Value and development of the relaxation, with new test's mode - under the influence of fatigue.

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ABSTRACT

In the prestressed structures and elements, of important influence are the steel losses -of different nature, course, performance and value- during the time or as final value. One of these losses is from the relaxation of the prestressed steel, which function of development and progress on time, as well as the presumed final value, depends from the type of steel and used reinforcement, from its initial tension and variation on time, etc..

This loss is quantified through functions elaborated by expensive tests, which need long time -a minimum of 120 hours up to 1,000 hours- under continuous monitoring and constant conditions of temperature and tension value. For this the author, thought to realize such tests under fatigue, permitting to realized them in a very short time, reducing to the minimum tests difficulty and costs.

In such a way one can be able to realize, for the same cost and less time, a greater number of these tests in order to know at the best the real behavior of prestressed steels under the action of various factors, both in its performance over time as well as in its last value. The first tests followed by the author in this direction, object of this article, gave results that validate the above idea and enable to correct the parameters and mode of future tests.

This article presents the research program of losses on prestressed steels, in the study of the relaxation phenomenon, describing the terms and characteristics of the test, after been modified by introducing on it the fatigue influence.

At the end, by the carried out tests, for the types of tested champions of steel, devices, methods and relative results, are illustrate the first considerations and formulas.

INTRODUCTION

In the prestressed structures and elements, of important influence are the steel losses -of different nature, course, performance and value- during the time or as final value. One of these losses is from the relaxation of the prestressed steel, which function of development and progress on time, as well as the presumed final value, depends from the type of steel and used reinforcement, from its initial tension and variation on time, etc..

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In the realization of the elements and structures on reinforced concrete, with the purpose to improve the behavior of the structure in exercise phase as well as at the final stage, the prestress has been introduced, with the advantage of having entirely section reacting. [1; 2; 3]

One of the main problems in the analysis and design of prestressed concrete structural members is the presence of the prestress losses and their estimation over an extended period of time. So, the losses become the principal and conclusive factor in the prestressed structure realization. Their value influences the initial and final choices; their course influences the constructive choices and the sequence of the phases during the realization of the work.

Prestress losses occur in pretensioned concrete elements due to several sources, including prestressing steel seating at transfer, elastic shortening of concrete, creep of concrete, shrinkage of concrete, etc, and relaxation of prestressing steel. On the figure 1 we have an general and global representation of all the prestress losses with their partial or total value, as well as their incidence along the life of the prestressed element.

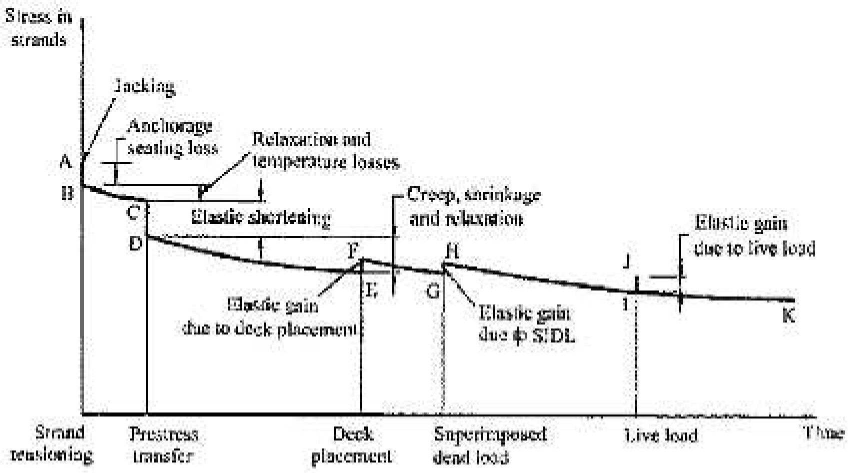

Figure 1 Total prestress losses

Creep and shrinkage of concrete and relaxation of prestressing steel cause time-dependent changes in the stresses and strains of concrete structures. These changes result in continuous reduction in the concrete compression stresses and in the tension in prestressing steel. These time-dependent phenomena are also dependent upon one another, hence cannot be separate completely. [4; 5]

Reasonably accurate estimate of the long-term prestress losses are needed to avoid any serviceability problems of the structure (due to cracking and/or excessive deflection).

RELAXATION OF PRESTRESSED STEEL

In the ample picture of the losses, the relaxation of the prestressed steel it is one of the factors, and not certain the last. Its influence to endless time can assume the value of 12% up to the 20% of the value of the initial tensions.

Similar to concrete, prestressing steel, subjected to stresses more than 50% of its ultimate strength, exhibits some creep. In practice, steel used for prestressing is usually subjected to stresses between 0,5 to 0,8 of its ultimate strength. When a prestressing steel cable is stretched between two points, it will be subjected to a constant strain. Because of creep, the stress in the steel cable decreases (or relaxes) with time to maintain the state of constant strain. This reduction in stress is known as intrinsic relaxation $\Delta\sigma_{pr}$. It depends on the type of prestressing steel cables (stress relieved or low-relaxation), the ratio of the initial stress σp_0 to the yield stress f_{py} and the time t from initial stressing.

For this, relaxation is a very complex phenomenon and very difficult to be evaluated. Different studies have been realized, among which can list to title of example [6; 7; 8; 9; 10; 11; 12; 13], trying to offer us very useful and necessary conclusions and, on the other hand several methods have been proposed for the calculation of all the prestress losses as well as for those of the relaxation. After divides the relaxation loss calculations into two parts, including the loss before transfer and the loss after transfer, some of these methods providing simplified lump sum estimates, while others providing a more detailed time step estimate. But they however are normally offering results different in their total and ultimate value of the phenomenon as well as in its development and course during the life-time.

So, for example, Ghali, A. & R.Favre, on 1986 [14] proposed, for the calculation of final value of relaxation R_∞, the following equation:

$$R_\infty = \eta \left((\sigma p_i / fp) - 0{,}4 \right)^{\wedge 2} \tag{1}$$

where η = 150 for normal-relaxation steel and
η = 67 for low-relaxation steel;
σp_i = initial steel strength;
fp = yield steel stress.

Another method is the one proposed by AASHTO-LRFD [15], where the loss due to relaxation $\Delta\sigma_{ps(relax)}$, is expressed as follows:

$$\Delta\sigma\ ps(relax) = 0.3\{20 - 0.3\Delta\sigma\ ps(fr) - 0.4\Delta\sigma\ ps(es) - 0.2(\Delta\sigma\ ps(sh) + \Delta\sigma\ ps(cr)\} \tag{2}$$

where f_{cgp} = concrete stress, at center of gravity of prestressing steel, at transfer;
Δf_{cdp} = change, as above, due to permanent loads applied after transfer;
RH = relative humidity in percent;
$\Delta\sigma_{ps(fr)}$ = prestress losses due to friction;
$\Delta\sigma_{ps(es)}$ = prestress losses due to elastic shortening;
$\Delta\sigma_{ps(sh)}$ = prestress losses due to shrinkage;
$\Delta\sigma_{ps(cr)}$ = prestress losses due to creep.

The CEB–FIP 1978 [16] method permit to calculate the very long-term relaxation $R\infty$ (in percent) through value as by the table 1

Table 1 Relaxation $R\infty$ value (in percent)

σpi/fp	0.6	0.7	0.8
Normal relaxation steel	6	12	25
Low relaxation steel	3	6	10

At last, Eurocode [17] methods as well as the NTC 2008 [18] ones, in absence of experimental data, permit to evaluated the fall of tension for relaxation $\Delta\sigma pr$ to a certain time t and for a temperature 20°C equal to the values calculated with the following formulas:

$$\Delta\sigma pr / \sigma p_i = 5{,}39\ \rho\ 1000\ e^{6{,}7\,\mu}\ (t/1000)^{0{,}75(1-\mu)}\ 10^{-5} \quad \text{for } 1^{st} \text{ Class steel cables} \tag{3a}$$

$\Delta\sigma pr / \sigma p_i = 0{,}66\ \rho\ 1000\ e^{9{,}1\ \mu}\ (t/1000)^{0{,}75(1-\mu)}\ 10^{-5}$ for 2nd Class steel cables (3b)

$\Delta\sigma pr / \sigma p_i = 1{,}98\ \rho\ 1000\ e^{8{,}0\ \mu}\ (t/1000)^{0{,}75(1-\mu)}\ 10^{-5}$ for 3rd Class steel cables (3c)

where ρ 1000 = the loss for relaxation (in percentage) after 1000 hours for initial steel strength equal to 0,7 of the resistance fp of the steel cable;
σp_i = initial steel strength;
μ = σp_i / fpk;
Fpk = characteristic resistance of the prestressed steel;
t = time of evaluating relaxation losses

In lack of specific experimentation, the values of ρ 1000 can be drawn by the Table 2.

Table 2 Recommended values of ρ 1000 (in percent)

Class of steel cables	ρ 1000
1st Class – ordinary steel	8,0
2nd Class – stabilized steel	2,5
3rd Class – rolled bar	4,0

The final fall for relaxation can be valued with the formulas above taking as last value for the time t = 500.000 hours.

The relaxation of steel cables that have suffer a thermal cycle after that they has been put under tension is opportune to be evaluated experimentally.

RELAXATION OF PRESTRESSED STEEL BEHAVIOR

There are a lot of methods, formulas, tables, on continuing evaluations, that try to describe more and better the real behavior of steel pre-loaded, just for giving the most exact final value as well as its variations on time, during all the time-life of the Prestressed.

All of them are different and their results are different one with the other.

Who can be the most real one?

To be able to have the correct knowledge about this phenomenon, during the time-life of steel cables as well on its final value, we have to wait until we arrive at the end-time of our prestressed elements… or we have to do more and more experimental tests on almost every type of steel and production.

That would be not only very expensive, but it would also result impossible, keeping in mind the very long necessary duration of the tests of relaxation.

How can we realize many relaxation tests in less time, not only for lowering the costs but also for having the possibility of many data and, as consequence, the real possibilities to elaborate them for having out more complete results of the complete relaxation phenomenon?

TESTS UNDER DYNAMIC LOAD

Looking for a possible solution of being able to effect so many complete tests and in less time, not only lowering the costs but also having so the possibility of many data and results, we thought "to exploit" the effect of the fatigue phenomenon, largely used and also studied in other fields of works, tests and scientific searches, [19; 20; 21], in our case.

This for the intention of influencing and decrease at their minimum value the times of the apparition of complete carrying out of the relaxation phenomenon.

Subsequently trying to verify the truthfulness of such idea, assimilating the phenomenon of the losses of relaxation with the phenomenon to it complementary of the extension in time of the steel cable under constant load, the author, accompanying different tests over prestressed anchorages and steel cables under dynamic load, decides to complete them with the additional application of some other instruments, for being able to record the complete development on time of the extension of the steel under these dynamic-fatigue tests.

DEFINITION OF THE CHAMPIONS

The tests for the study and definition of the phenomenon of relaxation, through the study of the extension in time under dynamic loaded, has been developed on different champions. Technical characteristics for only three of steel used of the 1st type of the prestressed cable are represented on Table 3 as above:

Table 3 Steel cables of 4 x 6 φ = 4,24 mm and soul φ = 4,40 mm

N.	Technical characteristics		Laboratory results	
	Area	f.pbk	Ultimate load	f.pbk
	mm2	MPa	kN	MPa
1	400	1.900,0	78,000	1.950,0
2	400	1.900,0	77,600	1.940,0
3	400	1.900,0	78,000	1.950,0

The same, technical characteristics for only three of steel used of the 2nd type of the prestressed cable are represented on Table 4 as above:

Table 4 Steel cables of 4 x 6 φ = 4,10 mm and soul φ = 4,20 mm

N.	Technical characteristics		Laboratory results	
	Area	f.pbk	Ultimate load	f.pbk
	mm2	MPa	kN	MPa
1	375	1.800,0	67,875	1.810,0
2	375	1.800,0	69,750	1.860,0
3	375	1.800,0	71,250	1.900,0

DEVICE OF TEST

The champions have lengths of around 120 cm, allowing so a free distance among the anchorages of test of 100 cm.

On the center of every cable have been attached 4 resistance-extension, than other two inductive and accelerometer are positioning between the cable anchorages and the base of the press, to allowed to check the evaluation on time of the champion under load extension. An electronic analytical reader and plotter, allows the tabular and graphic control of the deformations and its course. (Figure 2).

Figure 2 One of the champions tested

The complex “dynamic press – champion – manometer” used for the tests has preventively been set for repeated loads to be oscillated among the values (Figure 3):

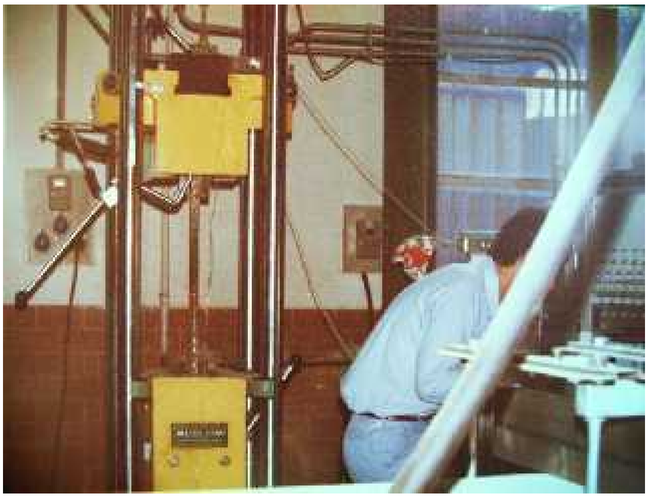

Figure 3 First relaxation tests under dynamic loads

$\sigma p_{0\ max}$ = 0,65 of the break load R_{ak} of the steel cable under test (4a)

$\sigma p_{0\ min}$ = 0,62 of the break load R_{ak} of the steel cable under test (4b)

CARRYING OUT OF THE TESTS

Steel cables of 4 x 6 φ 4,24 mm and soul φ = 4,40 mm.

The champions have been submitted to an oscillating load among a maximum value of 123,5 kg/mm^2 and a minimum of 118,5 kg/cm^2, for a total of 2.000.000 of cycles of load, to the frequency of 400 cycles/minute.

Only on two cases of the tests was noticed the breakup of a thread - equal to a 3,52% section reduction - without loss of both minimum or maximum load.

Steel cables of 4 x 6 φ 4,10 mm and soul φ = 4,20 mm.

The champions have been submitted to an oscillating load with maximum value of 1.170 MPa and a minimum of 1.120 MPa, for a total of 2.000.000 of cycles, to the frequency of 500 cycles/minute. All the champions have complete the cycles of load without problems.

Course of the dynamic test.

Putting the cables under the action of the repeated loads with their limit values as above, the variability of the course of the deformations is noticed in the function of the time.

In the first hours the additional extension has had an clearly escalation, and we can denote it throw tabular values as well as the plotted diagram. Going up on time and test, this extension after arrived at his maximum value goes on with an constant behavior (Figure 4).

Figure 4 Ending part of the plotter results

This phenomenon was noticed for the course of the total extension "Δl_i", well as for the course of the variation of its ampleness "δl_i", in the minimum and maximum values, following footstep to footstep the value of the applied loads. This course of the ampleness "δl_i", has been connected with the elastic-plastic behavior of the steel and the course of deformations "Δl_i", has been connected with the course of the relaxation.

So we can see that we have an initial rapid development of the phenomenon of relaxation and then a slower development in the following hours, up to its total development, and, all of these in a very restricted time. On this way, under the effect of the fatigue on the relaxation phenomenon, the maximum duration of a **whole test** was of about 85 hours, having the complete picture of the development of the phenomenon, with entire information about the final value and real behavior on time of this phenomenon.

To understand the priority of such tests, is enough to mention the fact that the so-called tests of relaxation of brief duration are of not less than 120 hours, however with the results of having only partial results, only indicative values to be used on formulas not absolutely sure, trying to be able to calculate the total value of the losses of relaxation to endless time.

By the other hand, having only the values for the time t = 120 hours and t = 1.000 hours, we cannot be sure about the real behavior along the whole time of the relaxation.

During the carrying out of the experimentations, for obvious reasons, the duration of the tests has been fixed in the limit of the 2.000.000 cycles, and not in the moment of the verification of the whole development of the phenomenon of steel extension/relaxation. However, from the effected tests, in different cases the "horizontal last line" was found, accompanied by constant values of the variation of the extensions, that gives the total information about entire development and behavior of the relaxation.

Throw these first tests under the fatigue effect, it has been possible to have the entire development of phenomenon and, on the same time, to be able to specify time duration of the tests, as well as interventions in the formalities of its carrying out and points to be checked.

CONCLUSIONS

Throw the elaborated tests we can arrived at the conclusion that we can really use the fatigue effect for having the possibility to realize relaxation tests on a very short time.

On this way we can have complete development with dates, results, considerations,… over all the relaxation phenomenon with tests realized within acceptable time.

On this way we can have a lot of such tests, arriving to carry out all of the necessary information about this phenomenon, with his last value as well as with his complete and most real behavior during all the life-time of the prestressed elements.

Meanwhile, from the tests up to now effectuated, for the phenomenon of relaxation on time Δσpr we can tried to simulate a possible last value proportional to (a$l_{ó}$ - al_{N}) with a course similar to the course of the extension Δl of the steel under these dynamic tests, where:

$$\Delta\sigma pr = f \{ \text{type of steel}; (0{,}5\ fptk \le \sigma pi = \sigma med \le 0{,}75\ fptk; nc/min) \quad (5)$$

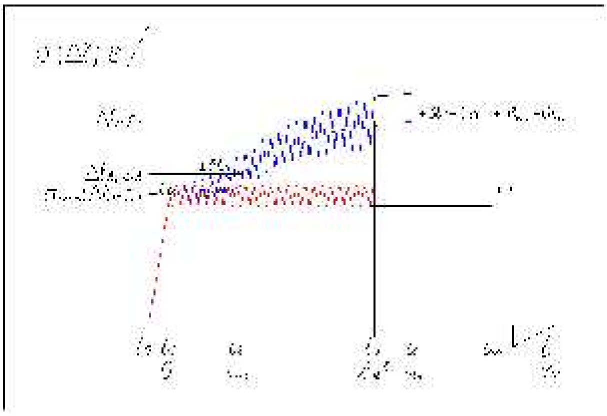

Figure 5 Generalization of the course of the steel extension under dynamic load tests

On this way, trying to be able to elaborate a first possible hypothetical analytical equation such to describe the recorded course of the steel under dynamic load, generalizing the whole results as in the figure 5), we can carry out:

for the 1° part of it, for the time from t_1 to t_2, with tests values:

- per ² = t_1 { ¬$_c$ = $n_{c\,1}$ = 0; ±$_{med}$; ± ±; al_1; ± ¢l_1 }

- per ² = t_2 { ¬$_c$ = $n_{c\,2}$; ±$_{med}$; ± ±; al_2; ± ¢l_2 }

a parabolic law, see the figure 1, as by the equation:

$$al\,(t_1 \le {}^2 \le t_2) = (al_2 - al_1)\,({}^2 - t_1)\,^{\wedge 2} / (t_2 - t_1)\,^{\wedge 2} \quad (6)$$

Subsequently, the course of the extension of the steel,

for the 2° part of it, from the time t_2 to t_3, when on verified the “horizontal comportment” and the course of the line, we can carrying out, with test values:

- per ² = t_2 { ¬$_c$ = $n_{c\,2}$; ±$_{med}$; ± ±; al_2; ± ¢l_2 }

- per ² = t_3 { ¬$_c$ = $n_{c\,3}$; ±$_{med}$; ± ±; al_3 = a$l_{ó}$; ± ¢l_2 = ± ¢$l_{ó}$ }

a parabolic law, see the figure 1, as by the equation:

$$al\,(t_2 \leq {}^2 \leq t_3) = al_3 - (al_3 - al_2)\,(t_3 - {}^2)^{\wedge 2} / (t_3 - t_2)^{\wedge 2} \qquad (7)$$

Through other more and more future tests and their successive computerized interpretation, it will be possible to make the precise and real connection among the course of the phenomenon relaxation under static –as by standard tests- with the phenomenon relaxation under repeated dynamic loads with the benefit of the fatigue effect -**the new modified tests**.

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