Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

PRESTRESS LOAD MODELING FOR CONTAINMENT DIGITAL TWIN MODEL

Matyas Ratislav[1], Jan Stepan[2], Sebastian Nase[3]

[1] CTU, Faculty of Civil Engineering, Prague, Czech Republic (matyas.ratislav@fsv.cvut.cz)
[2] Designer, UJV Rez div. Energoprojekt Praha, Prague, Czech Republic (jan.stepan1@ujv.cz)
[3] Designer, UJV Rez div. Energoprojekt Praha, Prague, Czech Republic (sebastian.nase@ujv.cz)

ABSTRACT

Containments represent a crucial component of the protective systems in nuclear power plants using VVER nuclear reactors, ensuring safety and integrity in case of emergency situations [1]. These containments are designed as prestressed reinforced concrete structures that utilize prestressing tendons to enhance strength and resilience [2] [3]. The use of a digital twin, which is a virtual model of a physical system, enables analyses and predictions of the behaviour of these structures.

It is important to have digital twin as precise as possible. On the other hand, we are not able to have full model with everything modelled as solid elements. It is important to have some simplifications, but these simplifications need to match the real structure.

The aim of this article is to develop a method for determining the surface load from prestressing on the tendon duct within a containment segment model. Calculations performed on this detailed model will be used to refine the digital twin, defined in this paper as a numerical model of the entire containment building. Therefore, the precision in defining load distribution from prestress in tendon ducts could directly impact the accuracy of the digital twin. This digital twin will enable improved assessment, prediction, and decision-making in future service-life extension processes for the structure.

FINITE ELEMENT MODELS AND LOADS

Finite element models

Containment of VVER-1000 reactor is a monolithic, post tensioned cylindrical reinforced concrete structure. Walls are prestressed by a cable system arranged in cross loops. This prestressing system consists of unbonded tendons arranged in helical pattern.

Two models were made. First one is model of whole containment, where cables and reinforcements are made by 1D elements. Concrete is made of 3D elements, mostly from HEXA solid elements and around openings, where using HEXA elements are almost impossible tetrahedrons are used. This model is used for global analysis of containment – is used as a digital twin of real containment.

Second model is model of typical cross-section of the containment structure, intentionally excluding the effects of openings, supports and the containment ring beam on the stress distribution within this segment. Due to the containment size, creating such a detailed finite element model for the entire containment is impractical, as it would result in extremely demanding computations. Modelled segment is three-dimensional finite element model. The chosen segment has a height of 2.12 meters, a thickness of 1.2 metres and an arc width of 3 metres at its midplane. The model includes reinforcing steel bars represented by 1D elements. The cable canals are modelled as cavities in concrete structure, which is modelled by

[1] CTU, Faculty of Civil Engineering, Prague, Czech Republic (matyas.ratislav@fsv.cvut.cz)
[2] Designer, UJV Rez div. Energoprojekt Praha, Prague, Czech Republic (jan.stepan1@ujv.cz)
[3] Designer, UJV Rez div. Energoprojekt Praha, Prague, Czech Republic (sebastian.nase@ujv.cz)

tetrahedral elements, with higher density of elements adjacent to the cavities. Forces from post-tensioning is applied to the inner walls of cavities. See the full model and segmented model on Figure 1.

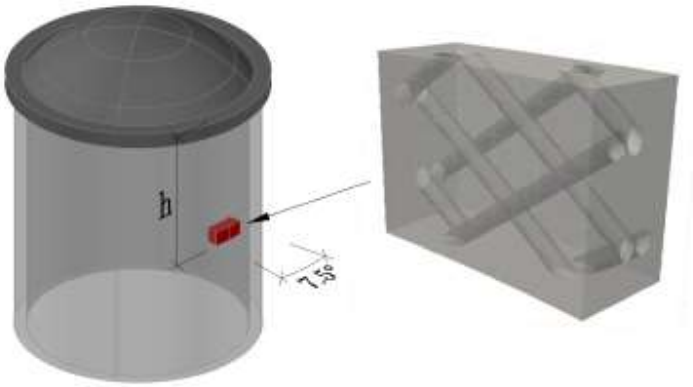


Figure 1. Full and segment mode

Line loads

It is necessary to establish the right total line load exerted by the cable along its length on the structure. This line load is constantly changing due to the losses of pretension by the friction. Two ways were calculated and compared. First option consists in the use of finite elements full scaled model. Model had to be improved, and cables had to be modelled much more accurately. Cavities and duct must be modelled, and right friction coefficient between cables and ducts must be settled. Last step of this method is moving ends of the cables in the direction of the cable, like during the prestressing. This option is very precise, but it is very time consuming. Both time of the designer during the modelling, and computation time during solving. From this reason it is almost impossible to make repetitive computation and shorter way had to be found.

Second way is by using formula. Main loss of pretension is by friction, and friction is based by some variables – length, friction coefficient and bending of the cable should be included in the formula. At the end final equations had been established

$$N(s) = N_0 \cdot \exp\left(\frac{s \cdot \tan(\theta)}{r \cdot (1 + \tan^2(\omega))}\right), \quad (1)$$

Where N_0 is the force at the prestressing location, tan(θ) is the friction coefficient, r is the radial distance of the cable from the containment axis, and ω is the vertical cable inclination [4]. This calculation is based on the parametrization of the prestressing cable paths along the arc. The line load from the prestressing cable (for detailed expalantion see [4]) acting in the radial direction to the containment center is given by equation 2:

$$f_{tot,cent} = \frac{N(s)}{r \cdot (1 + \tan^2(\omega))} \quad (2)$$

The line load acting in the direction of the prestressing cable can be calculated by using equation 3

$$f_{tot,fri} = f_{tot,cent} \cdot \tan(\theta) \quad (3)$$

For graphical representation of these loads, see Figure 2

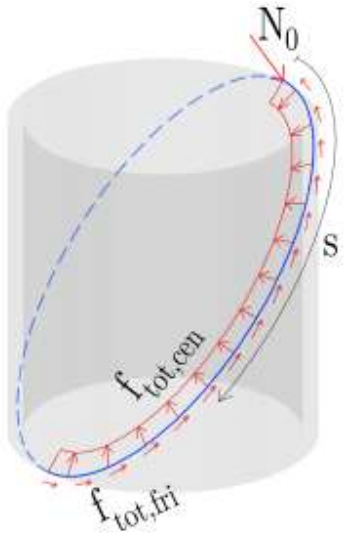
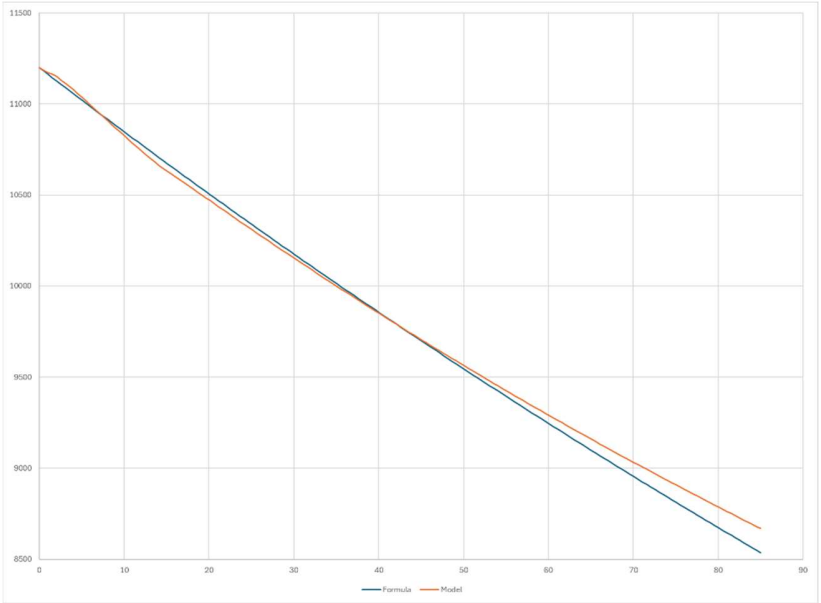


Figure 2. Schematic of line load from prestressing on containment structure

Comparison between model and formula was made. For the formula, the ω angle is considered stable along the whole path of the cable. In FE model and reality, the angle is slightly changing due to the construction inaccuracies. But even with these small inaccuracies the maximum difference between model and formula is under 2%. With more time and more precise inputs to the formula, better match would have been achieved. The final comparison can be seen on graph 1, orange line is model and blue line is formula:



Graph 1 Schematic of line load from prestressing on containment structure

From these results, it can be said that this formula is good to use for computation of pretension force after the losses by friction.

LOAD DISTRIBUTION ON DUCT SURFACE

In the previous chapter, the duct was considered as a 1D element defined just by his centerline. To calculate the magnitude of the load on the surface of the duct, linear load must be multiplied by load distribution coefficient E. This coefficient depends on the angle μ– the direction towards the center of the containment, see Figure 3.

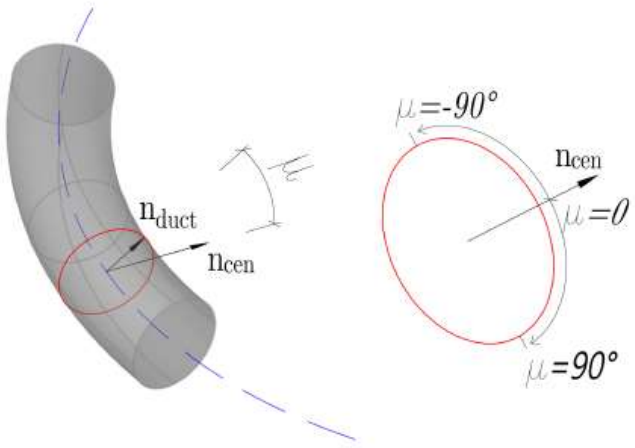


Figure 3. Schematic of μ angle definition

It can be observed that duct is being stressed only on one part of the surface, and it's the inner surface of the duct. From this reason, coefficient μ is going to be non-zero only in the interval -90° to 90°. Cumulative sum of the coefficient must be equal 1. Written as an equation, it is in this form:

$$\int_{-90°}^{90°} \xi(\mu)\, d\mu = 1 \tag{4}$$

Here lies the main task of this paper – setting the right formulation of function E. Before calculation of this function, some assumptions should be made. Cables are pressed as much as possible against the surface of the duct, individual wires are going to be densely packed.

The shape of distribution of wires is going to be determined on one side by surface of the duct, on the second by number of wires. The shape can be divided to two parts, accordingly what was spoken above. One is copying the shape of a duct – part of a circle, second part can be simplified to a parabola. Shape of the parabola is dependant on width of the wires - *w*, their amount, diameter of the duct and space between wires. Space between wires is important for total area taken by wires – it defines the parameters of parabola. To calculate whole area taken by wires, total amount of wires needs to be multiplied by coefficient η. Coefficient η is firstly calculated as a ratio of the areas $A_s + A_0$ to the area of wires A_s. Graphical demonstration of η is on figure 4:

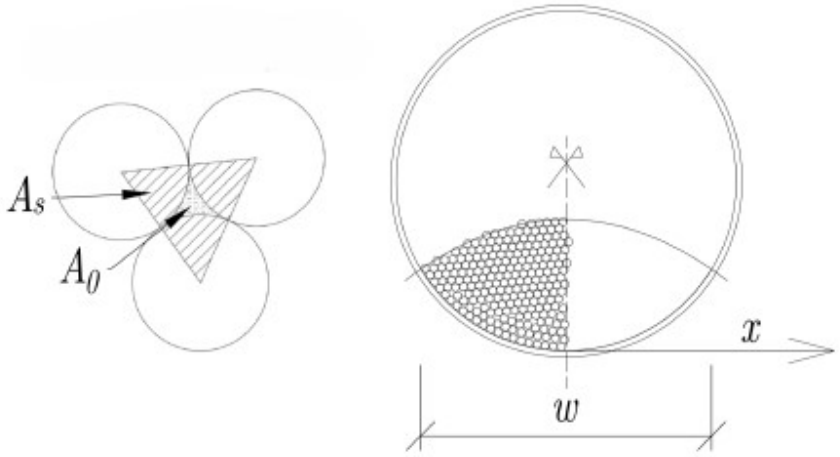


Figure 4. Graphical basis for η and w

For the duct with a diameter of 225 mm and 450 wires the η is around 1,15. The functions for the sides of the shape are:

$$f_d(x) = r_d - \sqrt{r_d^2 - x^2} \tag{5}$$

for the circular part and:

$$f_p(x) = ax^2 + b \tag{6}$$

for the parabola part.

Parameters a and b can be calculated from these equations:

$$2 \cdot \int_0^{w/2} \left(f_p(x) - f_d(x) \right) dx = A_p \cdot \eta \tag{7}$$

for $x = w/2$:

$$f_d(x) = f_p(x) \tag{8}$$

CONCLUSION

This study provides a better knowledge about prestressing force (provides formula co calculate prestressing losses by friction) and the force distribution on the duct surface based on number of wires, diameter of the wires and diameter of the duct.

The formula shows good match with FE model, which is calibrated to real structure. Due to this reason, in future models the formula can be used to determine the prestressing force along the cable instead of modelling the anchorages and displacements of the anchor and whole prestressing procedure. It could simplify the model and greatly reduce the computation and engineers time required to make any useful results.

The detailed distribution of forces on duct surface should be used in detailed models, where local abnormalities or cavities are expected. As it is shown on Figure 5, the simple uniform distribution, which is usually used, doesn't collaborate with wires distribution in the duct. Due to this reason functions and equations were proposed for better load distribution.

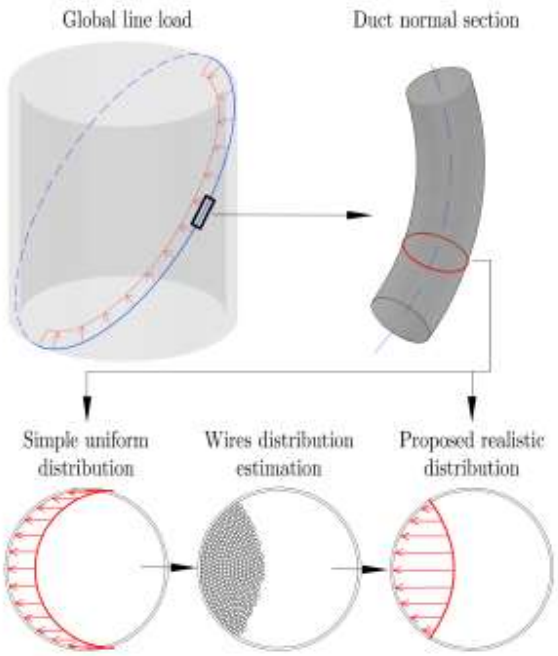


Figure 5. Schema of load evaluation and recommended load distribution

REFERENCES

[1] International Atomic Energy Agency. *Design of the Reactor Containment and Associated Systems for Nuclear Power Plants*. IAEA Safety Standards Series No. SSG-53. IAEA, Vienna, 2019.

[2] Z. Janda, J. Zeman, J. Šejnoha. Zjednodušené modely interakce volného přepínacího kabelu s konstrukcí. *Stavební obzor* **18** (2):44–48, 2009.

[3] Nuclear containments. Tech. Rep. 13, fib (International Federation for Structural Concrete), 2001. doi:10.35789/fib.BULL.0013.

[4] T. Krejčí, J. Šejnoha. Prognóza ztrát předpětí v kabelech válcové části ochranné obálky JETE. Tech. rep., České vysoké učení technické v Praze, Fakulta stavební, Katedra mechaniky, Praha, 2003.