Relaxation of Coldrawn Prestressing Steel Under Stationary and Transient Elevated Temperature

F. S. Rostásy, K. Thienel
Institut für Baustoffe, Massivbau und Brandschutz, Braunschweig, FRG

K. Schütz
SUSPA Spannbeton GmbH, Langenfeld, FRG

G. Becker
Hochtemperatur-Reaktorbau GmbH, Mannheim, FRG

INTRODUCTION

In course of the development of the gas-cooled high temperature reactor in the Federal Republic of Germany two alternatives for the reactor vessel are being investigated: a prestressed concrete reactor vessel PCRV and a prestressed cast-iron reactor vessel CIRV. Both types will be axially post-tensioned with unbonded tendons and circumferentially by wire winding. Because of elevated temperatures during regular operation and due to abnormal events, the prestressing steel will suffer relaxation losses being both unknown and in excess of those at normal temperature. Thus, a comprehensive experimental study dealing with relaxation at elevated temperature became necessary in order to be able to predict the losses for safety analysis. The experiments were performed at different Laboratories. Some of the results will be summarized here in context with the PCRV development (Becker et al, 1988).

PRESTRESSING STEEL

The prestressing steel of the axial BBRV-SUSPA cables is a St 1470/1670 (MPa) steel of 7 mm diameter. This is a pearlitic colddrawn wire which is finally stabilized to achieve a very low relaxation. For circumferential post-tensioning a seven-wire 3/8" strand of the St 1570/1770 (MPa) strength class was chosen. This material is also colddrawn and stabilized. Only the behaviour of the 7 mm wire will be dealt with here.

Fig. 1 shows some of the mechanical values of the steel as function of temperature. Only one heat of steel could be investigated. The elastic limit Rp0.01 which influences relaxation is markedly affected by temperatures T > 70 °C.

REGIMES OF STEEL STRESS AND TEMPERATURE

Determination of test parameters must be based upon the histories of the temperature and steel stress in the structure. These histories are shown schematically by Fig. 2. Post-tensioning will be performed at normal temperature NT: adm 0.01 = 1100 MPa. A rather small relaxation loss of prestressing force will occur prior to heat-up of reactor. Then, in course of heat-up the stressed steel will suffer an additional loss of stress due to instationary temperature and relaxation. During normal operation, the axial tendons will be subjected to a temperature T ≤ 70 °C and the circumferential strand to T ≤ 40 °C. During operation irregularities of the cooling system have to be taken into account, leading to an additional rise of temperature for a restricted lapse of time (dashed lines). This will lead to transient acceleration of relaxation.
Fig. 1: Temperature dependence of some mechanical properties of prestressing steel

Fig. 2: Histories of concrete temperature and steel stress of PCRV, schematically

PROGRAM OF EXPERIMENTAL WORK

Aim of Investigation

The experimental work had the following aims:
- determination of isothermal relaxation for different constant test temperatures over a long period of time
- determination of accelerated relaxation due to initial heat-up and multiple rise of temperature due to cooling disturbances
- elaboration of material laws for analytical work of safety analysis

Besides these aims, experiments have to serve to stipulated requirements for the selection and quality control of steel.

Test Program of Isothermal Tests

In the isothermal relaxation test, the unstressed specimen is heated to test temperature $T$ and then stressed to the desired initial stress:

$$\sigma_{pl}(t=0) = x RmT$$

(1)

Immediately after reaching the stress $\sigma_{pl}$, the corresponding initial strain $\varepsilon_{pl}$ is maintained constant. Relaxation is then measured versus time (up to 20,000 h):

$$R(t,T,\sigma_{pl}) = \frac{\Delta \sigma(t,T,\sigma_{pl})}{\sigma_{pl}(x)}$$

(2)

Test variables were: test temperature $T$ (20, 40, 75, 110, 130, ... 175 °C), the ratio $x$ and the observation time $t$. Experimental details are given in (Rostásy et al., 1987).

Test Program of Anisothermal Tests

In reality, the prestressing steel is stressed at NT. The initial heat-up of the PCRV causes an accelerated transient relaxation loss. Disturbances of cooling may
also cause additional losses. Other instationary temperature histories must be considered. The experimental work consequently comprised transient tests. In these tests which started at NT and the steel being stressed to $\Delta_p(20^\circ)$, the temperature was increased step-wise and then kept constant etc.

For all transient tests the initial steel stress at 20 °C was chosen to $\sigma_{pi} = 1185 \text{ MPa}$ at $R_m(20^\circ)$ Heating of steel took 10 to 15 hours, depending on the test temperature. Temperature strain was eliminated from total strain, mechanically induced strain $\varepsilon_{pi}$ was kept constant. The following transient histories were studied (Rostásy et al, 1987):

- history 1; initial activation
  20 °C/10 hrs $\rightarrow$ 70 °C/1000 hrs $\rightarrow$ 20 °C
- history 2; multiple activation
  20 °C/500 hrs $\rightarrow$ 70 °C/500 hrs $\rightarrow$ 130 °C/200 hrs $\rightarrow$ 20 °C
- history 3; multiple activation
  20 °C/10 hrs $\rightarrow$ 45 °C/500 hrs $\rightarrow$ 70 °C/500 hrs $\rightarrow$ 130 °C/200 hrs $\rightarrow$ 20 °C

Comparative isothermal tests for each temperature value were also performed. Experimental details are given in (Rostásy et al, 1987).

**TEST RESULTS AND DISCUSSION**

**Temperature Dependence of Relaxation**

Relaxation is the material's stress reply to imposed strain. It is due to visco-elastic/viscoplastic components in the mechanical behaviour of the material. It is, hence, related to creep which is the material's strain reply to mechanical stress. Relaxation is a thermally activated process; it is caused by the movement of dislocations. Thermal activation of the rate of relaxation can be expressed by

$$\dot{R}(t,T,\sigma_{pi}) = \varepsilon_{pi} C(T,t)e^{-Q/RgT_{abs}}$$  \hspace{1cm} (3)

with

$$\varepsilon_{pi} = \Delta_{pi}/E = \text{const}$$
$$C \ldots \ldots \text{function of grain structure, time and temperature}$$
$$A \ldots \ldots \text{activation energy of relaxation}$$
$$R_g \ldots \ldots \text{universal gas constant}$$
$$T_{abs} \ldots \ldots \text{absolute temperature in K}$$

Values for $C$ and $Q$ can only derived from tests. Evaluation of tests shows a very large scatter. Due to this fact empirical functions based on test results are presently more suited to describe the behaviour.

**Results of Isothermal Tests**

On basis of the test results the mean relaxation of the colddrawn and stabilized 7 mm wire can be described by

$$R(t,T) = a(t)e^{b(t)T}$$  \hspace{1cm} (4)

Fig. 3 shows that the results are well described by Equ. (4) within the following range:

$$\Delta_{pi} \leq 1185 \text{ MPa}$$
$$T \leq 130 \text{ °C}$$
Equ. (4) implicates that the loss $\Delta \sigma_p$ is proportionate to the initial stress. This is approximately valid if $T \leq 100 ^\circ C$ and if $\sigma_{\text{p}i} \leq 0.75 \sigma_{\text{m}T}$. If the temperature exceeds 100 $^\circ C$ relaxation will increase markedly. Relaxation is a scattering property. The 10% and 90% confidence limits can be expressed by

$$R_{90\% / 10\%} = R(1 + 0.1) \pm 0.5\%$$

(5)

if $R$ is expressed in percent

$$R = \frac{\Delta \sigma_p}{\sigma_{\text{p}i}} \times 100\%.$$ 

Thus, prediction of isothermal relaxation during service life of PCRV ($\approx 40$ years) can be based on Equ. (4) and (5).

**Results of Transient Relaxation Tests**

Fig. 4 shows results from the transient tests following history 2 (20 $\rightarrow$ 70 $\rightarrow$ 130 $^\circ C$). Heating from 20 $^\circ C$ to 70 $^\circ C$ causes the activation $R_A$. The rate of transient relaxation shows a maximum at about 5 hours after on-set of heating which lasted for 12 hours. It levels off $\approx 30$ hours after beginning of heating. Then, the relaxation curve follows the isothermal curve for 70 $^\circ C$, taking a shift of real time into account which will be explained. The observation for the step 70 $\rightarrow$ 130 $^\circ C$ is similar.

Evaluation of tests showed that the activation $R_A$ can be expressed by the temperature difference $\Delta T = T_2 - T_1$ ($T_2 > T_1$):

$$R_A = K(1 - \frac{R_h}{R_e}) \cdot \Delta T$$

(6)

with

$K$ .... constant; $0.05(1 \pm 0.25)$

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\( R_h \) ... isothermal relaxation at \( t=t_h \) and \( T_1: R(t_h,T_1) \)
\( R_e \) ... isothermal relaxation at \( t=t_e = 5 \times 10^5 \) hrs and \( T_2: R(t_e,T_2) \)

If the wire is cooled from \( T_2 \) to \( T_1 \), \( R_A \) is not regained. Unstressing of the steel at \( (t_f, T_1) \) leads to the elastic recovery of

\[
\varepsilon_{el}(t_f, T_1) = \varepsilon_{pi} - \Delta \varepsilon_{pl}(t_f)/E(T_1)
\]  

(7)

**Superposition Principle**

A wire tensioned at \( t = 0; T_1 = 20^\circ C \) will suffer the loss \( R(t_h,T_1) \) until the on-set of first heat-up. For the prediction of relaxation for multiple steps of heating and cooling a superposition principle must be developed. Fig. 5 shows the model for a two-step history. It can be generalized in the following way with \( R \) denoting isothermal relaxation and \( \hat{R} \) being the resultant relaxation:

\[
\begin{align*}
R(t, T_2) &= R(t + \delta t_h, T_2) \\
\hat{R}(t, T_2) &= \hat{R}(t + \delta t_h, T_2)
\end{align*}
\]

(8)

(9)

The sign and value of the integer \( \delta \) is decided with the following criteria:

\[
\begin{align*}
R(t_h, T_1) + R_A &> R(t_h, T_2) \quad \delta = 1 \\
R(t_h, T_1) + R_A &= R(t_h, T_2) \quad \delta = 0 \\
R(t_h, T_1) + R_A &< R(t_h, T_2) \quad \delta = -1
\end{align*}
\]

(10)

The activation \( R_A \) due to heat-up of the stressed wire is the premature exploita-
tion of the available relaxation potential \( R_e(t_e,T_2) \). Thus, in the long term the isothermal relaxation under \( T_2 \) cannot be transgressed. Equ. (8) and (9) are also valid for a third heating step \( T_2 \rightarrow T_3 \). Then, the resultant relaxation \( \hat{R}(t_h,T_2) \) must be compared with \( R(t_h,T_3) \) according to Equ. (10) for decision of the resul-
tant curve \( \hat{R} \). After each instance of heating, only that part of the relaxation under the then prevailing temperature can be activated which has not yet been ex-
ploded be preceding histories.

If the temperature \( T_2 \) is lowered again to \( T_1 \) at the time \( t_c \), the relaxation \( \hat{R}(t_c) \) is irrecoverable. This means that multiple cycles between \( T_1 \) and \( T_{i+1} \) will not cause excessive relaxation beyond the resultant curve \( \hat{R}(t_h,T_{i+1}) \) if \( T_{i+1} \) is the
maximum temperature due to disturbance and if $T_i = 70 \, ^\circ\text{C}$ for the axial tendons during regular operation. The proposed theory is well verified by the tests.

CONCLUSION

The safety analysis of the PCRV requires reliable knowledge of the prestressing force at any age and after multiple cycles of heating and cooling of the PCRV. On basis of experiments an extrapolation law for the isothermal relaxation could be established. A temperature rise above operational level causes transient relaxation. On the basis of tests the effects of multiple temperature changes could be modelled and verified.

REFERENCES
