STEEL IN CONCRETE

DESIGN ASSUMPTION OF RELAXATION LOSSES IN PRESTRESSING TENDONS

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Design engineers are often faced by the question of how to reckon with relaxation, this special kind of losses accompanying pretensioning or posttensioning. Manufacturers' tests usually concern pure relaxation values at ambient temperature $\Delta\sigma_{p,\mathrm{rel}}$ (CEB-FIP symbol) or r (as used in this paper) referring to constant base length. This is a case rather unfrequent in practice, if not for prestressed steel structures, soil and rock anchorages or a short period of pretensioning production process while tendons are stressed between fixed points of rigid moulds or of long prestressing beds (long-line system). The effective relaxation (symbol: r_x) is a part of actual loss $\Delta\sigma_{p,\infty}$ due partly to the slow deformation of concrete (shrinkage, creep) and partly to the relaxation of tendon stresses over a gradually decreasing base length hence at a corresponding lower rate (Fig. 1). Effective relaxation r_x is influenced by temperature changes already during the manufacture and throughout the service life of the structure. Other factors involved with prestressing losses are likely to be more precisely described in national standards or international recommendations than e.g. the excess relaxation losses caused by steam curing of pretensioned prestressed units. It is very advantageous for the design engineer to have pure relaxation curves of the chosen tendon up to 1000 h at disposal but in the very first stage of the work the designer has to estimate losses even

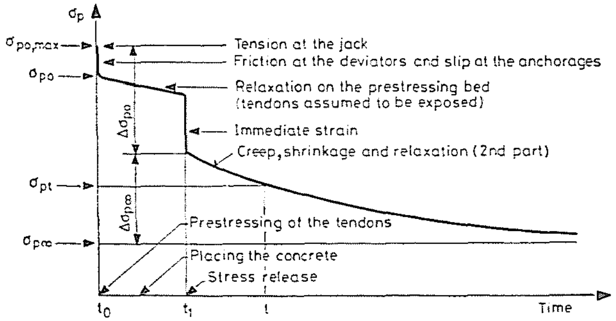

Fig. 1. Losses in a given section of pre-tensioned members (with symbols and processes in [11])

without the relaxation curve of a tendon. In the past decade, members of the *F.I.P. Commission on Prestressing Steels and Systems* endeavoured to evaluate the score of published measurement results, research reports and prescriptions made known, and to draw some conclusions in particular on relaxation losses due to the steam curing of concrete ([8] [9] and preliminary reports [1] through [7]). Some practical aspects likely of use for design engineers, contractors and testing laboratories will be outlined below.

1. The estimated final value of pure relaxation at ambient temperature

1.1 *Data from suppliers and/or recommendations*

The losses (extrapolated from measurements) for a period of 30 years or for $5 \cdot 10^5$ hours (abt. 57 years) or even 10^6 h (abt. 114 years) are often considered as "final" values. The new CEB-FIP Model Code (CFMC, [11]) says that "final relaxation can be considered to have been attained after $5 \cdot 10^5$ hours", which seems to be sufficient for design purposes. The former CEB-FIP Rec. [10] referred to test results with an initial stress $R_0 = 0.6-0.7-0.8\ R_{prk}$ (R_{prk} is the characteristic strength of the tendon) and with a minimum duration of 1000 h, and generally assumed that long-term ("final") pure relaxation r_∞ is abt. the double of r_{1000} at 1000 h:

$$r_\infty = 2 \cdot r_{1000}. \tag{1.1}$$*

This formula underestimated real losses if the initial stress level R_0/R_{prk} was low or if the tendon was of good quality: in both cases losses up to 1000 h are too small compared to the other part after 1000 h. From the straight line obtained by plotting losses r vs. log time t for tendons of *medium* quality, this formula seemed to give a rather close estimation, it was, however, changed to

$$r_\infty = 3\ r_{1000} \tag{1.2}$$

in the Final Draft of CFMC but not accepted and repeated in the final version of CFMC [11]. Preference is given the Swedish recommendation for prestressed concrete SBN-S seeming to be on the safe side with its formula based on 5000 h of measurements and considered to give losses for 57 years:

$$r_\infty \cong r_{57} = 2\ r_{5000} \tag{2.1}$$

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* Numbering of formulae comprises two ciphers, of them the first one refers to the problematic, and the second to the order.

for wires and strands; and

$$r_{\infty} \cong r_{57} = 1.5\, r_{5000} \tag{2.2}$$

for bars.

To shorten the test duration (e.g. in order to get more information with a given number of testing devices) it seems feasible to halve the log t section between 1000 and 5000 hours ($t = 3200$ h) and suppose

$$r_{57} \cong 2\, r_{3200} \tag{2.3}$$

to suffice instead of (2.1).

Netherland's NEN 3861 (1974) Specification and its suggested design formula should be followed, however, if test results are only available up to 1000 h (the usual case with manufacturers' instructions)

$$r_{\infty} = 3\, r_{1000}. \qquad (3) = (1.2)$$

According to the United Kingdom's Code of Practice CP 110 (1972): Part 1, the allowed maximum pure relaxation values r_{1000} specified in BS 2691 (cold-drawn steel wire), BS 3617 (seven-wire strand) and BS 4486 (cold worked alloy steel) may arbitrarily be used as expected final values of effective relaxation r_{∞}. Relaxation values also of the new BS 5896 (containing both wire and seven-wire strand specifications) are likely to be used in a similar way. It will be shown later that this approximation suggested by CP 110 lies on the unsafe side compared to test results (e.g. [15]) and even to other regulations.

1.2 *Formulae based on mechanical properties of tendons*

Without manufacturers' test results (which must be still extrapolated or simply compared to specified values) it is possible to estimate losses by means of formulae derived for a given type of steel using its mechanical properties such as tensile strength f_{pt} or characteristic strength f_{ptk} — (symbols according to [11]) and mean (or characteristic) values of 0.1 and/or 0.2 percent proof stress, as parameters. Mechanical properties (above) and predetermined initial stress f_0 are combined to stress ratios f_0/f_{pt} or $f_0/f_{0.1}$, ratios widely used in these formulae which, however, are only valid for a given type of products (with rather constant $f_{0.1}/f_{pt}$ and $f_{0.2}/f_{pt}$, etc.) and in a limited range of stress ratios. To estimate final (abt. 114 years') losses of pure relaxation, the formula [12] developed for wires may be used:

$$r_{114y}\% = 60\,[f_0/f_{0.1} - 0.55] \tag{4.1}$$

within the limits $0.55\, f_{0.1} \leq f_0 \leq f_{0.1}$. With $f_0 = 0.9\, f_{0.1}$ we get $r_{114y} = 21\%$.

The original shape of (4.1) as a function of time t:

$$r(t)\,\% = \frac{\log t}{10}\,[f_0/f_{0,1} - 0{,}55]\cdot 100 \tag{4.2}$$

and r vs. $\log t$ gives a straight line starting from the point $t = 1$ h and $r = 0$. This straight line is a poor approximation of the relaxation phenomenon of medium and good quality prestressing tendons.

The other version of this formula [12] is $\sigma_{p(t)} = \dfrac{f_0}{1+10^n}$ where

$$n = -1{,}3 + \frac{\log t}{3}\,[f_0/f_{0,1} - 0{,}55] \tag{4.3}$$

and turning stress $\sigma_p(t)$ to the more convenient form of loss:

$$r\% = \frac{100\cdot 10^n}{1+10^n}\,. \tag{4.4}$$

This, however, yields too high r_t values for 10^3 to 10^4 hours as its curve starts anyhow from point $r \cong 5\%$ $t = 1$ h, an impossibility for up-to-date prestressing steels. As for "final" losses obtained from the simpler form (4.2), $r_{57y} \cong 19.9\%$ and $r_{57y} \cong 18.7\%$ from the exponential one (4.3) for a stress level $f_0/f_{0,1} = 0.9$.

Formulae above suggest that there must be a relaxation if $f_0 > 0.55\, f_{0,1}$ which corresponds to test results rather than to suppose exemptness from relaxation for $f_0 < 0.5\, f_{pt}$ as it was recommended in [10], and followed in Hungarian Standard MSZ 15022/2—70.

Similar formulae have been developed for low-carbon (weldable) hot rolled bars (5.1) and for usual strands dia. 15 mm (5.2) on the basis of 1000 h tests [13]

For bars with $f_{0,1} \cong 1000$ N/mm² (mean)

$$r\% = 0.0112\,[f_0/f_{0.2} + 1]\cdot(4 + \log t) \tag{5.1}$$

which supplies for e.g. 57 years $r_{57y} = 19.3\%$ with $f_0/f_{0.2} = 0.8$.

For strands produced in the USSR:

$$r\% = 11\log t[f_0/f_{0.1} - 0.55] \tag{5.2}$$

and for strands made in the Netherlands (with $k = f_0/f_{0.2}$)

$$r\% = 5\log t\,[(k-0.55) + (k-0.55)^{5/3}]. \tag{5.3}$$

The formulae used earlier according to Hungarian Standard MSZ 15026 (Reinforced Concrete Structures) and in some COMECON countries (with actual tensile strength f_{pt}):

$$r\% = 27\, f_0/f_{pt} - 10, \text{ and} \tag{6.1}$$

$$r\% = 30\, f_0/f_{pt} - 10 \tag{6.2}$$

for stress relieved and as cold-drawn (mill coil) wires, respectively.

The recent formula of Hung. Stand. MSZ 15022/2—70:

$$r\% = 240\, [f_0/f_{pt} - 0.5]^2 \tag{6.3}$$

underestimates losses for $f_0 < 0.7\, f_{pt}$ but gives rather high (though not impossible) values for $f_0 \geq 0.8\ f_{pt}$.

This formula, too, much depends on the actual stress, as compared both to a "Skandinavian" one (7) [13] and to (6.1) and (6.2):

$$r = 50\, f_0/f_{pt} - 20 \tag{7}$$

and $r = 20\%$ if $f_0 = 0.8\, f_{pt}$.

As for the rate of dependence of relaxation on actual stress f_0, [10] assumes the change of relaxation loss $\Delta\sigma_{ap\infty}$ (N/mm^2) vs. initial stress (N/mm^2) to follow a parabolic law (2nd grade), but formula (6.3) is of 3rd grade if turned to actual stresses instead of $\Delta\sigma_{p,rel}/f_0$ percentage.

As mentioned earlier, these types of formulae are only valid for products the relaxation results evaluated were derived from, irrespective of whether the recommendation declares this restriction or not.

2. Time dependence of pure relaxation at ambient temperature

Formulae (4.2) (4.3) (4.4) and (5.1) (5.2) (5.3) are more or less efficient to describe relaxation as a function of time t. All the quoted formulae are so-called phenomenological functions without a definite physical purport or explanation and none of them tends to a limit value for relaxation although such a value must exist if only at infinite time.

The previous CEB/FIP document [10] and the "Final Draft" of CFMC gave more detailed suggestions in this respect than the final version of [11].

[10] has suggested the formula

$$\log r\% = k_1 + k_2 \log\ t \tag{8.1}$$

for not stabilized tendons plotted as a straight line to log-log scale, successfully applied even for very long durations [21]. The "Final Draft" of [11] suggests factor k to range from 0.15 to 0.25 and adopts the formula above in the form:

$$\log \frac{\Delta \sigma_{pt}}{\sigma_{pi}} = \log \frac{\Delta \sigma_{pT}}{\sigma_{pi}} + k(\log t - \log T) \tag{8.2}$$

where

σ_{p_i} is the initial stress in prestressing tendon; $\Delta\sigma_{pT}$ and $\Delta\sigma_{pt}$ are losses of stress due to relaxation at times T and t, resp. ($T \ll t$); and k is the line slope depending on the *type* of steel
not differentiating between normal and low-relaxation (stabilized) tendons.

Be $T = 10^2$ h and $t = 10^6$ h, and be the relaxation measured at time T say 5 percent, with $k = 0.25$:

$$\log r_t = \log T + 0.25(\log 10^6 - \log 10^2) \text{ and } r_r \cong 14.8\%$$

probably an underestimation of the final loss for abt. 114 years. If test results are evaluated to assess the straight according to (8.1) or (8.2) the readings up to 120 h have to be omitted and test duration must be at least 1000 h. To find a straight fitting line to the measured points, at least 10 data after 120 h are needed, but it seems useful to take readings for at least 6 weeks with the following schedule: 1—3—6—18—30—60 min and 2—4—8—(16)—24 hours, 2d, 4d (this is the first week) and thereafter 3 times a week which makes 15 readings after the first-week results, suggested to be omitted.

With a series of data up to $t \geq 5000$ h it seems possible to fit a straight line to measured data plotted to lin-log scale for *stabilized* tendons and for extrapolation:

$$r_t = r_{5000h} + k \log \frac{T}{5000} \tag{9.1}$$

and for "final value" at $5 \cdot 10^5$ hours:

$$r_{57y} = r_{5000h} + 2.0(r_{5000} - r_{500}), \tag{9.2}$$

r values in both formulae can be understood either as percentages or as actual stress losses (N/mm²).

The formula offered by [10] was adopted in a tentative COMECON standard prepared by Czechoslovakia relying on the national standard CSN 42 0355 assuming:

$$\Delta\sigma_{ap\infty} = \Delta\sigma_{ap,t} + k_3(\Delta\sigma_{ap,t} - \Delta\sigma_{ap120h}) \tag{9.3}$$

i.e. a straight line for relaxation vs. time to *linear* scale, where $t \gg 1000$ h (and as long as possible [10]).

The formula in [10], was, however, not adopted and reaffirmed either in "Final Draft" of CFMC [11] or in itself and, taking test results into account, (e.g. [15], [16]) formula (9.1) for stabilized tendons is preferred.

CFMC [11] deals less with relaxation values or approximate functions than former documents do and emphasizes that expected relaxation values for final prestress can be obtained

= from data given in approvals, documents; or
= by using arbitrary values; or
= from the results of reliable relaxation tests.

As for "arbitrary" values [17] is referred to (See Table 1) which, however, only maximum 1000 hours' pure relaxation values are to be taken from, in sharp contradiction to the text of CFMC [11] "the values given in FIP document [17] can be admitted as the maximum values for very long-term relaxation. The values given in Table 3.1 may be adopted as representative where group 2 comprises steels that were subjected to stabilization treatment." (Table 3.1 of [11] is reproduced here as Table 2.)

Table 1

Expected pure relaxation maxima at 20 °C after 1000 hours as percentages of the initial stress σ_{p0} [17]

σ_{p0}/f_{ptk}	0.6	0.7	0.8
Level 1*	4.5	8	12
Level 2**	1	2	4.5

* Cold drawn wires and strands
** Quenched and tempered wires, some bars and stabilized cold-drawn wires and strands (LR = low relaxation products)

Table 2

Very long-term arbitrary relaxation values for plain bars at 20 °C as percentages of initial stress σ_{p0} [11]

σ_{p0}/f_{ptk}	0.6	0.7	0.8
Group 1*	6	12	25
Group 2**	3	6	10

* Average representative values
** For stabilized steels

The expression "bars" used in the heading of Table 3.1 in [11] makes the confusion even greater as also in Table 1 (quoted from [17]) bars are mentioned and the numbers considered by CFMC [11] "as maximum values for very long-term relaxation" are clearly recommended by [17] only to estimate 1000 h relaxation maxima and are of course essentially lower than those tabulated by CFMC [11] (here: Table 2) actually for final values. The misleading quotations and references might be amended in CFMC [11].

As for evaluating *test results*, CFMC [11] repeats the formula (8.1) or rather (8.2) in its non-logarithmic form based on a single known (measured) relaxation value as follows:

$$\frac{\Delta\sigma_{p,rel,2}}{\Delta\sigma_{p,rel,1}} = \left(\frac{t_2}{t^1}\right)^{\beta} \tag{10}$$

where β — exponent assumed at 0.15 to 0.25 according to the *type of steel*; in absence of accurate indications it can be taken as 0.20. $t_2 > 1000$ h duration (with relaxation r_2 belonging to it is asked for) $t_1 = 1000$ h (with a known or supposed value of relaxation r_1) which is considered as a sufficient long duration for most cases [11].

Though [17] is of the opinion that exponent β (or k in [17]) depends upon the *initial stress level* (σ_{p0} or $\sigma_{p0}\, f_{ptk}$) and lower values (e.g. 0.15) correspond to higher initial stresses and vice versa, we suppose that both statements concerning function $\beta(k)$ are true because both high-grade steels with an average initial stress level of abt. 0.7 and medium or good quality steels with a lower stress level of abt. 0.6 show very damped relaxation in the first, say 1000 hours whereafter relaxation curve (r vs. $\log t$) gets steeper ascending. This phenomenon was recognized and the necessity of 4000 hours of measurements emphasized earlier [1], in accordance with a prolonged test duration for stabilized tendons recommended later in [10]. It may be concluded that both with high-grade steels and with low initial stress ratios f_0/f_{pt} the higher value of $\beta(k)$ should be applied *and* test duration (mainly with stabilized tendons) should be as long as possible. Unfortunately, this suggestion in [10] has not been adopted in CFMC [11].

Coming back to formula (10) and to the delivered final values, if $t_2 = 10^6$ h, $t_1 = 10^3$ h, and with $r_1 = \Delta\sigma_{p,rel,1} = 6.03\%$ (recorded 1000 h value for normal-grade Swedish prestressing steel with an initial stress level of 0.65, reported in [18], [4]) then with $\beta = 0.2$

$$\Delta\sigma_{p,rel,2} = r_{114y}\% = 6.03 \left(\frac{10^6}{10^3}\right)^{0.2} \cong 24\%$$

which is an unfavorably high value as compared to 12—16 percent obtained on the basis of relaxation readings up to $35 \cdot 10^3$ h from this set [18] by different extrapolating methods outlined in [4]. The "Skandinavian" estimating formula (7) yields $r = 12.5\%$, in very good agreement with more sophisticated extrapolations applied in [4].

For $t_1 = 35\,000$ h and $r_1 = 10.25\%$ (actual Swedish data) then, again with formula (10): $r_{114y}\% = 20.1\%$, remarkably higher than probable values of 12 to 16%.

This leads to the conclusion that if recorded data are available (let it be only of 1000 h duration, but with 10 to 15 readings after the first week) it is worth while indeed to use them all for extrapolation as suggested in [10] rather than to substitute the single last value $\Delta\sigma_{p\,rel,1} = r_1$ of the measured series into formula (10).

If approved documents' real or assumed 1000 h values rather than test results (readings) are available then use of formula (10) is left as a *last* possibility.

3. Pure relaxation at elevated constant temperatures

Comprehensive tests [19] showed that relaxation curves from tests at different temperatures between 22 and 100—150 °C tend (or seem) to meet in infinite time so that the higher the temperature the faster the curve approximates the guessed bound (highly instructive figures of [19] have been adopted in [8]). With an initial stress level of e.g. $\sigma_0/f_{pt} = 0.71$ the wire relaxation ranges up to the supposed "final" value of abt. 18% already after 10^4 h at 100 °C but lags behind at 22 °C so that the — extrapolated — value for 10^6 h is only 15%. This "final value" depends, however, on the stress level and is less than 14% with $\sigma_0/f_{pt} = 0.43$ but more than 23% with a stress level as high as 0.96.

This means that relaxation curves with a constant stress level but measured at different temperatures *cannot* run parallel unless approximately, and only for a short section of duration t and a narrow interval of temperatures T °C. On the other hand, many other tests support the possibility of a moderate parallelity (as quoted and explained in [8]) for curves belonging to higher temperatures, e.g. between 50 and 100 °C. An overall validity of formulae of the type

$$r_T = r_{20} + c(T - 20) \tag{11}$$

must be denied, let alone since the relaxation increment of stress relieved tendons does not change linearly with temperature increment as indicated by the second term of (11) and dealt with in detail in [8], [20], although stabilized tendons roughly obey the law (11). To clear the behaviour of tendons at different temperatures it is reasonable to plot the data in two separate ways: once $r\%$ vs. log t (with different temperatures T as parameters) and also $r\%$ vs. temperature T (with different durations t as another parameter). If the two sets of curves run similarly (i.e. the higher the temperature or the longer the duration, the higher the relaxation loss) a *Larson—Miller* extrapolation is possible ([5], [8]).

The measured data (at least for 1000 h) are to be extrapolated similarly to those at ambient temperature: probably in most cases a straight fitting line to recorded r vs. log t data will arise.

The constant elevated temperature curves may be of interest when dimensioning special structures exposed to constant high temperatures, e.g. containers, tanks for hot liquids, etc.

4. Relaxation under anisothermal circumstances (steam curing)

This special question was studied thoroughly and reported by the Author [7], [8], [9]. Recently the *FIP Commission on Prefabrication* itself has been concerned with practical details of this problem [24], partly relying on former papers [22], [23]. The loss of prestress due to temperature changes — typical of steam cured prefabricated pretensioned members — differs from those caused by any — low or high — constant temperature from two aspects.

1. Exposure for 6 to 10 hours to an elevated temperature of 60 to 90 °C causes a rapid increase both of relaxation rate and relaxation itself resulting in a relaxation increment Δr_s (s for steam curing) over ambient temperature data. At the end of steam curing, just before stress release, this Δr_s — little depending upon initial stress level, but rather upon the type of tendon (cold drawn or hot rolled, alloyed, etc.) — amounts to 5 to 8 percent with normal-relaxation wires and strands and to 0.5 to 2 percent with stabilized (low-relaxation) ones.

Deformations concomitant to stress release keep, however, the actual prestress (including already the loss Δr_s) low enough to dampen further relaxation which will lag much behind the values in the corresponding time interval for tendons cured at normal temperature.

There is nevertheless a slow increase of relaxation losses even after steam curing unless initial stresses were chosen relatively low (e.g. $f_0 = 0.65 f_t$). This possibility is reflected by F.R.G. prescriptions giving overall relaxation losses for pretensioned tendons applied in steam-cured members as constant values valid immediately after steam curing and throughout the service life. (See clause 4.3. in [8].) It is worth while to mention, that pure relaxation r after steam curing measured over a constant gauge length may be as high as 3% in 1000 h but the share of effective relaxation r_x arising after steam curing over a decreasing gauge length might be negligible in case of rather low stress levels initially or at the end of steam curing [25].

2. The relaxation due to temporarily elevated temperatures is always accompanied by the loosening of tendons originally pretensioned between

fixed jacks (long-line method). This excess loss $\Delta\sigma'_L$ (L stands for loosening) is often ignored both by the designer and the manufacturer.

The interaction between tendons and green concrete — hardening but also expanding upon heating — is influenced by the bond strength between them as well as by the reinforcement percentage and many other factors explained clearly in [26]. This interaction hinders but does not stop the development of the theoretical overall loss due to loosening $\Delta\sigma_L = \alpha \cdot \Delta T.E.$ According to test results [26] even for a prolonged constant temperature pre-curing period of 7—8 hours before beginning with heating up, still there is an actual loss $\Delta\sigma'_L$ of at least 40% of the theoretical value rising to 60% for a pre-curing period of 4 h often leading to the assumption of the impossibility of a perfect bond to exist (see Fig. 40 in [26]). Polish building code suggests to take $\Delta\sigma'_L$ as half the theoretical value — a very good approximation indeed. Be $E = 200\,000$ N/mm², $\Delta T = 70$ °C and $\alpha = 10 \cdot 10^{-6}/°C$ then $\Delta\sigma_L = 140$ N/mm² and for all practical cases $\Delta\sigma'_L = 70$ N/mm². If initial prestress $f_0 = 1200$ N/mm² and $\Delta r_s = 7\%$ i.e. 84 N/mm² then excess losses $\Delta\sigma$ at the end of steam curing are abt. 150 N/mm² i.e. 12.5% of the initial prestress f_0. The relaxation r_N at normal temperature in say 24 h should be added to the former excess value $r_N \approx 0.5$ to 2% largely depending upon the quality of steel while $\Delta\sigma_L$ or $\Delta\sigma'_L$ is entirely independent of all steel characteristics but α, likely to exceed the widely used value of $10 \cdot 10^{-6}/°C$.

Excess losses $\Delta r_s + \Delta\sigma'_L$ are irreversible as loosened and relaxed tendon and concrete with the same α value do shorten freely and simultaneously after stress release, during cooling down, and there is no more possibility to recover some of the loss by "self-stressing" like cooling down between fixed jacks.

Thus further actual loss $\Delta\sigma'_L$ proper to the long-bed system of production has to be reckoned with but the lower stress level (still enhanced by further length change due to creep and shrinkage) usually results in a final, constant loss just after cooling down, roughly equal to the value attained at normal temperature *only in infinite time.* The Model Code [11] gives instructions on how to calculate relaxation, creep and shrinkage losses and their interaction, without, however, mentioning immediate excess losses Δr_s and $\Delta\sigma'_L$.

Summary

Possibilities are suggested to make a good guess on relaxation losses. Formulae based on mechanical properties alone or on measured data up to 1000 h (normal relaxation tendons) and to 5000 h at least (low relaxation tendons) and suggested in national and international codes are confronted with one another and with the Author's experience. Some unclear notions in the Model Code are referred to, and the questions of high temperature and anisothermal relaxation (not dealt with in the Model Code) are discussed.

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