Evaluation of long-term prestress losses according to NBR 6118:2023 and ACI PRC-423.10:2016

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Summary
Prestress losses can be classified according to two groups: immediate losses and long-term losses. This article emphasizes losses due to concrete shrinkage, creep of concrete, and relaxation of tendons according to Brazilian and the American standards. To evaluate the long-term prestress losses, an isostatic beam with 24 (twenty-four) meters spam was chosen, in which each parabolic tendon had 8 (eight) strands of 15.2 mm in diameter in the CP-190 category, totalling 3 (three) tendons in the bonded post-tensioning system. The long-term prestress losses were considered by isolating each variable and also through simplified equations proposed by the standards to reflect on the suggested methods. Finally, the American standard for estimating long-term prestress losses was more simplistic and practical. On the other hand, the Brazilian standard reflects the experience of projects in the country, however, divergent values can be observed between the standards.

1 INTRODUCTION

Long-term losses occur due to the change in concrete and the prestressing steel behavior in the structural element over time, so that the result of this interaction between the materials causes a variation of the prestressing force over time. One of the phenomena that occur in concrete comes from the shrinkage resulting from the spontaneous reduction of the volume of the structural element without the influence of applied loading and by the loss of free water during the hydration process of the cement. On the other hand, the creep of concrete occurs from the increase of the shortening deformation due to the application of the permanent compression action. Finally, the prestressing steel undergoes relaxation, in other words, a reduction in the force required to maintain a certain elongation of steel as constant over time. Understanding concrete shrinkage, creep of concrete and steel relaxation become essential topics to measure long-term losses values.

According to [1], it is possible to estimate the values of long-term losses through equations that contemplate the effects described with a greater or lesser degree of refinement to obtain the results, identified as: simplified process, approximate process and general method of calculation. With regard to [2] it is possible to evaluate each phenomenon separately through simplified equations, as well as to use a proposed calculation model to contemplate long-term losses through a single equation and also explore more sophisticated and detailed methods. The evaluation of long-term losses should be considered as an estimate, since the actual losses may be greater or less than the calculated value due to several constructive factors.

It is also important to evaluate the calibration of models for both immediate and long-term losses, since through this operation it can be determined the total prestressing losses and consequently know the intensity of the minimum prestressing force in sufficiently long time considered as infinite (P_{inf}). This force contributes significantly to the accurate checks of the SLS (Serviceability Limit State) and the ULS (Ultimate Limit State) so that the designer engineer must remain attentive to avoid unforeseen circumstances in the investigation of displacements and bends, tensile and compressive stresses at the bottom and top of the concrete element in order to comply with the limits established by the standards and considered satisfactory. The objective of the article was precisely to test how discrete these results produced of long-term prestress losses by NBR 6118:2023 and ACI PRC -423.10:2016 could be.

2 METHODOLOGY

Properly assessing long-term losses has become a challenge in design, perhaps not by the constructive system of pretensioned or post-tensioned elements, but rather to ponder the numerous criteria that in a way can affect the accuracy and quality required by the construction. Therefore, this article discusses the considerations recommended by the standards [1] and [2] taking into account theoretical aspects as well as the presentation of a numerical example in order to highlight the differences and methodologies considered

2.1 CRITERIA OF ABNT NBR 6118:2023

The Brazilian standard [1] allows evaluating long-term losses through the following predictions: simplified process, approximate process and general method of calculation, so that arguments and parameters will be discussed in the next steps.

2.1.1 General Method of Calculation

This method assumes that when the permanent actions / dead loads (gravitational effect or prestressing) are applied in different ages, the shrinkage and creep of each concrete layer and the relaxation of each prestressing tendon should be considered separately. Therefore, this method has a higher degree of refinement and its recommendations presented in Annex A to the standard, but it is important to emphasize that the prescriptions of this annex are informative and, in the absence of better data, can be used in design. A relevant fact about this method is that there is the possibility of considering coefficients with values different from those proposed in Annex A, provided that they are supported by international standards or technical literature.

2.1.2 Simplified Process

The simplified process lays down conditions that the concreting of the structural element and applying prestressing force can be carried out in sufficiently close phases, in which [3] recommends a period of time not exceeding 30 days to disregard reciprocal effects from one stage over the other. In addition, the method recommends that the prestressing tendons have small distances from each other in relation to the height of the structural element, making the resulting equivalent or representative tendon suitable for obtaining the results. The equation (1) represents the reduction of prestress loss between the ages, taking into account the simultaneous effects of concrete shrinkage, creep of concrete and steel relaxation.

$$\Delta\sigma_p(t,t_0)=\frac{\left|\varepsilon_{cs}(t,t_0)\right|E_p+\alpha_p(t)\sigma_{c,p0g}\varphi(t,t_0)+\sigma_{p0}\chi(t,t_0)}{\chi_p+\chi_c\alpha_p\eta\rho_p} \tag{1}$$

2.1.3 Approximate Process

The approximate process allows one to evaluate long-term losses in a more compact way provided that some premises are respected. The first one states that the same conditions of application of the simplified process remain in addition to that the shrinkage does not differ by more than 25% of the value[-$8*10^{-5}\varphi(\propto,t0)$], and according to [3] it can be considered completed for works with RH > 55% and concrete slump less than 9 cm. The equation (2) evaluates the relative long-term losses in percentage (%) considering the use of only low relaxation strand (LR) since the standard [4] was changed and excluded the use of stress relieved strand (SR) in Brazil.

$$\frac{\Delta\sigma_p(t_\propto,t_0)}{\sigma_{p0}}=7{,}4+\frac{\alpha_p}{18{,}7}\left[\varphi(t_\propto,t_0)\right]^{1{,}07}\left(3+\sigma_{c,p0g}\right) \tag{2}$$

2.2 CRITERIA OF ACI PRC-423.10:2016

The American standard [2] evaluates long-term losses using isolated and simplified equations to take into account the phenomena of concrete shrinkage, creep of concrete and steel relaxation. However, the calculation model used by [5] allows to estimate long-term losses through a single equation involving all the mentioned rheological phenomena. Finally, for more sophisticated projects where it is necessary, the standard presents more detailed methods to estimate long-term losses at any time of the useful life of the structure.

2.2.1 Isolated Equations: Concrete Shrinkage, Creep of Concrete and Steel Relaxation

The application of the independent equations to determine each portion of the long-term losses proved to be a very direct, simple and practical process, an intrinsic characteristic of the standard in question. Thus the equations (3) and (4) denote the portions of creep of concrete, considering the constructive systems for bonded post-tensioned and unbonded post-tensioned members, respectively. The equations (5) and (6) reflect the portions arising from concrete shrinkage and steel relaxation. The sum of all the portions of the equation (7) represents the long-term losses.

$$\Delta f_{pCR} = K_{cr}\left(\frac{E_p}{E_c}\right)(f_{cir} - f_{cds}) \tag{3}$$

$$\Delta f_{pCR} = K_{cr}\left(\frac{E_p}{E_c}\right)(f_{cpa}) \tag{4}$$

$$\Delta f_{pSH} = 8{,}2*10^{-6} K_{sh} E_p (1 - 0{,}0024\frac{V}{S})(100 - RH) \tag{5}$$

$$\Delta f_{pRE} = [K_{re} - J(\Delta f_{pSH} + \Delta f_{pCR} + \Delta f_{pES})]C \tag{6}$$

$$\Delta f_{pLT} = \Delta f_{pCR} + \Delta f_{pSH} + \Delta f_{pRE} \tag{7}$$

2.2.2 AASHTO LRFD – Estimation of Long-Term Losses

Surprisingly, the standard [2] added an equation derived from [5] to estimate long-term losses taking into account some criteria: Elements molded with concrete of normal specific weight, concrete curing (steam or wet), prestressing steel (strand or bars) with low or normal relaxation (stress relieved), exposure conditions and temperatures at the construction site. The equation (8) expresses the estimate of long-term losses using this methodology.

$$\Delta f_{pLT} = 10{,}0\frac{f_{pi}A_{ps}}{A_g}\gamma_h\gamma_{st} + 83\gamma_h\gamma_{st} + \Delta f_{pRE} \tag{8}$$

2.2.3 Detailed Models

Some projects do not have a trivial scope, therefore simplified solutions cannot be applied, thus requiring more detailed models for determining long-term losses with adjustments in the concrete shrinkage and creep models, adjustment of the modulus of elasticity of the concrete according to age, as well as incremental analysis with step-by-step characterization of the variation of the prestressing force. This standard brings a series of advanced features to these cases suggesting even the use of software that has the pre-defined models for choice, including also the effect of the concrete temperature on the bridge decks with the pre-launched beams.

3 NUMERICAL ANALYSIS AND RESULTS

The numerical analysis was developed through an isostatic beam with 24 meters of span with 3 parabolic tendons, each tendon being composed of 8 strands CP-190 LR (low relaxation) steel of 15.2 mm of diameter using the bonded post-tensioned system. The evaluation of the immediate loss of prestressing was carried out by admitting the execution of the prestressing (applying prestressing force) after 30 days end of moist curing and that the tendons were tensioned from both sides of the part and sequentially. The initial data were: Initial Force (P_i = 1500 kN/tendon), coefficient of friction (strand– sheath) 0.20 ras $^{-1}$, wobble friction coefficient = 1% rad/m and anchor set = 6 mm. The Fig. 1 represents the geometry of the typical cross-section and the position of the tendons in the mid-span section. The Fig. 2 shows the graph of resulting prestressing tendon force after immediate losses. The data used were based on a typical problem of special road engineering works of art in which the longitudinal post-tensioned beam construction occurs in the site of work for the solidarization of the additional deck at the final construction site.

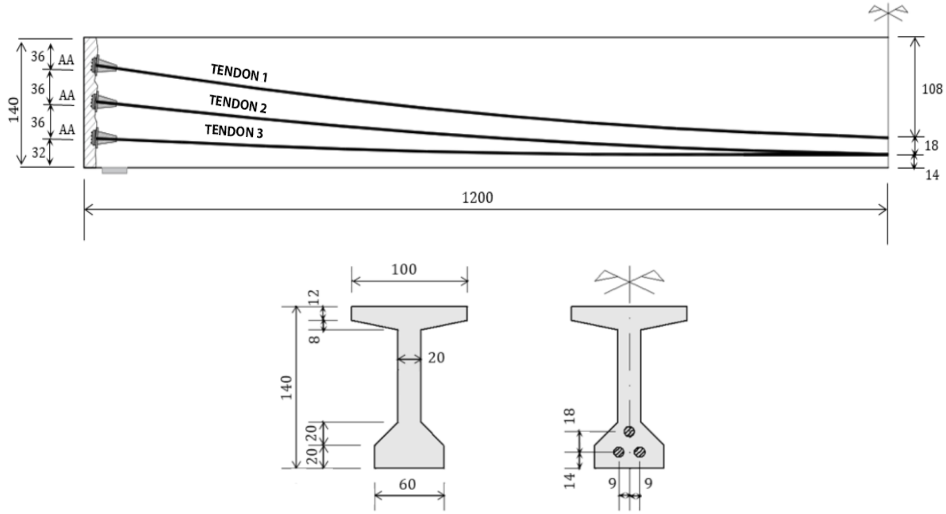

Fig. 1 The image shows the typical cross-section geometry and the position of the tendons in the mid-span section with units in centimeters (cm).

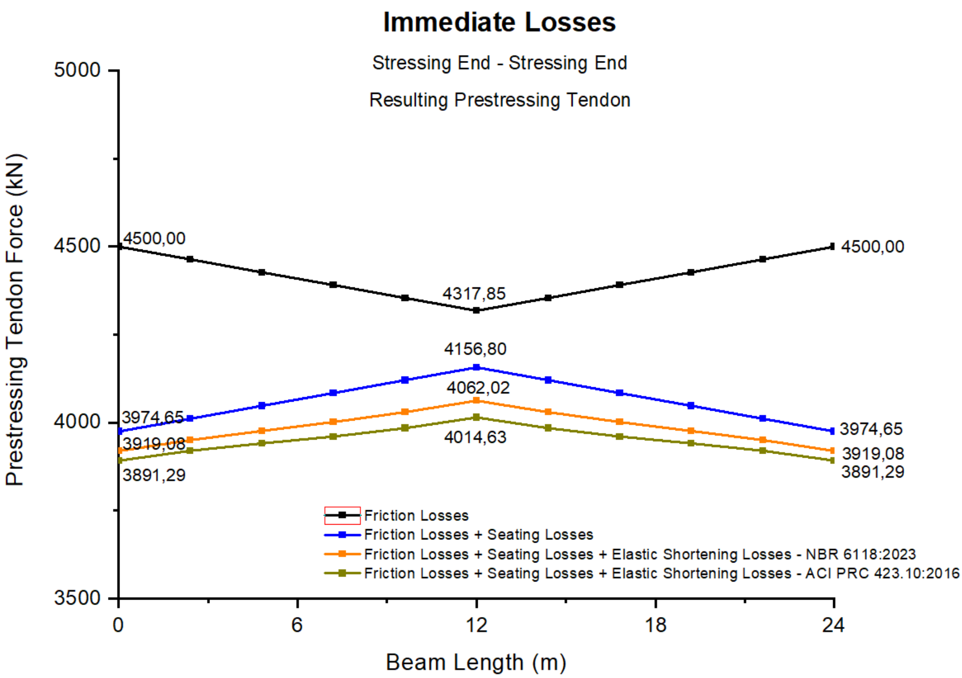

Fig. 2 Graph of resulting prestressing tendon force from friction losses, seating loss and elastic shortening of concrete.

3.1 SIMPLIFIED AND APPROXIMATE PROCESSES – ABNT NBR 6118:2023

The simplified and approximate processes estimate long-term losses through compact equations composed of variables derived from environmental characteristics, exposure conditions, geometric properties of the element and the execution of the work. Therefore, the following aspects were considered in this numerical example: Average ambient relative humidity = 70%, α_{ep} = 6,45, linear interpolation for the value of Ψ_{1000}, concrete with f_{ck} = 30 MPa, E_{ci} = 31 GPa, and ratio of prestressing steel to area of gross concrete section at the cross section = ρ_p = 0,65% e E_p=200 GPa.

3.2 GENERAL METHOD OF CALCULATION – ABNT NBR 6118:2023

The general method of calculation takes into account the requirements of Annex A to [1]. Thus, the following variables were considered for this example: Lifetime of the structure = 50 years, CP II cement, applying prestressing force = 30 days, concrete with slump of 9 cm and average daily temperature of 25º C. The Fig. 3 shows the graph of resulting prestressing tendon force after long-term losses taking into account the 3 procedures admitted by [1].

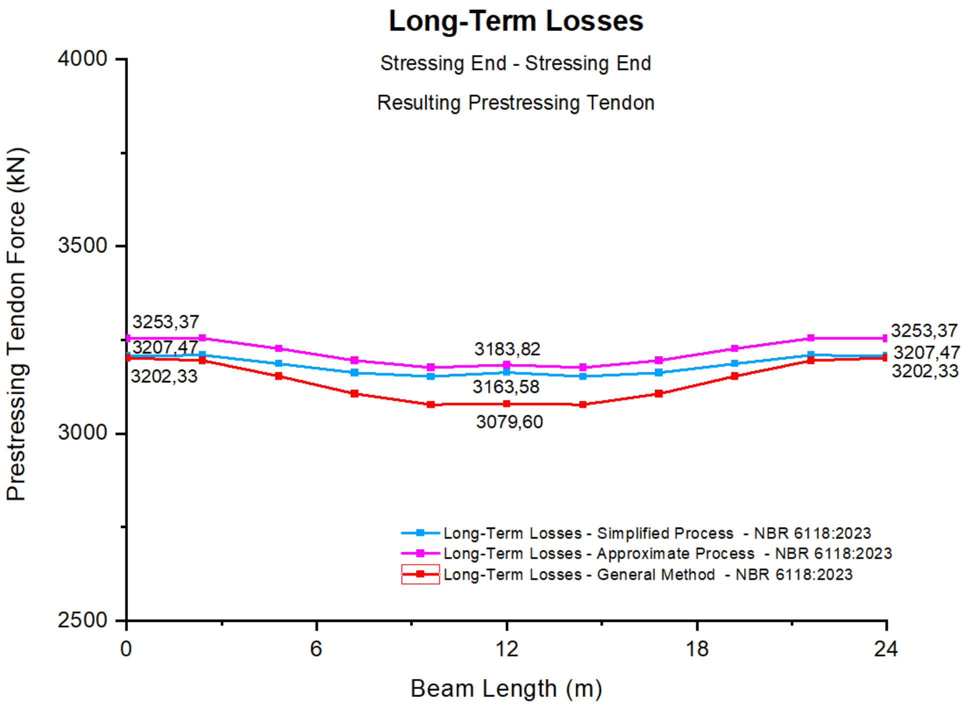

Fig. 3 Graph of resulting prestressing tendon force after long-term losses according to NBR 6118:2023.

3.3 METHOD PROPOSED BY ACI PRC-423.10:2016

Taking into account the criteria by [2], two different conditions were considered: The first taking into account the long-term losses by isolated equations and the second through the simplified equation proposed by [5]. The Fig. 4 shows the graph of resulting prestressing tendon force after the long-term losses took into account the two criteria recommended by [2].

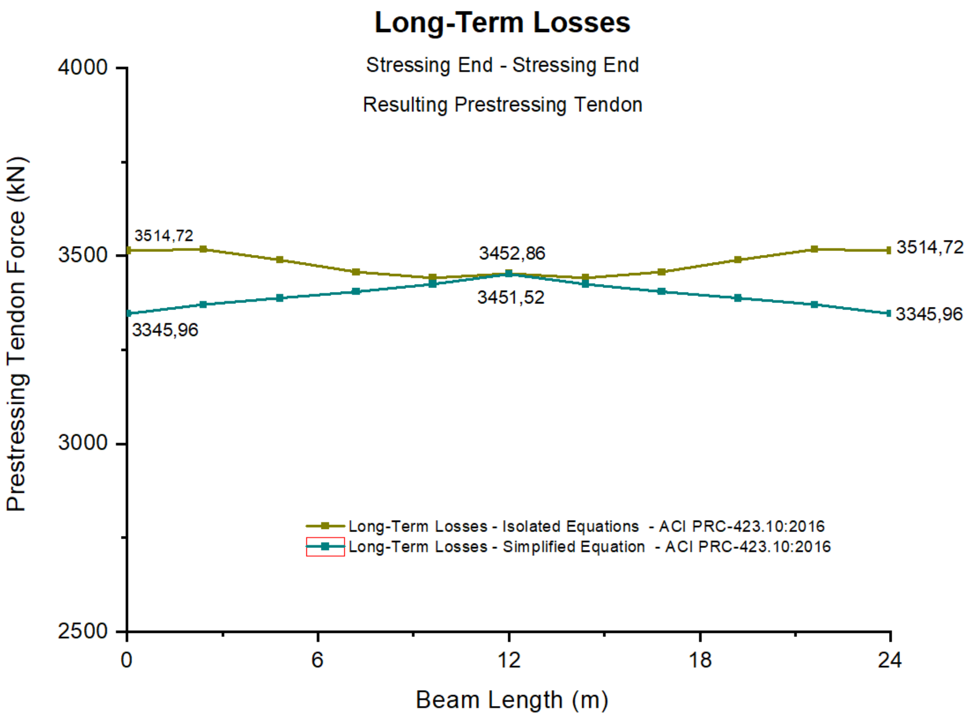

Fig. 4 Graph of prestressing force in the resulting tendon after long-term losses according to ACI PRC-423.10:2016.

4 DISCUSSION OF THE RESULTS

The first condition observed refers to the analysis of immediate losses that, although not within the scope of the article, may contribute to the variation of total losses found are even greater. In this case, there was a difference in the values obtained in the elastic shortening of the concrete through that recommended by [1] in relation to [2], in which the American standard presented the greatest losses of this variable, with values around 3.16% and the Brazilian standard around 2.11%. Regarding the methods proposed by [1], comparing complexity levels to obtain the results of long-term losses, it can be stated that the approximate process has a small level of complexity, the simplified process a medium level of complexity and the general method of calculation a high level of complexity. Regarding the methods proposed by [2] it can be classified that the results obtained by the isolated equations have a high level of complexity, however the method proposed by the simplified equation differs and has a small level of complexity. The criterion adopted to classify at levels of complexity was not necessarily the size of the equation, but the difficulty in obtaining its variables. Regarding the results obtained by the methods proposed by [1], it was observed that the three methods obtained values close to each other differing at the edge of the beam in a variation of 1.43% to 1.59% and in the middle of the beam span a difference of 0.64% to 3.38% was reached. Regarding the results obtained by the methods proposed by [2], it was understood that the two methods obtained practically equal results in the middle of the beam span and at the end of the beam (edge) there was a variation of 5.04%.The Table 1 shows the results as a percentage of immediate losses, long-term losses and, consequently, the total losses of each method analyzed according to [1] and [2], in which the percentage value was taken in relation to the lower tendon prestressing force found.

Table 1 Relative long-term loss results of each method analyzed

Method	Immediate Losses (%)	Long-Term Losses (%)	Total Losses (%)
Simplified Process – NBR6118:2023	9.73	22.12	29.70
Approximate Process – NBR 6118:2023	9.73	21.62	29.25
General Method – NBR 6118:2023	9.73	24.19	31.56
Isolated Equations – ACI PRC-423.10:2016	10.79	13.99	23.27
Simplified Equation – ACI PRC-423.10:2016	13.53	14.01	25.65

The total losses in Table 1 do not include the direct sum as a percentage of immediate losses and long-term losses, but obtained with the methodology of [3]. In addition to the results obtained from the total losses, one can appreciate how discrepant the values found for creep, shrinkage and relaxation of the steel differ in each proposed method, in which these values related to total progressive loss can be contemplated in Table 2.

Table 2 Percentage creep, shrinkage and steel relaxation of each proposed method

Method	Creep of Concrete (%)	Concrete Shrinkage (%)	Steel Relaxation (%)
Simplified Process – NBR6118:2023	61.93	23.42	14.65
Approximate Process – NBR 6118:2023	65.77		34.23
General Method – NBR 6118:2023	58.99	24.73	16.28
Isolated Equations – ACI PRC-423.10:2016	78.59	13.55	7.86
Simplified Equation – ACI PRC-423.10:2016	44.86	47.30	7.84

The standard [5] mentions that an estimate of 2.4 ksi (16.55 MPa) can be adopted for steel relaxation losses taking into account the use of low relaxation prestressing strands, thus Table 3 presents the recalculation of the new relative percentage for relaxation losses considering this hypothesis for the procedures used in this article.

Table 3 Percentage of steel relaxation corresponding to 2.4 ksi (16.55 MPa) for each proposed method

Method	Steel Relaxation (%)
Simplified Process – NBR6118:2023	6.90
Approximate Process – NBR 6118:2023	4.32
General Method – NBR 6118:2023	6.46
Isolated Equations – ACI PRC-423.10:2016	9.89
Simplified Equation – ACI PRC-423.10:2016	9.87

5 CONCLUSIONS

The evaluation of long-term losses is an action of extreme importance to verify the variation of the long-term prestressing force, reflecting on the choice of the initial prestressing force. The analysis of the results presented in this article can be concluded that:

- The standards considered in this article presented different results for long-term losses and the equations recommended by the regulatory bodies of each country considered the usual local materials and technologies and adjusted over time according to the regional constructive experience.

- The results of long-term losses obtained with the American standard showed slightly lower values than those obtained with the Brazilian standard.
- Out of the evaluated methods, the one that presented the lowest long-term losses was the isolated equations - ACI with 13.99% and the one that presented the highest long-term losses was the general method - NBR with 24.19%. The discrepancy of the results between the methods can be considered inevitable since they presented higher levels of complexity to adopt the empirical coefficients.
- The standards proposed formulations with levels of complexity considered small to obtain the final results and both the approximate process – NBR and the simplified equation – ACI, presented close results for the total losses.
- The values obtained from the total losses by the three methods proposed by the Brazilian standard were congruent, in other words, even varying the level of complexity between them from small to high, all presented close values. Similarly, analyzing the two methods proposed by the American standard, the same occurrence was identified among them.
- It is known that the composition of long-term losses passes through the losses due to creep of concrete , concrete shrinkage and steel relaxation, thus deepened in the percentages of each effect considering the total sum being 100%. It was identified that the two effects with the greatest influence on long-term losses were creep of concrete and concrete shrinkage, with creep of concrete being the most relevant portion.
- The absolute results for the total losses with the approximate process – NBR and the simplified equation – ACI were close to each other. However, when each effect was dismembered in a relative way, discrepant values of creep of concrete, concrete shrinkage and steel relaxation were obtained when compared to each other. In fact, the simplified equation method - ACI recommends requirements to be followed for the method in question, but the objective of the article was precisely to test how discrete these results could be.
- The American standard mentions that for the simplified equation - ACI it is possible to adopt an estimate of 2.4 ksi (16.55 MPa) for the losses due to steel relaxation, having as parameter the use of low relaxation strand (as considered). It was found that the isolated equation - ACI and the simplified equation - ACI presented little impact of this variable since the value found for the steel relaxation was 12.87 MPa initially. However, the simplified process –NBR, the approximate process - NBR and the general method presented greater discrepancies in the results when using that hypothesis.
- When there was a replacement of the values of 2.4 ksi (16.55 MPa) for the recalculation of steel relaxation, there was a small impact on the equations of the American standard and a great impact on the results calculated with the Brazilian standard.
- Finally, it is concluded that the values of total losses were acceptable for all methods, but the choice of procedure should be compromised with the more realistic behavior of the structural element in question.

Acknowledgements

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