A STUDY ON THE LONG-TERM CREEP DEFORMATION OF
PC RIGID FRAME BRIDGE WITH CENTRAL HINGE

Takahisa Fukushima¹

Abstract

It has been reported that PC rigid frame bridges with central hinge can experience displacement of the central hinge to a degree that exceeds the deformation predicted at the time of construction. Therefore, this paper provides an analysis to grasp the cause of deviations between the design value and the actual value. The analysis method set up conditions that divided the analysis model into upper slab, web, and lower slab. As a result, when reproductive calculations of the deformation are done over a long period of time, we found mostly good agreement with actual measurements.

1. Introduction

Many PC rigid frame bridges with central hinge were built using the Dywidag method during the 1960’s to 1980’s. This was because the structural design is comparatively simple and construction costs are low. However, since there is a hinge, displacement increases over due to concrete drying shrinkage or even long-term creep deformation. Therefore, there have been reports that the displacement of the central hinge exceeds the deformation and/or deflection predicted at the time of construction.

Hanshin Expressway includes four PC rigid frame bridges with central hinges in its inventory. One, the Kireuriwari bridge, was massively reinforced. Also, the hinge deflection of the Sueyoshi Bridge has progressed beyond the deflection predicted at the design stage. This phenomenon was analyzed and considered as follows.

Differences in shrinkage a appears in concrete of identical composition in different sections such as the upper slab, web, and lower slab of a box girder cross section. This is because sectional curvature can boost the deformation. Therefore in this study, our experimental analysis considered the increase in strain over time for each

¹ Maintenance Engineering Group, Osaka Business and Maintenance Department, Hanshin Expressway Company Limited
factor of cross-section size, cross-section shape, relative humidity, reinforcing bar and difference in intensity of restraint with PC steel used for upper slab, web, and lower slab. As a result, we found that the deflection value is actually larger than what was predicted in the design. In doing this, we gathered basic data to contribute to future maintenance management.

2. Specifications of the bridge

<table>
<thead>
<tr>
<th>Route</th>
<th>Loop Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Sueyoshi Bridge</td>
</tr>
<tr>
<td>Length</td>
<td>L=166.000m</td>
</tr>
<tr>
<td></td>
<td>(48.000m+70.000m+48.000m)</td>
</tr>
<tr>
<td>Width</td>
<td>w=17.000m</td>
</tr>
<tr>
<td>superstructure</td>
<td>3 span continuous PC box girder bridge</td>
</tr>
<tr>
<td>substructure</td>
<td>rigid frame piers (3), T-type (1)</td>
</tr>
<tr>
<td>Foundation</td>
<td>piled foundations (4)</td>
</tr>
<tr>
<td>Intersection</td>
<td>Route 308, Higashi Yokobori river</td>
</tr>
</tbody>
</table>

3. Reproduction of long-term deflection Using Creep Analysis

3.1 Outline of analysis

This analysis used long-term deformation prediction formulas taken from the Japan Standard Specifications for Concrete Structures – 2012 “Design”. The analytical model divides a box girder section into an upper slab, web, and lower slab. Creep analysis was conducted using this analysis model. The flow chart of a creep analysis is shown in Figure 3.
START

Creation of an analysis model

- cross-section shape, cross-section size
- material characteristic value
- construction profile (PC steel, reinforcing bar)
- support condition

Set stress value just after completion
(Initial stress)

Analysis condition are set up for each section.

shrinkage strain, creep coefficient

Initial value setting of calculation conditions
- unit cement amount $C$ (kg/m$^3$)
- unit water amount $W$ (kg/m$^3$)
- relative humidity $RH$ (%)
- volume/surface ratio $V/S$ (mm)
- compressive strength $\sigma_{ck}$ (N/mm$^2$)
- drying shrinkage start time $t_{sh}$ (day)
- type of cement $C$ type=1 (normal)

Execution of creep analysis
(Calculation of response value)
- Analysis from 1964 to present

Comparison against actual measurement

OK
END

NG
Reexamination of the RH (%) of upper slab, web, and lower slab

Figure 3  Outline of analysis

Figure 4  Concept diagram of the analysis model
3.2 Analysis condition

Analysis conditions are shown in Table 2.

### Table 2  Analysis Conditions

<table>
<thead>
<tr>
<th>analytical model</th>
<th>A PC box girder with overhang was modeled. Analytical model divides a box girder section into an upper slab, web, and lower slab and uses this fiber model. (Figure 5)</th>
</tr>
</thead>
</table>
| materials                                | concrete  
  - design strength  $f_{ck}: 40 \text{N/mm}^2$  
  - unit cement amount  $C: 447 \text{kg/m}^3$  
  - unit water amount  $W: 170 \text{kg/m}^3$  
  - water-cement ratio  $W/C: 38\%$  
  - PC steel, reinforcing bar  
  - Adopted the value of as-built drawings |
| environmental condition                  | Annual average relative humidity:  64%  
  Average relative humidity from 1965 to 2013  
  (Data of the Meteorological Agency) |
| initial sectional force                  | Long-term Creep Deformation shall be based on the load just after completion. The direct entry of sectional force just after completion computed by design calculation is carried out. The sectional force in that case is shared for each upper slab, web, and lower slab. |
| construction schedule                    | The days of overhang erection were considered. (Figure 6) |

![Figure 5  Analytical model](image)

![Figure 6  Construction Schedule](image)
3.3 Long-term deformation prediction formula

This analysis targets a calculation of long-term creep deformation. Therefore, we defined the creep coefficient and drying shrinkage progress curve for calculating the long-term creep deformation.

3.3.1 Creep coefficient

Creep factor is calculated by the following formula. (Standard Specifications For Concrete Structures – 2012 “Design”5.2.9 is applied)

\[
\phi(t, t') = \frac{4W \left(1 - \frac{RH}{100}\right) + 350}{12 + f_c'(t')} \cdot \log_e (t - t' + 1) \cdot 10^{-6} \cdot E_c(t')
\]

(formula-1)

- \(t\): material age of the concrete at time of focus (day)
- \(t'\): material age of the concrete at time of loading (day)
- \(W\): unit water amount (kg/m³) (\(W \leq 175\) kg/m³)
- \(RH\): relative humidity (%) (50 ≤ RH ≤ 80%)
- \(f_c'\) (\(t'\)): compressive strength (N/mm²) at the age of \(t'\) (day)

3.3.2 Drying shrinkage strain

Shrinkage strain at the age of \(t\) (day) using the following formula.

\[
\epsilon_s(t) = \epsilon_{ds}(t, t_0) + \epsilon_{as}(t, t_s)
\]

(formula-2)

- \(\epsilon_{ds}(t, t_0)\): drying shrinkage strain (×10⁻⁶) at the age of \(t'\) (day)
- \(\epsilon_{as}(t, t_s)\): shrinkage strain of the concrete of a seal state from a concrete setting time to \(t\)

3.4 Creep analytical method

This analytical method evaluations allow consideration of relief from creep to the stress which occurs for every interval. It also considers the includes one by one, the influence of the stress fluctuation with the change of properties of matter, drying shrinkage or curing history, temperature history to calculation. To compute stress and strain is \(\sigma(t_i+1/2)\) and \(\varepsilon(t_i+1/2)\) at the time of \(t_i+1/2\). Therefore, this yields the following formula.
\[ \varepsilon \left( t_{i+1/2} \right) = \frac{\sigma \left( t_{i+1} \right) - \sigma \left( t_{i-1} \right)}{E(t_i)} \left( 1 + \varnothing \left( t_{i+1/2}, t_i \right) \right) \]
\[ + \sum_{j=1}^{i-1} \frac{\sigma \left( t_{j+1/2} \right) - \sigma \left( t_{j-1/2} \right)}{E(t_j)} \left( 1 + \varnothing \left( t_{i+1/2}, t_j \right) \right) + \varepsilon_f \left( t_{i+1/2} \right) \]  

(formula-3)

In this analysis, creep analysis used formula-3.

3.5 Analysis result
3.5.1 Shrinkage strain and creeping coefficient

The change of a value to the progress day of shrinkage strain and creeping coefficient is shown in Figure 7 and 8. The shrinkage strain has a larger ratio for large volume/surface than for the small ratio. Creeping coefficient becomes equivalent by all the components. This is because changes in the relative humidity is the same for all materials.
3.5.2 Calculation of long-term creeping deformation

The calculation result of long-term creeping deformation is shown in figure 9. An analysis level has a tendency to become the value smaller than the actual value. Therefore, parametric scrutiny is needed for more accurate reproduction of deformation condition.
4. Reproduction of the long-term deflection by the creeping analysis

4.1 How to reproduce

The variable points of analysis conditions is shown in Table 3.

<table>
<thead>
<tr>
<th>creep coefficient</th>
<th>How to reproduce</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper slab</td>
<td>It takes into consideration that moisture supply by rain water is performed.</td>
</tr>
<tr>
<td>relative humidity</td>
<td>at 95%.</td>
</tr>
</tbody>
</table>

Table 3  How to reproduce

<table>
<thead>
<tr>
<th>drying shrinkage strain</th>
<th>According to the Standard Specifications For Concrete Structures – 2012, &quot;In order to set contraction by dryness to 0, relative humidity is set up to 95%.&quot; … analysis condition(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>However, in the Specifications for Highway Bridges, $\varepsilon_{s0}$ becomes about $+5 \times 10^{-5}$ with 95% of relative humidity. Therefore, drying shrinkage strain in consideration of the moisture supply by rain water is taken as 20% of drying shrinkage strain progress at 64% of relative humidity (design level). … analysis condition(3) (Table 4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>post dead load</th>
<th>Noise barrier and inspection way were built in 1994.</th>
</tr>
</thead>
<tbody>
<tr>
<td>volume/surface ratio</td>
<td>Pavement and bridge surface waterproofing were given to the upper slab. Therefore, the set up notes that only the underneath surface of upper slab is exposed to the air. … analysis condition (4)</td>
</tr>
</tbody>
</table>

Table 4  Value of $\varepsilon_{s0}$ by the environmental condition

(Specifications for Highway Bridges table-2.2.3)

<table>
<thead>
<tr>
<th>environmental condition</th>
<th>$\varepsilon_{s0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the water</td>
<td>$-10 \times 10^{-5}$</td>
</tr>
<tr>
<td>RH 90%</td>
<td>$+10 \times 10^{-5}$</td>
</tr>
<tr>
<td>RH 70%</td>
<td>$+25 \times 10^{-5}$</td>
</tr>
<tr>
<td>RH 40%</td>
<td>$+50 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

4.2 Analysis result

4.2.1 Shrinkage strain and creep coefficient

The change of a value to the progress day of shrinkage strain and creep
coefficient is shown in Figures 10 and 11. In drying shrinkage strain, shrinkage strain of the upper slab is small. This is because the floor version was made into about 20% of relative humidity to other parts of 95% of relative humidity. In the creep coefficient, upper slab with high relative humidity becomes a value smaller than others.

Figure 10  Shrinkage strain

Figure 11  Creep coefficient
4.2.2 Calculation of long-term creeping deformation

The calculation result of long-term creeping deformation is shown in Figure 12. It is a value of the initial analysis and the value that accumulated in each case. This makes it possible to see the effect of the changed parameter.

The results show that the differentiation of post dead load, effective thickness and creep coefficient does not contribute significantly. On the contrary the 20% reduction of drying shrinkage strain in the upper slab influences the most on the differentiation greatly. In addition, vertical displacement exceeded an actual value when assumed the dry shrinkage strain of the upper slab 0 like a condition of Standard Specifications for Concrete Structures – 2012. Present situation reproduction is in this way possible by the analysis that considered a shrinkage difference to each material.

![Figure 12](image)

**Figure 12** Calculation of long-term creep deformation (center hinge)

4.3 Sensitivity analysis of each parameter

The sensitivity-analysis result of each parameter is shown in Table 5. This result showed that relative humidity greatly influenced long-term Creeping Deformation.
Table 5  Sensitivity analysis of each parameter

<table>
<thead>
<tr>
<th>parameter</th>
<th>Influence of long-term deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (W)</td>
<td>water (W) is increased to 200 kg/m³ → increases 7 mm</td>
</tr>
<tr>
<td>Cement (C)</td>
<td>water-cement ratio (W/C) is increased to 0.5 → increases 11 mm</td>
</tr>
<tr>
<td>relative humidity (RH)</td>
<td>all materials at 95% relative humidity (RH) → decreases about 60 mm</td>
</tr>
<tr>
<td></td>
<td>all materials at 40% Relative humidity (RH) → increases 60 mm</td>
</tr>
<tr>
<td></td>
<td>only upper slab at 95% Relative humidity (RH) → increases 150 mm</td>
</tr>
<tr>
<td>volume / surface ratio (V/S)</td>
<td>surface area of inside the box girder web and lower slab is disregarded (increase V/S) → increases 17 mm</td>
</tr>
<tr>
<td></td>
<td>only underneath surface of upper slab is exposed to the air → decreases about 25 mm</td>
</tr>
<tr>
<td>compressive strength (σ&lt;sub&gt;ck&lt;/sub&gt;)</td>
<td>compressive strength is lowered in 30Ns/mm → increases 30 mm</td>
</tr>
<tr>
<td></td>
<td>compressive strength is upper in 50Ns/mm → decreases 25 mm</td>
</tr>
</tbody>
</table>

5. Future prediction

The creeping deformation analysis result of 100 years later is shown in Figure 13. It is assumed that the deformation appears continuously with age although its quantity remains around 10 mm over time.

![Figure 13](image_url)

Figure 13  Reproduction of the long-term deflection by the creep analysis (center hinge)
6. Conclusion

Creep analysis conducted with new knowledge was performed on the Sueyoshi bridge. When reproductive calculations of the deformation were carried out for long period of time, we confirmed mostly good agreement with actual measurement findings.

- The deformation continues if long-term deformation prediction formula is used based on Standard Specifications for Concrete Structures – 2012 “Design” from prediction relation used conventionally over an extended period.
- The Analysis model divided box girder sections into an upper slab, web, and lower slab. The deformation in agreement with the actual measurement by the analysis which considered material specific shrinkage differences.
- Pavement and bridge surface waterproofing are applied on the upper slab. Therefore, the upper slab is different from the web and lower slab in environmental condition. By considering relative humidity and volume/surface ratio, the analytical value can obtain the result which is mostly in agreement with an actual measurement.
- In reproduction of the long-term deflection by the creeping analysis, relative humidity (RH) is a dominant factor. Therefore, the accuracy of the relative humidity of each component is important.
- The deformation will continue for the next 100 years and the quantity of the deformation will be around 10mm.