Crack width*

Maximum crack widths of test beams are shown in Figure 6. Crack widths increased in first 6 months and then show some decreasing. The reason of this is not clear, but temperature change can affect. Maximum crack widths of beam B2, C2 and D2 loaded to have almost the same tensile stress in tensile longitudinal reinforcement have

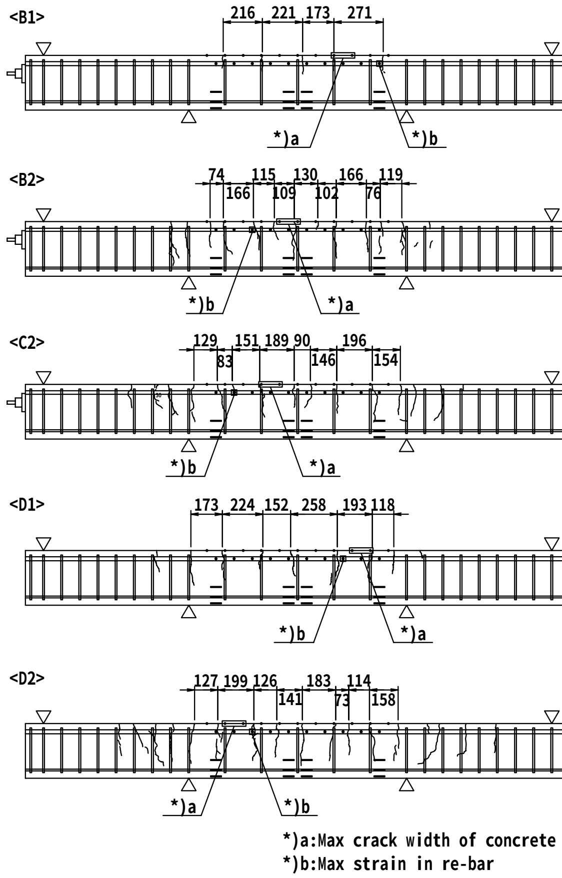


Figure 4. Cracking maps after one sustained load test.

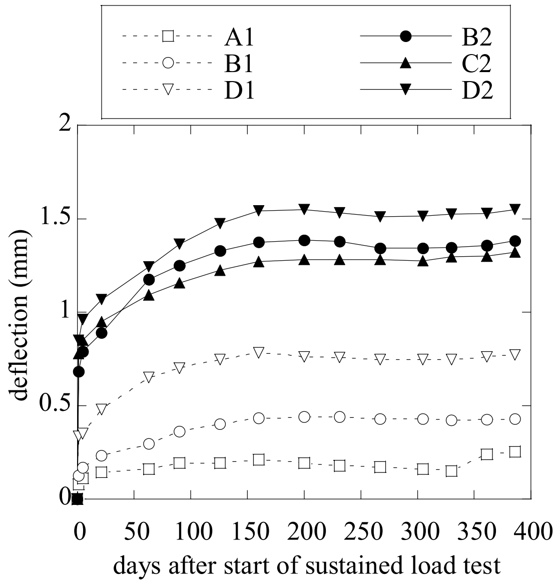


Figure 5 Change of the mid-span deflection of each beam.

been increased approximately 0.1mm through sustained flexural test. The effect of prestressing force to the long-term behavior of crack width is not clear.

Maximum crack widths of beam D1 on which the half of D2 bending moment was applied has been increased approximately 0.07mm.

While there is no crack in beam B1 when the sustained load test was started, changing of measured lengths with the contact strain gauge are calculated and maximum crack width has been increased approximately 0.04mm.

Measured crack widths in beam B2 are shown in Figure 7. Increased crack widths in sustained load test have been different in each measured point. However, there are relatively bigger cracks and smaller cracks on the surface of beam B2 and this tendency has been kept through test period.

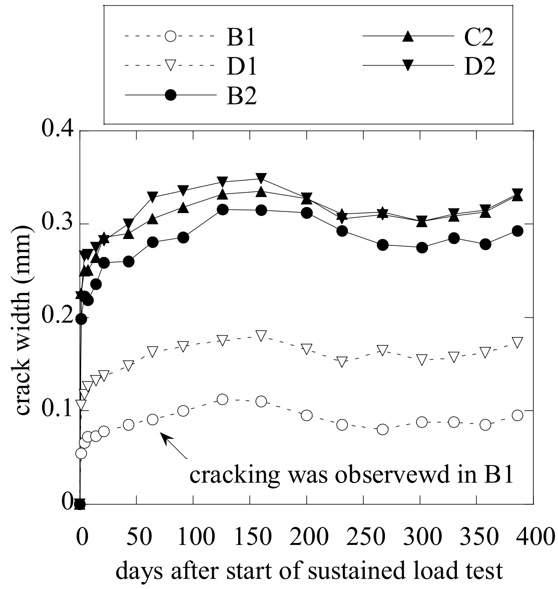


Figure 6. Change of the maximum crack width of each beam.

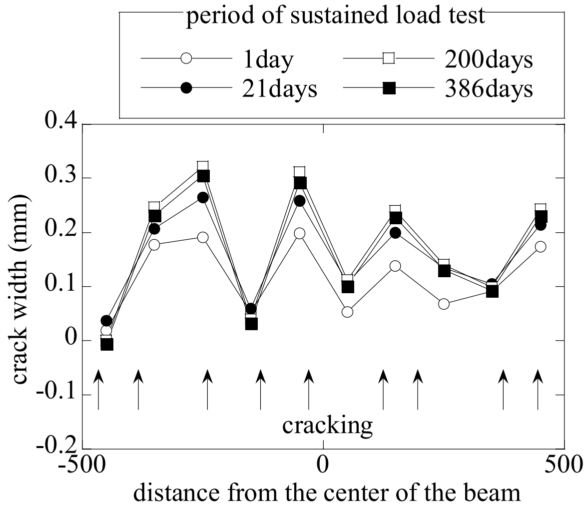


Figure 7. Change of the distance (crack width) on the tension side concrete surface of beam B2.

*Strain of concrete and tensile longitudinal reinforcement*

Strain at concrete surface in four sections and strain of tensile longitudinal reinforcement in ten sections are monitored through the test. In Figure 8, average values of these data in beam B1 and B2. In Figure 8, results of linear regression analysis with strain of concrete are shown.

In beam B2, compressive strain of concrete has increased approximately $900 \times 10^{-6}$ and strain of tensile longitudinal reinforcement has increased approximately $500 \times 10^{-6}$ through sustained load test. Change of strain of tensile longitudinal reinforcement corresponds with change of regression line calculated with strain of concrete. Also in beam C2, D1 and D2, strain of section looks to be proportional to the distance from the neutral axis.

In beam B1, when sustained load test started, strain of tensile longitudinal reinforcement is almost zero as there was no crack in beam B1 and tension force was mainly sustained by concrete. Strain of tensile longitudinal reinforcement in beam B1, however, has been increased with time. This should be the effect of cracking and decrease of tension force shared by concrete in tension area.

From the data of strain of concrete and tensile longitudinal reinforcement, deflection of each beam was calculated as curvature and shown in Figure 9. Change of curvature is in good accordance with mid-span deflection shown in Figure 5.

*Distribution of strain in tensile longitudinal reinforcement*

From the difference of numbers of crack, crack widths and strain in tensile longitudinal reinforcements between beam B1 and B2, effect of tension stiffening would be different in two beams. To discuss it, distribution and change of strain of tensile longitudinal reinforcement where equal bending moment is loaded are shown in Figure 10.

In beam B1, strain of tensile longitudinal reinforcement was uniform when sustained load test was started and this uniformity was kept before cracking while strain of reinforcement

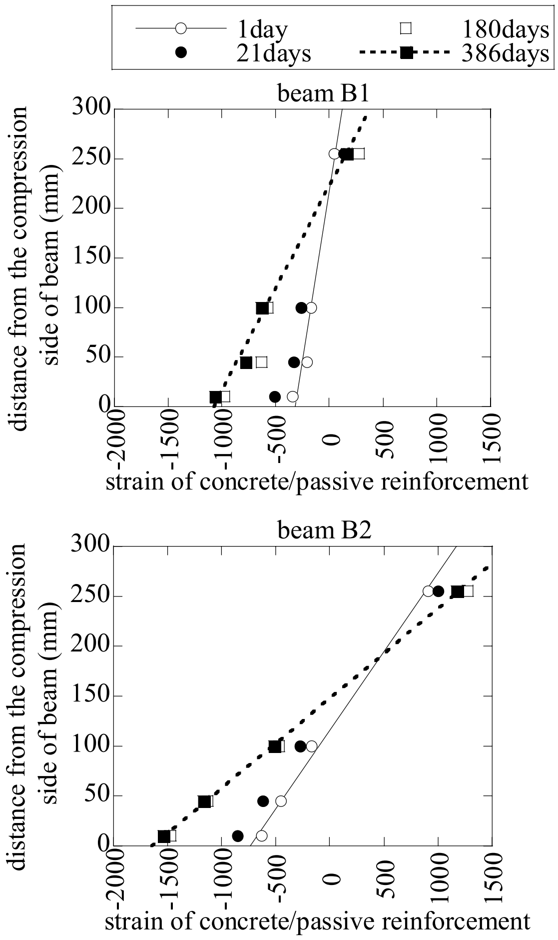


Figure 8. Change of the distance (crack width) on the tension side concrete surface of beam B2.

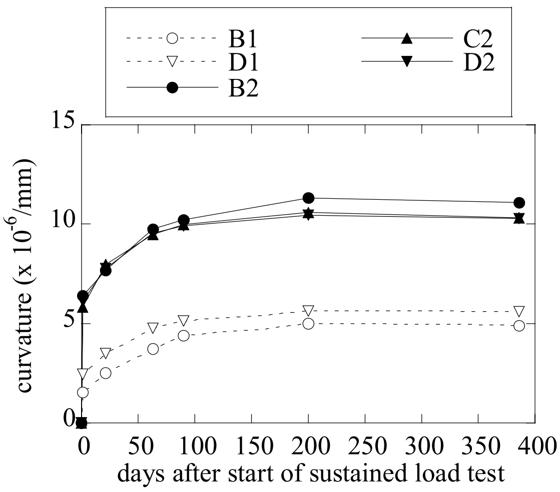


Figure 9. Change of mid-span curvature calculated with the data of strain gauges on concrete and tensile longitudinal reinforcement.

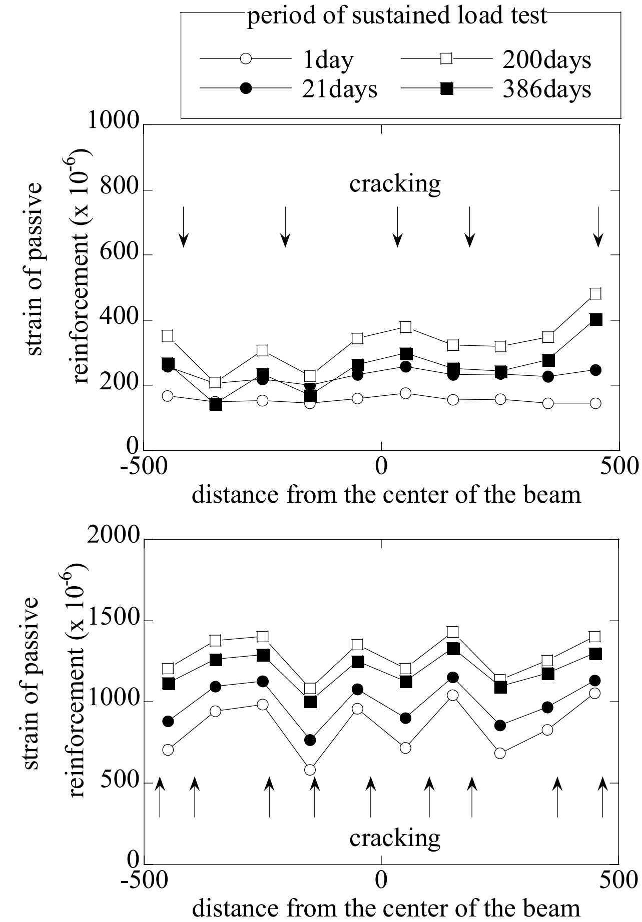


Figure 10. Distribution of strain of tensile longitudinal reinforcement.

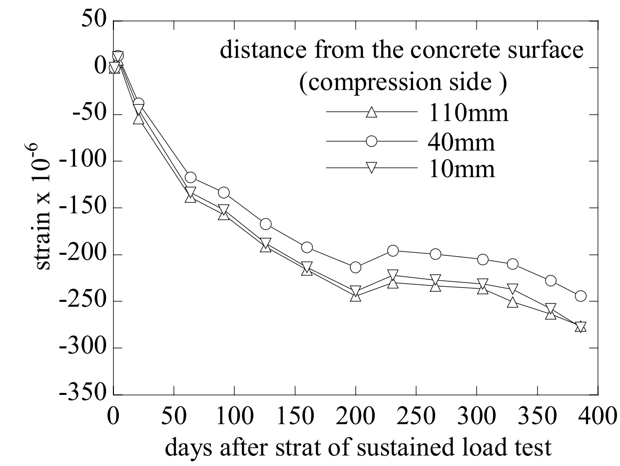


Figure 11. Strain of concrete in the test beam that is not loaded.

increased with time. After cracking, strain of reinforcement has increased more in the area near bending crack.

Cracks in B1 were observed after 60days loading and the tensile creep can affect the cracking. Tensile strength of concrete is known to become smaller when loading rate is small. In B1, tensile stress of concrete under the sustained flexural load is closet to the tensile strength of concrete.

In beam B2, there is no newly cracking under the sustained load and change of strain of tensile longitudinal reinforcement under the sustained load is al-most same in each strain gauge. In beam C2 and D2 under 2.0Md sustained load, also in beam D1 under 1.0Md sustained load, strain of tensile longitudinal reinforcement changed alike. Bond between concrete and tensile longitudinal reinforcement has not changed in these beams.

*The effect of drying shrinkage of concrete*

One of the beam specimen, arrangement of reinforcements is the same as B1 and B2, has been placed upside-down on steel H-beam without prestressing force and sustained load. Drying shrink-age of this test beam is shown in Figure 11. Progress of drying shrinkage in three monitored point of this test beam is similar to that of plain concrete shown in Table 3.

Drying shrinkage of plain concrete after through the period of sustained load test is 305 × $10^{-6}$ (Table 3) and maximum space between cracks in beam B2, C2 and D2 is 199mm (Fig. 4). Increase of crack width caused by drying shrinkage is estimated to be approximately 0.06mm. However, this calculation result is half of actual crack widening in beams under 2.0Md sustained load (Fig. 6). Crack widening under sustained load test, therefore, can not be explained by drying shrinkage only.

## COMPARISON WITH PROPOSED ESTIMATION METHOD FOR CRACK WIDTHS

In JSCE (Japan Society of Civil Engineer) standard specification for concrete structure, examination for flexural crack width should be done with Equation 1 and given permissible crack width. In other specifications for PRC bridges, framework of examination method is similar.

$$w = 1.1k_1k_2k_3\{4c + 0.7(c_s - \phi)\}\left(\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd}\right) \quad (1)$$

where, $k_1$,$k_2$,$k_3$ = constant values to take into account the effect of surface geometry of reinforcement, concrete quality and multiple layers of tensile reinforcement on crack width; c = concrete cover(mm); $c_s$ = center to center distance of tensile reinforcement (mm); $\phi$ = diameter of tensile reinforcement (mm); $\varepsilon'_{csd}$ = compressive strain for evaluation of increment of crack width due to shrinkage and creep of concrete; $\sigma_{se}$ = increment of stress of reinforcement from the state in which concrete stress at the portion of reinforcement is zero N/mm$^2$.

However, the value of $\varepsilon'_{csd}$ for designing PRC bridge has not been established yet. To compare with proposed design values as $\varepsilon'_{csd}$, $\varepsilon'_{csd}$ in each beam is calculated with maximum crack width and increase of tensile longitudinal reinforcement in each beam and shown in Figure 12, as calculated value of w in Equation 1 virtually shows maximum crack width.

Calculated values of $\varepsilon'_{csd}$ after one year sustained load test range are bigger than proposed value, 150 × $10^{-6}$ by JSCE in beam C2, D1 and D2. Calculated values of $\varepsilon'_{csd}$ is smaller in PRC beam than RC beam. However the cause of this tendency is not clear.

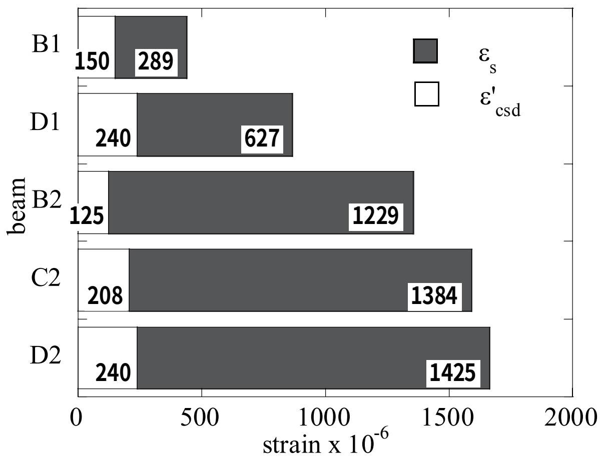


Figure 12. Calculated values of ε'csd and εs after 390 days sustained load test.

## CONCLUSIONS

Increase of the mid-span deflection and bending crack width are observed in beams under sustained flexural load and prestressing force dose not affect the rate of it when tensile strain of tensile longitudinal reinforcement is same.

Strain of concrete and tensile longitudinal reinforcement in beams under sustained flexural load has been proportional to the distance from the neutral axis generally.

Bond between concrete and tensile longitudinal reinforcement has not been affected significantly by sustained flexural load.

Compressive strain for evaluation of increment of crack width due to shrinkage and creep of concrete ($\varepsilon'_{csd}$) was bigger than proposed value by JSCE in some test beams.

## References

JSCE (2002) Standard specifications for concrete structures-2002 “Structural Performance Verification”

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