

## **Addin for Autodesk Robot® for the SLS Design of Prestressed Concrete Beams with Post-tensioned Bonded Tendons**

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### **Abstract**

This work presents an interactive graphics computational tool for the verification of prestressed concrete beams with post-tensioned bonded tendons to the serviceability limit state (SLS) stress check according to the Brazilian code NBR 6118. The software Autodesk Robot Structural Analysis Professional® is adopted as a structural modeling platform.

With data supplied by the user through a graphics user interface, the program calculates the prestressing's equivalent load considering all relevant prestress losses that occur throughout the structure's life-cycle. In order to adopt an incremental method for the calculation of the differed losses, modifications had to be done to the equations given in the NBR 6118. Examples and results are also presented, validating the adopted methodology.

At the end of the software's calculation, the user receives two outputs: the prestress' equivalent loads in the Robot model and a spreadsheet. The equivalent loads may be used in other calculations, such as shear reinforcement. The spreadsheet contains the resultant stresses in the beam during its lifespan and alerts the user as to whether these are greater than the permissible stresses in the SLS stress check.

*keywords: Prestressed concrete beams, NBR 6118, Serviceability limit state stress check*

## **Addin para o Autodesk Robot® para a verificação de vigas de concreto protendido com pós-tração aderente**

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### **Resumo**

Este trabalho apresenta uma ferramenta computacional gráfico-interativa para a verificação ao estado limite de serviço (ELS) de vigas de concreto protendido com pós-tração aderente de acordo com a NBR 6118. O software Autodesk Robot Structural Analysis Professional® é adotado como plataforma de modelagem estrutural.

A partir de dados apresentados pelo usuário por meio de uma interface gráfica, o programa calcula o carregamento equivalente da protensão considerando todas as perdas de protensão relevantes ao longo da vida-útil da estrutura. Para adotar um método incremental de cálculo das perdas progressivas, modificações foram feitas às equações definidas na NBR 6118. Exemplos e resultados também são apresentados, validando a metodologia adotada.

Ao final do cálculo do programa, o usuário recebe duas saídas: os carregamentos equivalentes da protensão no modelo do Robot e uma planilha. Os carregamentos equivalentes podem ser utilizados pelo usuário em demais cálculos, tais como o dimensionamento ao cisalhamento. A planilha contém as tensões resultantes na viga ao longo da sua vida-útil e alerta o usuário se estas forem maiores que as tensões admissíveis no estado limite de serviço.

*palavras-chave: Vigas de concreto protendido, NBR 6118, Verificação ao estado limite de serviço*

## 1 Introduction

The Building Information Modeling (BIM) philosophy is revolutionizing structural engineering. The fundamental concept is to bring all the information from the disparate disciplines into a single database. One then has a single structural model which incorporates all the structure's life-cycle information: architectural, structural, hydraulic, electric, mechanical, as-built, and maintenance projects. Prestressed concrete structures, however, tend to be modeled separately in specialized software which does not attempt to follow the BIM philosophy.

To aid in the unification of prestressed structural models with BIM, this work presents a computational tool for the serviceability limit state stress check of bonded post-tensioned concrete beams according to Brazilian codes via Autodesk Robot Structural Analysis Professional®, henceforth referred to as **Robot**. This software, named **Prestress**, is an add-in for **Robot**, leveraging its structural modeling capabilities to obtain the loads and stresses arising from the prestress.

**Robot** was chosen as the platform for **Prestress** because it is part of the Autodesk environment. BIM does not require that a single company's package be adopted, but open-source databases, commonly represented by IFC files, cannot as of yet contain all of the "intelligence" of a model [1]. For this reason, though it is not strictly necessary, adopting a company's closed environment simplifies the implementation of the BIM philosophy for now. With **Robot** as a platform, **Prestress** can now unify the prestressing calculations to those of the global structure. Though not yet implemented, **Prestress** can still be extended to add the prestressing to an Autodesk Revit 4D model to check for possible interferences and inclusion in the structure's life-cycle analysis.

From a structural model created within **Robot** and prestressing data given by the user, prestress losses are calculated, isostatic bending moments are obtained and equivalent loads are applied. The program's calculations are boundary-condition-agnostic, successfully dealing with isostatic and statically indeterminate beams. The effects of the boundary conditions are considered by **Robot** and incorporated in **Prestress**. Once the (possibly statically indeterminate) stresses are obtained, the software then performs a serviceability limit state stress check on the beam and generates an .xlsx file containing the results.

A limitation of **Prestress** at present is that it cannot correctly calculate structures which are built in stages. While **Robot** has what it calls "phase structures", its API does not implement any method by which external programs (such as **Prestress**) can retrieve information regarding the different construction phases [2]. It is therefore impossible for **Prestress** to accurately calculate segmental bridges or prefabricated beams with cast-in-place decks which are usually considered to work with the beam for live-loads.

There are at present already multitudes of software in the market which aid the engineer in the design of prestressed concrete structures. **midas Civil**®, **SAP 2000**®, **ADAPT-ABI**®, **ADAPT-PT/RC**®, **RAPT**® and **Nemetschek Scia**® are but a few of the available options. All of these are evidently far more advanced and robust than the software here developed. However, of the above only **ADAPT-PT/RC**® currently performs the calculations and serviceability checks according to the Brazilian codes, but it is a 2D-only platform. There

are other programs, such as those developed by Bortone [3] and Lazzari *et al.* [4], which fall into the same category.

**Prestress** is unique in that it follows the Brazilian codes and allows the user to work in a 3D space. Compared to the works of Bortone and Lazzari *et al.*, it also has the advantage of not being a stand-alone program. This means the engineer need not create two structural models: one to calculate the prestressed element and another to obtain the behavior of the rest of the structure. Having the prestressing loads within the global structural model also allows the user to observe the effect of the prestress in the entire structure.

The following sections will present the procedures adopted by the software and two examples. One example is that of an isostatic beam, while the other is of a statically indeterminate structure. Each example presents the information relevant for prestressing and the file containing the results.

## 2 Procedure

### 2.1 Input

The **Prestress** software requires that the user already have a complete structural model defined in **Robot**, including constraints and load cases. It is essential that the beam be allowed to deform according to the real boundary conditions, therefore great care must be taken in the definition of the constraints. For instance, if a beam's two extremities have constraints which do not allow the beam to be compressed, a large part of the prestress will be lost.

The user then selects the beam to be prestressed, which may be composed of one or more bar segments. Via a graphical user interface, the engineer may input the requisite prestressing data. This includes the number of cables, each cable's longitudinal layout, section area, pull stress, and relevant prestress loss coefficients, as well as material properties for both concrete and steel and the desired level of prestress: limited or complete prestress. Partial prestress, which permits the concrete to crack in tension, is not allowed. The units adopted by **Prestress** are taken directly from the **Robot** model, so as to allow the user to work with the unit system (s)he has previously defined.

Another key piece of data the user must present is the different phases of a structure's lifecycle. The suggested minimum number of such phases is four [5], representing: the age of concrete at prestressing; when loads other than self-weight and prestress are applied; one year; and the end of the structure's service life. The user, however, is free to alter both the number and dates of phases. Each phase is defined by the concrete's age at the end of the phase, the dead and live loads that are applied and the cables that are jacked on that phase, along with representative values of temperature and humidity for that phase. Should the prestressing operation occur in multiple stages, this should be represented in the user's input, preferably by including additional phases. Figure 1 shows the windows where the user enters all relevant data.

With this data **Prestress** then calculates all relevant prestressing losses: friction, anchorage slippage, concrete elastic deformation, creep and shrinkage, and steel relaxation.

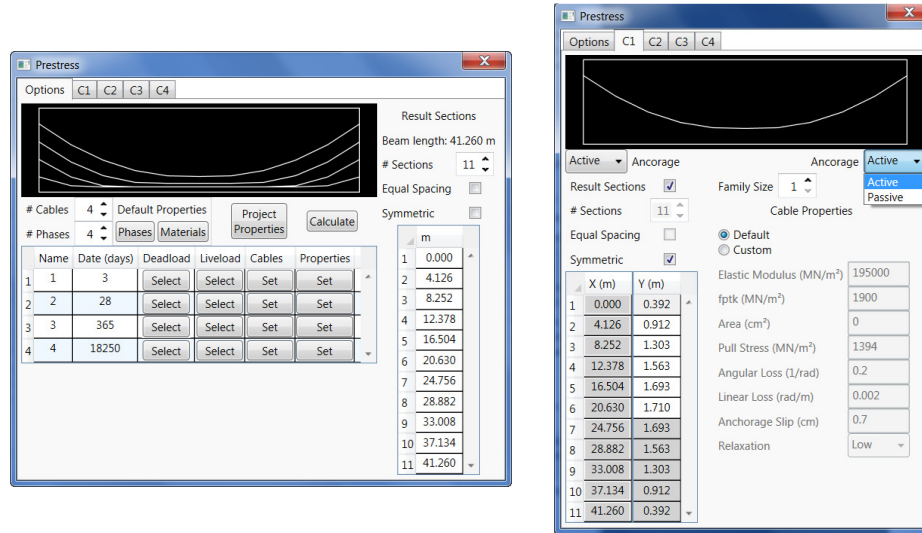


Figure 1 – Prestress' user interface

## 2.2 Equivalent loads

A curved cable under tension tends to straighten, but this is impeded by the concrete and its self-weight, so the cable applies a distributed force along the beam's span. The standard method of defining an equivalent load to simulate this force was presented by Lin [6]. For a beam with a parabolic cable of length  $L$ , pull-force  $P$  and maximum deflection  $e$ , the equivalent distributed load is given by Equation 1.

$$q = \frac{8P \cdot e}{L^2} \quad (\text{Equation 1})$$

This method, however, is not generic since it requires a beam of constant section [7]. It is therefore necessary to adopt a more generic function for equivalent loads. The adopted solution applies concentrated loads according to Equation 2 at every section  $i$  where the cable's layout was defined, where  $M_i$  and  $M_{i+1}$  are the isostatic prestressing bending moments at the current section and the following one, respectively, and  $\Delta M$  is the difference between the bending moment immediately to the right and left of the current section.  $\Delta M$  is therefore only non-zero if there is a cross-section discontinuity at point  $i$ . If such a discontinuity occurs, a concentrated moment equal to  $\Delta M$  must also be applied.

$$Q_i = \frac{M_{i+1} - M_i - \Delta M}{L} - \sum_{j=1}^{i-1} Q_j \quad (\text{Equation 2})$$

This method generates a polygonal approximation of the beam's prestressing bending moment diagram, regardless of the boundary conditions. If the structure is statically indeterminate, then the boundary conditions will naturally generate the correct diagram. This equivalent load method also satisfies the condition of being self-balanced, generating no reactions on supports in isostatic structures. Prestress losses are also trivially

considered, since the values of  $M_i$  and  $M_{i+1}$  are naturally calculated after all relevant losses. Figure 3 shows an example of a beam without cross-section discontinuities (therefore  $\Delta M$  is always null) under a constant distributed load and the linear approximation via Equation 2. The errors here are of approximately  $\pm 1\%$ , but this is evidently affected by the number of points where concentrated loads are defined.

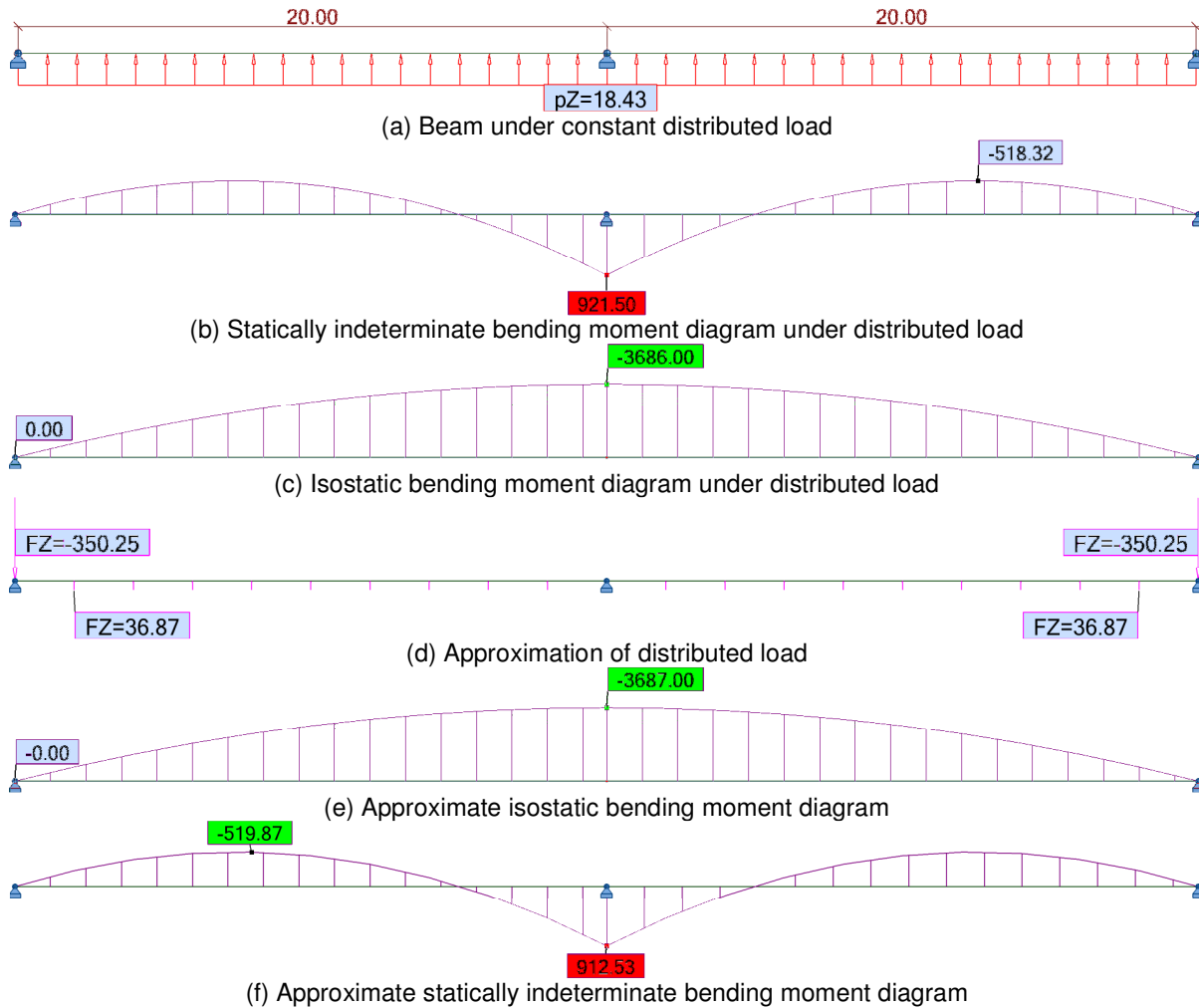


Figure 3 – Beam under distributed and equivalent loads

The equivalent loads of each phase of the structure's service life are left in the model after **Prestress** is complete, allowing the user to make use of these loads if so desired.

### 2.3 Prestress losses

The cable's stress is not constant along the cable's length, nor is it constant in time. The losses can be simply bundled into two groups: immediate and progressive losses. The immediate losses, as the name would imply, happen at the act of jacking. These are



losses due to: friction between the cable and its duct; anchorage slippage; and the elastic deformation of the concrete. The progressive losses are time-dependent, increasing throughout the beam's service-life. These are the losses due to steel relaxation and concrete creep and shrinkage. The methods adopted are summarized below.

Friction losses are calculated according to item 9.6.3.3.2.2 of the NBR 6118:2014 [8], which is itself simply the traditional equation for such losses, seen in Equation 3, where  $P_0$  is the pull force;  $\mu$ , the angular friction coefficient;  $\alpha(x)$ , the total absolute angular variation from the anchorage until point  $x$ ; and  $k$ , the linear friction coefficient.

$$P(x) = P_0 \cdot e^{-\mu\alpha(x)-k \cdot x} \quad (\text{Equation 3})$$

Anchorage slippage losses are calculated by solving Equation 4, where  $A_p$  is the cable's cross-section's area;  $E_p$ , the cable's modulus of elasticity;  $\delta$ , the anchorage's slip length;  $\Delta P(x)$ , the loss of prestress due to anchorage slippage until point  $x$ ; and  $X$  is the point where these losses end. **Prestress** adopts the cable's stress diagram after friction losses and finds  $X$  by incrementally calculating the area between this diagram and its version mirrored over  $P(X)$ .

$$A_p \cdot E_p \cdot \delta = \int_0^X \Delta P(x) dx \quad (\text{Equation 4})$$

Losses due to the elastic deformation of concrete from prestressing and dead loads are also considered. The stresses due to dead loads and equivalent prestressing loads are calculated by **Robot** and Equation 5 is applied, where  $\Delta\sigma_p$  is the change of stress in the steel;  $\Delta\sigma_c$ , in the concrete; and  $\alpha_p$  is equal to the ratio of the steel and concrete moduli of elasticity.

$$\Delta\sigma_p = \Delta\sigma_c \cdot \alpha_p \quad (\text{Equation 5})$$

**Prestress** currently only calculates post-tensioned bonded cables. Such cables only suffer elastic deformation losses due to the prestressing of subsequent cables, but not due to their own jacking. If cables are pulled at different dates, then the effect of the jacking of the latter cables will only be computed at that later date. This allows the software to consider the effect of the differed losses (discussed below) on the former cables prior to the influence of the elastic deformation losses.

The treatment of the progressive losses is more complex. These losses are interdependent, with the result of one altering the result of the other and visa-versa. The methods adopted by **Prestress** are those present in Annex A of the NBR 6118 [8]. However, they do not allow for the consideration of this interdependence and therefore had to be slightly modified. Below are described the methods used by the software. When calculating each differed loss for a phase  $i$  the program assumes the stresses in phase  $i-1$  are constant. With a sufficient number of phases (at least four, as described in Section 2.1), this allows for an approximation of the true results [5].

Creep losses are calculated by the traditional method of considering a factor  $\varphi$  which represents the deformation increment over time, as seen in Equation 6:

$$\Delta\sigma_p = \varphi \cdot \sigma_c \frac{E_p}{E_c} \quad (\text{Equation 6})$$

Item A.2.2.3 of the NBR 6118 [8] considers  $\varphi$  as the sum of three parts:  $\varphi_a$ , which represents the quick, plastic deformation which occurs in the first 24 hours;  $\varphi_f$ , the slow, plastic deformation; and  $\varphi_d$ , the slow, elastic deformation.

$\varphi_a$  is calculated by Prestress precisely as in the Brazilian code according to Equation 7, where  $\beta_1$  is the fraction of the concrete's 28-day strength present on  $t_0$ , the moment the load is applied. The code actually defines the boundaries differently, with the first case being used for concrete's with a compressive strength between 20 and 45MPa, and the second for concrete's between 50 and 90MPa. Those used here are equivalent, but also allow for concrete's with strengths between 45 and 50MPa. Conservatively, such concretes would fall under the second case. Since this portion of the concrete's creep occurs in the first 24 hours, it is only considered in the first phase after a load is applied.

$$\phi_a(t_0) = \begin{cases} 0,8(1 - \beta_1(t_0)) & \text{for } f_{ck} \in [20,45]\text{MPa} \\ 1,4(1 - \beta_1(t_0)) & \text{for } f_{ck} \in (45,90]\text{MPa} \end{cases} \quad (\text{Equation 7})$$

$\varphi_f$  is calculated in a form almost identical as that given in the code, as shown in Equation 8, where  $\varphi_{f\infty}$  is the asymptote of  $\varphi_f$  and  $\beta_f$  is a time function for such losses. The only difference between this function and the one in the NBR 6118 [8] is that instead of being restricted to  $t_0$ , the moment the load is applied, it allows the creep increment to be found between any two moments in time. This allows the creep from a load applied at  $t_0$  to be computed from  $t_0$  to  $t_1$  and from  $t_1$  to  $t_2$ ... all the way to  $t_n$ , which defines the end of the structure's life-cycle. Both  $\varphi_{f\infty}$  and  $\beta_f$  are functions of the humidity in the air, which means that calculating different phases with varying humidity leads to a different result than if an average value were considered. Figure 4(a), for instance, demonstrates a fictitious example of a beam in an environment with ever-increasing humidity. Notice how the final result considering only the humidity of the last phase (which represents 49 of the beam's 50-year service life) leads to a result which is 25% lower than if the varying humidity in the first year is considered.

$$\varphi_f = \varphi_{f\infty} (\beta_f(t_i) - \beta_f(t_{i-1})) \quad (\text{Equation 8})$$

$\varphi_d$  is the portion which is most modified. For the first increment of time its value is obtained via Equation 9a, precisely as defined in the Brazilian code [8]. For every other increment of time, however, Equation 9b must be used. This occurs due to the peculiar behavior of the code's method, which implies in a non-zero  $\varphi_d$  for  $t_1 \approx t_0$ .

$$\varphi_d = 0,4 \frac{t_1 - t_0 + 20}{t_1 - t_0 + 70} \quad (\text{Equation 9a})$$

$$\varphi_d = 0,4 \left( \frac{t_i - t_0 + 20}{t_i - t_0 + 70} - \frac{t_{i-1} - t_0 + 20}{t_{i-1} - t_0 + 70} \right) \quad (\text{Equation 9b})$$



The implementation of prestressing losses due to concrete shrinkage does not require any modifications to the method present in the NBR 6118 [8], seen in Equation 10, where  $\epsilon_{cs\infty}$  is the maximum value and  $\beta_s$  is a time function. Given the deformation increment between two moments, Prestress then needs only to multiply this value by the steel's modulus of elasticity to obtain the relevant loss of stress. Figure 4(b) shows the shrinkage losses over time for a structure in an increasingly humid environment.

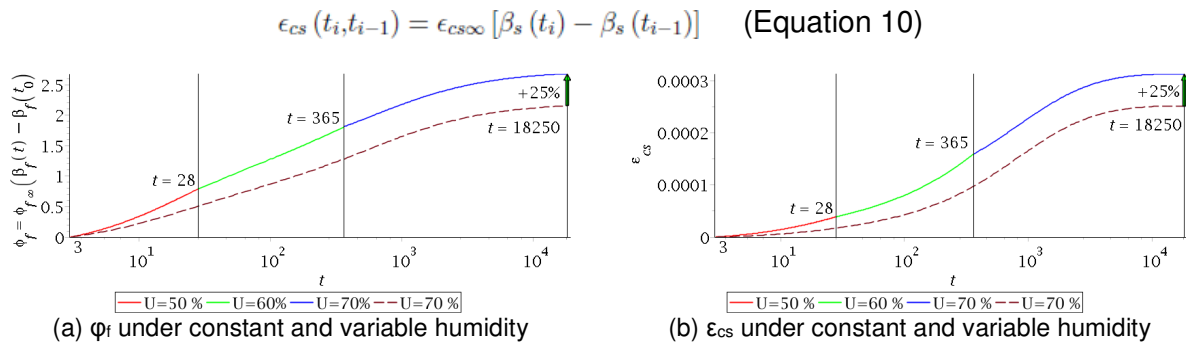


Figure 4 – Examples of the effect of variable environmental conditions on concrete behavior

There is, however, one note that must be made in regards to shrinkage losses and that is that the actual value of shrinkage deformation is a function of a beam's boundary conditions. The beam segment of a plane frame, for instance, will suffer less shrinkage deformation than a simply supported beam due to the stiffness of the pillars. Such effects are not considered by the software, which assumes for these losses that the beam has no restrictions to axial deformations. This is a conservative assumption which leads to greater prestressing losses.

Steel relaxation losses are calculated based on item 9.6.3.4.5 of the NBR 6118 [8]. The method, however, had to be modified somewhat to allow for an incremental method as shown in Equation 11, where  $\psi_i$  is the relaxation that occurs between  $t_i$  and  $t_{i-1}$ ;  $\psi_{1000,i-1}$ , the relaxation coefficient for 1000 hours, obtained in the code's Table 8.4, considering the cable stress at moment  $t_{i-1}$ ; and  $t_0$ , the moment the cable was pulled. Since  $\psi_{1000}$  is a function of steel stress, which is altered by the other progressive losses, the value of  $\psi_{1000}$  is in fact variable in time.

$$\psi_i = \psi_{1000,i-1} \left( \left( \frac{24(t_i - t_0)}{1000} \right)^{0.15} - \left( \frac{24(t_{i-1} - t_0)}{1000} \right)^{0.15} \right) \quad (\text{Equation 11})$$

After calculating each of these losses for every phase of a beam's service life, Prestress can then apply equivalent loads which simulate the prestress. With these equivalent loads in combination with the live and dead loads along the structure's service life, the software can then perform the serviceability limit state stress check.

## 2.4 Servicing limit state stress check

A prestressed structure must be checked against two limit states: ultimate and serviceability. The ultimate limit state (ULS) certifies that the structure will not collapse when under load. The serviceability limit state (SLS) checks that, if ULS is also satisfied, the structure will be adequate for use. A beam which withstands a load but does so with excessive cracking or deflection will not give its users peace of mind and may forbid the use of sensitive machinery. Both limit states are equally important, but only SLS, which is usually the critical verification [9], is checked by **Prestress**. The user must therefore perform ULS checks by some other means.

The Brazilian code defines three levels of live loads, each of which is given a coefficient: rare ( $\psi_0$ ), frequent ( $\psi_1$ ), and almost-permanent ( $\psi_2$ ). For a nominal live load  $Q$ , the frequent load is therefore equal to  $\psi_1 Q$ , for example. The values of the coefficients can be found in Table 11.2 of NBR 6118 [8] or Table 6 of NBR 8681 [10].

Table 13.4 of NBR 6118 [8] states that depending on the environmental conditions (CAA, as defined in Table 6.1 of the code), different stresses are permissible:

- If the environmental conditions are defined as CAA I or II, concrete cracking is permitted with a specified maximum nominal crack width ( $w_{k,max} = 0,2\text{mm}$ ) considering frequent loading. This is defined as partial prestress;
- For CAA III or IV, stresses must be checked in two conditions: there must be no tensile stresses in the concrete under almost-permanent loads (ELS-D) and tensile stresses below the concrete's tensile strength in flexure ( $f_{ct,f}$ , as defined in item 8.2.5 of NBR 6118) are permissible under frequent loads (ELS-F). This is defined as limited prestress;
- Though never obligatory for post-tensioned structures, there is also a stricter check which only allows tensile stresses below the concrete's tensile strength under rare loads (ELS-F) and forbids tensile stresses under frequent loads (ELS-D). This is defined as complete prestress.

Another SLS check is for excessive compression in the concrete (ELS-CE) as per item 17.2.4.3.2.a) of the NBR 6118 [8]. Here the compression must not be greater than 70% of the concrete's strength  $f_{ckj}$  on the date in question, considering a factor of 1.1 on the prestressing loads. **Prestress** performs SLS checks under either limited or complete prestress.

Item 9.6.1.3 of the NBR 6118 [8] states that the nominal prestress can be considered equal to the value obtained after all required losses as calculated in Section 2.3, unless the losses are greater than 35% of the initial jacking force. In such a case, the nominal prestress must be considered as  $\pm 5\%$  the calculated value. Regardless of the magnitude of the losses, **Prestress** always considers this variation of the nominal prestress force.

The stress and SLS-check results for the top and bottom fibers of each section are saved in an .xlsx file, examples of which can be seen in Section 3.

### 3 Example

The Jacareí Viaduct II [11] is a structure composed of three effectively isostatic spans. The central span of 32,70m will be considered here. The cross-section is composed of five prefabricated beams supporting a 20cm-thick cast-in-place deck. The beams are placed on neoprene bearing pads which allow them to deform in all directions. Figure 5 and Table 1 present all the relevant information for the prestressing of the beams.



Figure 5 – Prestressing tendons' profiles for Jacarei Viaduct II (Cerne Engenharia [11])

Table 1 – Properties of Jacarei Viaduct II (Cerne Engenharia [11])

Properties		Limited Prestress	
Area (m <sup>2</sup> )	0,7855	Steel	CP-190 RB
Perimeter (m)	6,15	$f_{ptk}$ (kN/cm <sup>2</sup> )	190
$I_y$ (m <sup>4</sup> )	0,2092	$f_{pyk}$ (kN/cm <sup>2</sup> )	170
$y_i$ (m)	0,716	$\sigma_{pi}$ (kN/cm <sup>2</sup> )	140,6
$y_s$ (m)	0,734	$E_p$ (kN/mm <sup>2</sup> )	195
Concrete Type	CPV-ARI	$A_p$ (mm <sup>2</sup> )	1260,0
Aggregate	Granite	$\mu$	0,28
$f_{ck}$ (MPa)	40	$k$	0,0028
$E_c$ (MPa)	35417,5	$\delta$ (mm)	7
$\gamma_c$ (kN/m <sup>3</sup> )	25		
Slump (cm)	5 - 9		
Service life (years)	50		
CAA	III		
Temperature (°C)	20		
Humidity (%)	75		

The **Robot** model adopted is shown in Figure 6. As stated in Section 2.1, it is important to observe the boundary conditions. Since the beams are supported by neoprene pads which allow for both rotation and displacement of the beams, the model was created with all but one of the supports resisting only vertical displacements. A single support is given additional constraints in order to create a stable model. Also note the difference in cross-section properties between the model and the information given in Table 1 due to the simplification of the section. Since **Prestress** will adopt the section given in the model, the

results will not be the same as if the true cross-section were used. A more precise representation could have been accomplished via the custom “Section Definition” option available in **Robot**.

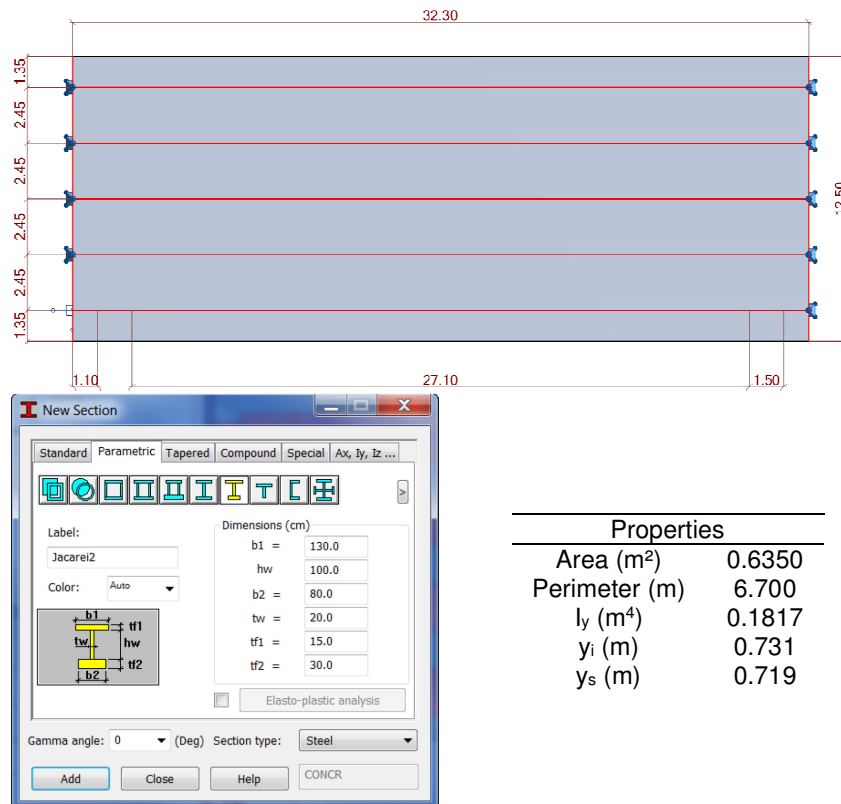


Figure 6 – **Robot** structural model for Jacarei Viaduct II

The fact that it is impossible for any add-in to consider structures built with construction phases means that the model had to suffer some simplifications. The cross-beams at the supports and mid-span were not considered in the model (they are replaced by concentrated loads on the beams) and the slab is defined as a “cladding”, which serves only to distribute loads and does not add to the structure’s stiffness. These simplifications are necessary since the beams are in fact prestressed prior to being hoisted and therefore the entire prestressing load is resisted by the isolated beam. If the cross-beams and the slab added to the stiffness of the model, they would absorb significant portions of the prestress load from the beam, leading to imprecise results. However, since the slabs have no stiffness, they do not distribute applied loads correctly. For this reason, the results especially due to live-loads are excessively large, since the truck loads applied directly over a beam are not partially distributed to its neighbors.

The dead loads are divided into two parts: the beams’ self-weight and that of the slab, pavement (including future repaving) and concrete barriers. The beams’ self-weight load is applied on the structure as soon as the first phase of prestressing takes place. The remainder is assumed to all take place when the concrete is 28 days old. The live load is

the TB-45 described in NBR 7188 [12], with a dynamic factor as per item 7.2.1.2 of NBR 7187 [13]. This must be done by the user (via a load combination) since **Prestress** has no way of knowing a priori whether such load factoring must take place.

Figure 7 presents **Prestress**' output in .xlsx format. The stresses and SLS checks are presented for each section at each phase (only the results for the final phase are shown here). As can be observed at midspan, whenever one of the SLS checks fails, a flag is raised. In this case, the ELS-D condition was not satisfied, since the concrete is in tension under almost-permanent live loads. The file also contains the estimated elongation of the cables prior to anchorage slippage losses. As with the input window, the units adopted in this results file are taken from the **Robot** model.

Seção		Momentos (kNm)		Δ Protensão		σ Solicitante (MN/m²)			Δσ Prot (MN/m²)	σ Total (MN/m²)				Verificar	
		Δ Perm	Acidental		M (kNm)	N (kN)	Δ Perm	Acidental		Perm + Prot	Perm + Prot + Acidental				
			+	-				Max	Min		ELS-D	ELS-F	ELS-CE		
1	Sup	0.0	0.0	-198.6	-25.6	-338.3	0.00	0.71	0.00	0.38	-6.11	-5.61	-5.47	-7.01	-
	Inf	0.0	0.0	-198.6	-25.6	-338.3	0.00	0.00	-0.71	0.20	-2.71	-2.56	-2.56	-3.89	-
2E	Sup	0.0	221.8	0.0	-3.8	-314.9	0.00	0.00	-0.79	0.29	-6.96	-6.74	-6.74	-8.43	-
	Inf	0.0	221.8	0.0	-3.8	-314.9	0.00	0.79	0.00	0.26	-1.79	-1.33	-1.17	-2.46	-
2D	Sup	0.0	222.6	0.0	-3.8	-314.9	0.00	0.00	-0.65	0.27	-6.24	-6.04	-6.04	-7.53	-
	Inf	0.0	222.6	0.0	-3.8	-314.9	0.00	0.73	0.00	0.24	-1.73	-1.31	-1.16	-2.37	-
3	Sup	0.0	695.0	0.0	25.9	-314.9	0.00	0.00	-2.75	0.39	-11.86	-11.57	-11.57	-15.53	-
	Inf	0.0	695.0	0.0	25.9	-314.9	0.00	2.80	0.00	0.60	-4.05	-2.71	-2.15	-5.62	-
4	Sup	0.0	1770.0	0.0	96.5	-306.8	0.00	0.00	-7.01	0.10	-14.29	-14.24	-14.24	-21.45	-
	Inf	0.0	1770.0	0.0	96.5	-306.8	0.00	7.12	0.00	0.87	-2.20	0.73	2.15	-4.63	ELS-D
5	Sup	0.0	2199.0	0.0	142.6	-317.3	0.00	0.00	-8.70	-0.06	-15.64	-15.54	-15.54	-24.45	-
	Inf	0.0	2199.0	0.0	142.6	-317.3	0.00	8.85	0.00	1.07	-1.50	2.12	3.89	-4.52	ELS-D
6	Sup	0.0	2148.8	0.0	163.4	-324.3	0.00	0.00	-8.51	-0.14	-15.82	-15.66	-15.66	-24.50	-
	Inf	0.0	2148.8	0.0	163.4	-324.3	0.00	8.65	0.00	1.17	-1.61	2.03	3.76	-4.88	ELS-D
7	Sup	0.0	2198.3	0.0	142.6	-317.3	0.00	0.00	-8.70	-0.06	-15.64	-15.54	-15.54	-24.44	-
	Inf	0.0	2198.3	0.0	142.6	-317.3	0.00	8.84	0.00	1.07	-1.50	2.12	3.89	-4.52	ELS-D
8	Sup	0.0	1772.0	0.0	96.5	-306.8	0.00	0.00	-7.01	0.10	-14.29	-14.24	-14.24	-21.46	-
	Inf	0.0	1772.0	0.0	96.5	-306.8	0.00	7.13	0.00	0.87	-2.19	0.73	2.15	-4.63	ELS-D
9	Sup	0.0	697.1	0.0	25.9	-314.8	0.00	0.00	-2.76	0.39	-11.86	-11.57	-11.57	-15.54	-
	Inf	0.0	697.1	0.0	25.9	-314.8	0.00	2.80	0.00	0.60	-4.05	-2.70	-2.14	-5.62	-
10E	Sup	0.0	231.8	0.0	-3.2	-314.9	0.00	0.00	-0.69	0.27	-6.31	-6.10	-6.10	-7.63	-
	Inf	0.0	231.8	0.0	-3.2	-314.9	0.00	0.76	0.00	0.25	-1.74	-1.30	-1.15	-2.39	-
10D	Sup	0.0	210.4	0.0	-4.4	-315.6	0.00	0.00	-0.75	0.29	-6.94	-6.72	-6.72	-8.37	-
	Inf	0.0	210.4	0.0	-4.4	-315.6	0.00	0.75	0.00	0.26	-1.81	-1.37	-1.22	-2.48	-
11	Sup	0.0	0.0	-198.4	-25.6	-338.3	0.00	0.71	0.00	0.38	-6.11	-5.61	-5.47	-7.01	-
	Inf	0.0	0.0	-198.4	-25.6	-338.3	0.00	0.00	-0.71	0.20	-2.71	-2.56	-2.56	-3.89	-

Figure 7 – **Prestress**' output containing SLS stress checks for Jacarei Viaduct II

## 4 Conclusions

**Prestress**, the software here developed, allows the user to perform serviceability limit state checks on post-tensioned beams with bonded tendons in a simple and expedient form, therefore also enabling the iteration between multiple different prestressing solutions. There are multiple different tools which perform similar tasks to **Prestress**, such as **midas Civil**®, **SAP 2000**®, **ADAPT-ABI**®, **ADAPT-PT/RC**®, **RAPT**®, and **Nemetschek Scia**®, among others. All were developed by professional teams and most contain tools which are far more advanced than those demonstrated here. Only **Prestress**, however, works directly in tandem with **Robot** and therefore allows for a far greater interoperability with the rest of the Autodesk package (**Revit**®, for instance). **Prestress** therefore stands as a (small) first step towards including the calculation of prestressed beams within this philosophy.

This software is evidently nothing more than a tool to be placed in one's toolbelt. As with any other software, it runs the inescapable risk of "garbage in, garbage out". If the user presents it with incorrect data (including, and perhaps most importantly, the structural model), the results will be equally incorrect. It is therefore essential that the add-in be used



by an engineer who is familiar with the concepts behind prestress and who is capable of analyzing the results with a critical eye and of recognizing that which is incorrect.

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