Coupling model for calculating prestress loss caused by relaxation loss, shrinkage, and creep of concrete

CAO Guo-hui, HU Jia-xing, ZHANG Kai
1. College of Civil Engineering, Hunan City University, Yiyang 413000, China; 2. College of Civil Engineering, Hunan University, Changsha 410082, China

© Central South University Press and Springer-Verlag Berlin Heidelberg 2016

Abstract: The calculation model for the relaxation loss of concrete mentioned in the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG D62—2004) was modified according to experimental data. Time-varying relaxation loss was considered in the new model. Moreover, prestressed reinforcement with varying lengths (caused by the shrinkage and creep of concrete) might influence the final values and the time-varying function of the forecast relaxation loss. Hence, the effects of concrete shrinkage and creep were considered when calculating prestress loss, which reflected the coupling relation between these effects and relaxation loss in concrete. Hence, the forecast relaxation loss of prestressed reinforcement under the effects of different initial stress levels at any time point can be calculated using the modified model. To simplify the calculation, the integral expression of the model can be changed into an algebraic equation. The accuracy of the result is related to the division of the periods within the ending time of deriving the final value of the relaxation loss of prestressed reinforcement. When the time division is reasonable, result accuracy is high. The modified model works excellently according to the comparison of the test results. The calculation result of the modified model mainly reflects the prestress loss values of prestressed reinforcement at each time point, which confirms that adopting the finding in practical applications is reasonable.

Key words: prestress; relaxation loss; shrinkage and creep; theoretical analysis; calculation model

1 Introduction

When the shrinkage and creep of concrete and the relaxation loss in prestressed reinforcement redistribute internal stress in a prestressed component, the compressive prestress in concrete and the tensile stress in prestressed reinforcement may be reduced. To calculate prestress loss precisely, a calculation model for the shrinkage and creep of concrete and the relaxation loss in prestressed reinforcement should be first established. The interactions between the shrinkage and creep of concrete and the relaxation loss in prestressed reinforcement should be thoroughly considered. The relations between the shrinkage and creep of concrete and the relaxation loss in prestressed reinforcement are ignored in the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG D62—2004) [1]. The relationship between the time and the relaxation loss in prestressed reinforcement has not been clearly addressed in this standard. Other factors, such as the uncertainty of prestress loss, are also not considered. Only a few values of the ratio of the period relaxation loss to the final relaxation loss in prestressed reinforcement can be traced. Research shows that over 30% of the total prestress loss is caused by the shrinkage and creep of concrete and the relaxation loss in prestressed reinforcement. This finding indicates that the shrinkage and creep of concrete and the relaxation loss in prestressed reinforcement are important factors that may lead to prestress loss. However, current calculation methods for prestress loss remain imperfect and have led to errors between the calculated and measured values [2–3]. The phenomenon of excessive mid-span sags and cracks in the web occurs under such background. Further research is required to address this issue.

At present, foreign scholars have conducted considerable research on prestress loss [4–13]; however, only a few studies have focused on calculation methods related to the interaction between the time-varying relaxation loss in prestressed reinforcement and the shrinkage and creep of concrete. The influences of both the time-varying relaxation loss in prestressed reinforcement and the situation in which prestressed reinforcement has varying lengths are considered. Studying the coupling expression of prestress loss caused by the relaxation in prestressed reinforcement and the shrinkage and creep of concrete is necessary to develop reliable and accurate calculation methods.

Foundation item: Project(51551801) supported by the National Natural Science Foundation of China; Project(14JJ4062) supported by the Natural Science Foundation of Hunan Province, China

Received date: 2014–12–11; Accepted date: 2015–03–14
Corresponding author: CAO Guo-hui, PhD, Professor, Tel: +86–737–4628808; E-mail: cgfcivil@163.com
2 Deriving a new model for prestress loss caused by relaxation in prestressed reinforcement and shrinkage and creep of concrete

In the *Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts* (JTG D62—2004), the final values of relaxation loss can be calculated using the following equation:

\[ \sigma_{lt} = \psi \cdot \zeta (0.52 \frac{\sigma_{pk}}{f_{pk}} - 0.26) \sigma_{pc} \]  

where \( \sigma_{lt} \) is the final value of relaxation loss; \( \psi \) is the tension coefficient, for one time tension, \( \psi = 1.0 \) and for over-tension, \( \psi = 0.9 \); \( \zeta \) is the relaxation coefficient of steel reinforcement, for grade I steel (ordinary steel), \( \zeta = 1.0 \), and for grade II steel (low relaxation), \( \zeta = 0.3 \); \( \sigma_{pc} \) is the anchorage stress of steel reinforcement, for post-tensioned prestressed concrete members, \( \sigma_{pc} = \sigma_{cc} - \sigma_{s1} - \sigma_{st} - \sigma_{stt} \), and for pre-tensioned prestressed concrete members, \( \sigma_{pc} = \sigma_{cc} - \sigma_{st} / f_{pk} \) is the ultimate tensile strength of prestressed reinforcement; \( \sigma_{s1} \) is the prestress loss caused by friction between prestressed reinforcement and pipe wall; \( \sigma_{st} \) is the prestress loss caused by anchorage deformation, retraction, and joint compression; \( \sigma_{stt} \) is the prestress loss caused by elastic compression of concrete.

Equation (1) shows the relationship between the final values of relaxation loss and the anchorage stress of a reinforced steel bar. Relaxation loss is ignored when \( \sigma_{pc} / f_{pk} \leq 0.5 \). Moreover, the tensile and relaxation coefficients are considered to reflect the relationship between the final values of low-relaxation steel and ordinary steel. The final value of low-relaxation reinforcement is 1/3 lower than that of ordinary reinforcement.

However, the standard only provides prestress relaxation loss for a few periods and does not offer a method to calculate the exact value of prestress relaxation loss at any point in time. The ratio of the intermediate relaxation loss to the final relaxation loss in prestressed reinforcement is presented in Table 1.

Table 1 shows that given the influence of prestressed tension, the amount of prestress relaxation loss that occurs during the early stage is considerably large such that 50% of the entire relaxation loss is completed within the first 2 days, and another 11% is realized in the next 8 days. Then, prestress relaxation loss gradually stabilizes. According to Table 1, prestress relaxation loss is completed within 40 days. This phenomenon obviously disagrees with the test result.

Table 1 Ratio of intermediate relaxation loss to final relaxation loss in prestressed reinforcement

<table>
<thead>
<tr>
<th>Time/d</th>
<th>2</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>0.50</td>
<td>0.61</td>
<td>0.74</td>
<td>0.87</td>
<td>1.00</td>
</tr>
</tbody>
</table>

LU et al [14–15] researched on the relaxation properties of high-strength steel wire produced by the main prestressed steel factory in China. This study presented factors such as the prestress relaxation loss of initial stress, time, over-tension technology. All these factors influenced the relaxation properties of high-strength steel wire. The long testing period reached 27500 h in this test, with 42 specimens tested and 3000 data obtained. The detailed test data are given in Table 2. The experiment was conducted for a long time, and the maximum measured values were regarded as the final values of relaxation loss. The data in Table 2 were transformed into the ratio of the intermediate relaxation loss to the final relaxation loss in prestressed reinforcement. The results are provided in Table 3. The time-varying curve of the ratio is shown in Fig. 1.

The time-varying curve (ratio of the intermediate values to the ultimate values) shown in Fig. 1 is fitted with the least square method. The fitting curve is assumed as follows:

\[ R(t) = 1 - \exp[-a(\sigma_i / R_i)^t] \]  

where \( a \) is a function of \( \sigma_i / R_i \) (the relative initial stress) in Eq. (2), and the fitted values are given in Table 4.

Table 4 shows that the values of \( a \) can be determined through the demarcation point located at...
Table 3 Measured ratio of intermediate to final relaxation losses in prestressed reinforcement

<table>
<thead>
<tr>
<th>Number</th>
<th>$R_p^i$/MPa</th>
<th>Elongation/%</th>
<th>$\sigma_i/R_p^i$</th>
<th>Ratio of intermediate to final values of measured data, $\sigma_R(t)/\sigma_R$ (end)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1599.2</td>
<td>4.5</td>
<td>0.24</td>
<td>0.01 h 0.4 h 1 h 5 h 41.7 h 125 h 253 h 418 h 646 h 833.3 h 1145.8 h</td>
</tr>
<tr>
<td>2</td>
<td>1696.0</td>
<td>5.0</td>
<td>0.15</td>
<td>1599.2 4.5 0.8 0.24 0.41 0.46 0.57 0.76 0.84 0.92 0.95 0.98 1.00</td>
</tr>
<tr>
<td>3</td>
<td>1714.3</td>
<td>5.0</td>
<td>0.06</td>
<td>1696.0 5.0 0.7 0.15 0.29 0.35 0.46 0.68 0.78 0.80 0.88 0.92 0.96 1.00</td>
</tr>
<tr>
<td>4</td>
<td>1785.7</td>
<td>5.0</td>
<td>0.04</td>
<td>1714.3 5.0 0.6 0.06 0.16 0.18 0.33 0.57 0.71 0.73 0.84 0.91 0.96 1.00</td>
</tr>
</tbody>
</table>

$R_p^i$ — Ultimate tension of prestressed reinforcement; $\sigma_i$ — Initial tension control stress of prestressed reinforcement.

Table 4 Values of $a$ under different initial tension control stress levels

<table>
<thead>
<tr>
<th>$\sigma_i/R_p^i$</th>
<th>0</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A(\sigma_i/R_p^i)$</td>
<td>0.0040</td>
<td>0.0139</td>
<td>0.1691</td>
<td>0.3342</td>
<td></td>
</tr>
</tbody>
</table>

The data in Table 5 are fitted with a power function using the least square method. The fitting curve is as follows:

$$R(t) = 1 - \exp(-0.022t)$$

Considering the time-varying relaxation loss in prestressed reinforcement and combining Eqs. (1), (2), and (3), the computational model for prestress relaxation loss under high-strength and low-relaxation prestressed tension can be modified as follows:

$$\sigma_{lt}(t) = \psi \cdot \zeta (0.52 \sigma_{pe}/f_{pk} - 0.26) \sigma_{pe} [1 - \exp(-a(\sigma_i/R_p^i)t)]$$

(4)

The relaxation loss of prestressed reinforcement under different initial tension control stress levels and periods can be calculated using Eq. (4). However, the calculation model should also consider the influence of the shrinkage and creep of concrete because the wire length of prestressed reinforcement is changeable and gradually shortens under the working state. This variation in reinforcement will change the relaxation loss in prestressed reinforcement; hence, the actual relaxation loss will be less than the fixed relaxation loss. According to Ref. [17], the relaxation reduction coefficient is derived from the following formula:

$$\lambda = 1 - \frac{2(\sigma_{po}/f_{pk})(3 - \Omega) - 1.35}{6(\sigma_{po}/f_{pk} - 0.45)}$$

(5)

Based on Eq. (5),

$$\Omega = \frac{\sigma_{1i}(t) - \sigma_{po}(t)}{\sigma_{po}}, \quad \sigma_{po}/f_{pk} > 0.45$$

(6)

$$\sigma_{LR}(t) = \lambda \sigma_{pe}(t)$$

(7)
where $\sigma_0(t)$ is the actual relaxation loss of prestressed reinforcement; $\sigma_1(t)$ is the long-term loss of prestressed reinforcement; $f_{pk}$ is the standard design strength of prestressed reinforcement.

The specific parameters are provided in Ref. [17]. First, assume $\lambda=0.7$, and then calculate iteratively until the results can satisfy precision requirements. SUN and LU [18] also used the initial stress reduction coefficient to calculate relaxation loss approximately in prestressed concrete members, typically $\sigma'_0(t) = 0.9\sigma_0(t)$.

However, these expressions do not reflect the mutual coupling relation between the shrinkage and creep of concrete and the relaxation loss in prestressed reinforcement, i.e., the formula does not reflect the shrinkage and creep factor. To improve the prediction accuracy of the relaxation loss in prestressed reinforcement, researching on prestress relaxation loss caused by concrete shrinkage and creep is necessary.

According to the superposition principle, when considering the effects of the shrinkage and creep of concrete, the typical relationship between stress and strain in concrete can be expressed as follows:

$$
\varepsilon_c(t) = \frac{\sigma_c(t)}{E_{ct}(t)} + \sum_{t_i=t_0}^t \frac{\Delta \sigma_c(t)}{E_{ct}(t)} (1 + \varphi(t_i,t_0)) + \varepsilon(t)_{sh(t_0)}
$$

(8)

When loading age is $t_0$ and stress in the concrete structure changes continuously, time-varying shrinkage and creep can be considered using the effective modulus method to adjust loading age. According to Trost’s equation, there is

$$
\varepsilon_c(t) = \frac{\sigma_c(t)}{E_{ct}(t)} (1 + \varphi(t_0,t_0)) + \frac{(\sigma_c(t) - \sigma_c(t_0))(1 + \chi(t_0)\varphi(t_0,t_0))}{E_{ct}(t)} + \varepsilon(t)_{sh(t_0)}
$$

(9)

The strain caused by shrinkage and creep can be expressed as

$$
\varepsilon'(t) = \frac{\sigma_c(t)}{E_{ct}(t)} \varphi(t_0,t_0) + \frac{(\sigma_c(t) - \sigma_c(t_0))\chi(t,t_0)\varphi(t_0,t_0)}{E_{ct}(t)} + \varepsilon(t)_{sh(t_0)}
$$

(10)

where $\chi(t,t_0)$ is the concrete aging coefficient; $\varepsilon_c(t)$ is the concrete strain of $t$ moment; $\varepsilon_c(t_0)$ is the concrete strain of $t_0$ moment caused by shrinkage and creep; $\varphi(t_0,t_0)$ is the concrete creep coefficient of $t$ moment; $\sigma_c(t_0)$ is the concrete instantaneous strain of $t_0$ moment; $\sigma_c(t)$ is the concrete instantaneous strain of $t$ moment; $\varepsilon(t)_{sh(t_0)}$ is the concrete shrinkage strain; $E_{ct}(t)$ is the modulus of elasticity of the loading age at $t_0$.

When prestressed reinforcement is at the same level, then we can obtain the following equation according to the deformation compatibility between prestressed reinforcement and concrete:

$$
\varepsilon_c(t) - \varepsilon_c(t_0) = \frac{\Delta \sigma_p(t,t_0)}{E_p}
$$

(11)

where $E_p$ is the modulus of elasticity of prestressed reinforcement.

From Eq. (11), we can deduce

$$
\Delta \sigma_p(t,t_0) = (\varepsilon_c(t) - \varepsilon_c(t_0))E_p
$$

(12)

Hypotheses are as follows:

(1) The initial stress of prestressed reinforcement is that the tension control stress reduces the values caused by concrete shrinkage and creep;

(2) The relaxation curve slope of prestressed reinforcement with a variable length is the same as that of the initial tension control stress, which is equal to the fixed length of a specimen at some point in time.

In particular, the initial relative stress can be expressed as follows:

$$
\sigma_p(t)/R_y = (\sigma_i - \Delta \sigma_p(t,t_0))/R_y
$$

(13)

By combining the preceding formula with Eq. (12), we can obtain

$$
\sigma_p(t)/R_y = \frac{\sigma_i - (\varepsilon_c(t) - \varepsilon_c(t_0))E_p}{R_y}
$$

(14)

From Eqs. (1)–(4) and (8)–(13), we can derive the calculation model that considers time-varying relaxation loss and relaxation loss caused by the variable length of prestressed reinforcement under shrinkage and creep, as follows:

$$
\sigma_{t_0}(t) = \psi \cdot \zeta \cdot (0.52 \frac{\sigma_{pe}}{f_{pk}} - 0.26) \cdot \sigma_{pe} \cdot \left(1 - \exp\left(-a\left(\frac{(\varepsilon_c(t) - \varepsilon_c(t_0))E_p}{R_y}\right)\right)\right)
$$

(14)

Prestressed reinforcement is under the working state with variable lengths; hence, different working lengths correspond to various final values of prestress relaxation loss. However, Eq. (14) only reflects the time-varying function of prestressed reinforcement with variable length, which does not reflect the different final values of prestress relaxation loss under various working lengths. Considering the effect of the variable length of reinforcement on the ultimate relaxation loss of prestressed reinforcement, the final values of prestress relaxation loss at any moment are given as follows:
\[
\sigma_{13}(t) = \frac{(0.52 \sigma_{pc} - (\epsilon_c(t) - \epsilon_c(t_0))E_p) - 0.26}{f_{pk}},
\]
\[
(\sigma_{pc} - (\epsilon_c(t) - \epsilon_c(t_0))E_p).
\]

Considering the influences of concrete shrinkage and creep on the final values of the prestress relaxation loss and the time-varying function of the relaxation loss in prestressed reinforcement during the entire process, the mathematical expressions of prestress relaxation loss in variable-length prestressed reinforcement caused by shrinkage and creep can be derived according to a mathematical function, as follows:

\[
\sigma_{13}(t) = \frac{\psi \cdot \zeta^n}{t_u} \frac{(0.52 \sigma_{ps} - (\epsilon_c(t) - \epsilon_c(t_0))E_p) - 0.26}{f_{pk}}.
\]

\[
(\sigma_{pc} - (\epsilon_c(t) - \epsilon_c(t_0))E_p)dt.
\]

\[
(1 - \exp(-a(\sigma_{13} - (\epsilon_c(t) - \epsilon_c(t_0))E_p))(t)). (18)
\]

**3 Experimental verification**

A prestressed concrete rectangular beam and a T-beam are tested. The rectangular beam includes two prestressed reinforcements, each measuring 527 cm (length) × 30 cm (height) × 15 cm (width). A total of 1860 steel bars are used as prestressed reinforcements under post-tensioned treatment. The pre-tensioned prestressed steel is called N1, whereas the post-tensioned reinforcement is called N2. The configuration of three prestressed reinforcements comprises a T-beam with a length of 1000 cm, a height of 58 cm, a roof width of 53 cm, a horseshoe width of 18 cm, a horseshoe height of 9 cm, and a web thickness of 10 cm. A total of 1860 steel bars are used as prestressed reinforcements under post-tensioned treatment. The pre-tensioned prestressed steel is called N1, whereas the post-tensioned reinforcement is called N3. The initial tension control stress levels of the rectangular beam and the T-beam are both 0.7f pk. Using HPB235 for regular reinforcement, the concrete strength design value is C40. The size and reinforcement of the rectangular beam section are shown in Figs. 2 and 3.

To calculate the stress change in prestressed reinforcement of the rectangular beam, stress changes in N1 and N2 are measured using sensors 1 and 2. For the T-beam, the stress changes in N1 and N3 are measured using sensors 3 and 4. The short-term results are presented in Fig. 4.

In the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG D62—2004), prestress loss caused by the concrete shrinkage and creep of the members in tension and compression areas can be calculated according to the following equations:

\[
\sigma_{16}(t) = \frac{E_p \epsilon_{cs}(t, t_0) + \alpha_{tcp} \sigma_{ps} \phi(t, t_0)}{1 + 15 \rho \rho_p}.
\]

\[
\sigma_{16}'(t) = \frac{0.9 \left[ E_p \epsilon_{cs}(t, t_0) + \alpha_{tcp} \sigma_{ps} \phi(t, t_0) \right]}{1 + 15 \rho \rho_p}.
\]

The meaning of the parameters of these formulas can be found in Ref. [1]. From Eqs. (19) and (20), the calculated values of prestress loss caused by concrete shrinkage and creep are shown in Table 6.

Based on Fig. 5 and Table 6, creep and shrinkage have significant effects on prestress loss during the first stage. Prestress loss appears to stabilize gradually after 100 d but continues increasing. According to Eq. (18), considering that tension methods are different, prestress...
loss caused by stress relaxation is given in Table 7. The time-varying curve of the final prestress loss at different times is shown in Fig. 6. The time-varying prestress relaxation loss curve is shown in Fig. 7.

As shown in Fig. 6, the relaxation loss of the rectangular beam gradually becomes stable after 300 d, whereas that of the T-beam gradually becomes stable after 1100 d. As shown in Fig. 7, the prestress loss caused by relaxation is relatively smaller than that caused by shrinkage and creep. In the entire relaxation process, prestress loss is mostly developed during the early stage. For the rectangular beam, the prestress relaxation losses in N1 and N2 are approximately 14.0 MPa and 11.0 MPa, respectively. For the T-beam, the prestress relaxation losses in N1 and N3 are approximately 23.0 MPa and 17.0 MPa, respectively. The calculated results of prestress relaxation loss are superimposed with prestress loss caused by shrinkage and creep. The calculated results are compared with the measured results (Table 8).

Table 8 shows that the calculated results are close to the measured results, which can basically reflect the time-varying law of prestress loss. The calculation results are satisfactory.
Fig. 3 Size and reinforcement of T-beam section (Unit: cm): (a) Prestressed steel longitudinal layout of T-beam; (b) Section reinforcement diagram of T-beam; (c) T-beam section
Fig. 4 Time-varying curve of measured values of prestress loss

Table 6 Calculated values of prestress loss caused by concrete shrinkage and creep

<table>
<thead>
<tr>
<th>Time/d</th>
<th>Prestress loss of rectangular beam/MPa</th>
<th>Prestress loss of T-beam/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N1 N2</td>
<td>N1 N2</td>
</tr>
<tr>
<td>2</td>
<td>42.5 33.8</td>
<td>39.5 35.2</td>
</tr>
<tr>
<td>5</td>
<td>54.4 43.2</td>
<td>50.6 45</td>
</tr>
<tr>
<td>10</td>
<td>66.4 52.7</td>
<td>61.7 54.8</td>
</tr>
<tr>
<td>15</td>
<td>72.9 57.9</td>
<td>67.8 60.3</td>
</tr>
<tr>
<td>20</td>
<td>74.3 59</td>
<td>69.1 61.4</td>
</tr>
<tr>
<td>410</td>
<td>116.5 92.6</td>
<td>108.3 96.3</td>
</tr>
<tr>
<td>420</td>
<td>116.9 92.8</td>
<td>108.7 96.6</td>
</tr>
<tr>
<td>430</td>
<td>117.1 93</td>
<td>108.8 96.7</td>
</tr>
</tbody>
</table>

Fig. 5 Time-varying curves of prestress loss caused by concrete shrinkage and creep

Table 7 Calculated values of prestress relaxation loss

<table>
<thead>
<tr>
<th>Time/d</th>
<th>Prestress loss of rectangular beam/MPa</th>
<th>Prestress loss of T-beam/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N1 N2</td>
<td>N1 N2</td>
</tr>
<tr>
<td>2</td>
<td>2.2 3.2</td>
<td>3.2 5.0</td>
</tr>
<tr>
<td>5</td>
<td>4.3 6.3</td>
<td>6.4 9.8</td>
</tr>
<tr>
<td>10</td>
<td>6.4 9.2</td>
<td>9.6 14.5</td>
</tr>
<tr>
<td>15</td>
<td>7.7 10.9</td>
<td>11.6 17.2</td>
</tr>
<tr>
<td>20</td>
<td>8.7 12.1</td>
<td>13.1 19.0</td>
</tr>
<tr>
<td>410</td>
<td>11.1 14.3</td>
<td>17.2 22.5</td>
</tr>
<tr>
<td>420</td>
<td>11.1 14.3</td>
<td>17.2 22.5</td>
</tr>
<tr>
<td>430</td>
<td>11.1 14.3</td>
<td>17.2 22.5</td>
</tr>
</tbody>
</table>

Fig. 6 Time-varying curve of final values of prestress loss

Table 8 Calculated values compared with measured values

<table>
<thead>
<tr>
<th>Time/d</th>
<th>Prestress loss of N1 in rectangular beam/kN</th>
<th>Prestress loss of N2 in rectangular beam/kN</th>
<th>Prestress loss of N1 in T-beam/kN</th>
<th>Prestress loss of N3 in T-beam/kN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated Measured Difference</td>
<td>Calculated Measured Difference</td>
<td>Calculated Measured Difference</td>
<td>Calculated Measured Difference</td>
</tr>
<tr>
<td>2</td>
<td>6.3 5.0 1.3</td>
<td>5.2 3.8 1.4</td>
<td>6.0 5.8 0.2</td>
<td>5.6 2.7 2.9</td>
</tr>
<tr>
<td>5</td>
<td>8.2 5.9 2.3</td>
<td>6.9 4.6 2.3</td>
<td>8.0 6.8 1.2</td>
<td>7.7 3.3 4.4</td>
</tr>
<tr>
<td>10</td>
<td>10.2 6.8 3.4</td>
<td>8.7 5.4 3.3</td>
<td>10.0 8.7 1.3</td>
<td>9.7 4.4 5.3</td>
</tr>
<tr>
<td>15</td>
<td>11.3 7.4 3.9</td>
<td>9.6 6.0 3.6</td>
<td>11.1 9.1 2.0</td>
<td>10.9 4.8 6.1</td>
</tr>
<tr>
<td>20</td>
<td>11.6 8.4 3.2</td>
<td>10.0 7.2 2.8</td>
<td>11.5 10.6 0.9</td>
<td>11.3 6.2 5.1</td>
</tr>
<tr>
<td>410</td>
<td>17.9 19.9 –2.0</td>
<td>15.0 20.2 –5.2</td>
<td>17.6 22.7 –5.1</td>
<td>16.6 19.1 –2.5</td>
</tr>
<tr>
<td>420</td>
<td>17.9 20.6 –2.7</td>
<td>15.0 20.9 –5.9</td>
<td>17.6 23.0 –5.4</td>
<td>16.7 19.3 –2.6</td>
</tr>
<tr>
<td>430</td>
<td>17.9 20.3 –2.4</td>
<td>15.0 20.6 –5.6</td>
<td>17.6 22.9 –5.3</td>
<td>16.7 19.3 –2.6</td>
</tr>
</tbody>
</table>
4 Conclusions

A modified calculation model for prestress relaxation loss is proposed. New factors have been taken into account in the revised model. The effect of the variable length of prestressed reinforcement on relaxation loss is considered by changing the initial tension control stress. Time-varying prestress relaxation loss is also considered, including the influence of prestressed reinforcement with a variable length under the working state. A close relationship between prestress relaxation loss and experimental observation is significant, and will pave the way to satisfy the requirements of practical engineering solutions.

References


(Edited by YANG Bing)