A method for the sag-tension calculation in electrical overhead lines

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Abstract – *The sag and tension values of overhead conductors are influenced by the creep developed during the line lifetime. This paper presents a method for the sag-tension calculation of overhead conductors that is characterised by the creep sequential calculation. Thus, the creep developed in previous stages influences the creep developed in subsequent stages. Two periods are differenced in the creep development: the installation period and the operation period. The relation between the creep development and the factors that influence it such as the installation process and the operation conditions during the line lifetime is described step by step.*

Keywords*: Sag-tension, Overhead conductor, Creep*

I. Nomenclature

T	tension
L	length
A	area
E	elastic modulus
α	coefficient of thermal expansion
ω	weight
θ	temperature
s	span length
σ	stress
ε	total strain
ε^{θ}	strain related to temperature
ε^{T}	strain related to tension
ε^{mc}	strain related to metallurgical creep
ε^{gs}	strain related to geometrical settlement
t	time
g	related to span geometry
c	related to conductor
core	related to core
a	related to aluminium
o	related to reference condition

II. Introduction

The aim of the sag-tension calculation is the calculation of the installation tension as a function of the sag and tension limits. Sag-tension calculation methods allow the calculation of the conductor sag and tension for different conductor temperatures, and wind and ice load conditions, taking into account the evolution of the conductor creep during the line lifetime [1]. The tension is limited by the tension limit of the conductor and the towers. The sag limit is related to the security distance to ground and line crossings. If the crossing distance is below the security distance, line faults could occur [2-5].

The most complete methods are those that consider an independent core and aluminium behaviour and obtain the creep value from experimental tests [6-8]. These methods calculate the aluminium tension and for this reason they calculate the knee-point temperature where the aluminium gets slack.

The most widely used method is the graphical method [6] that is implemented in commercial software programs such as SAG10 or PLS-CADD. This method is based on stress-strain and creep experimental curves. The core and the aluminium curves are obtained separately.

The strain summation method [7] was proposed as an alternative to the graphical method. The method is characterized for having the conductor strain as the dependent variable. The strain can be caused by tension, temperature and creep. The creep is the result of the addition of metallurgic creep and geometrical settlement. Each of these strains is evaluated individually and they are added to obtain the total strain.

In [8], the authors developed a method for the special requirements of the gap-type conductors. The method was based on the strain summation method but some changes and improvements were carried out. For example, independent core and aluminium reference lengths were considered and the calculation of the creep developed during the installation was defined in detail.

The authors have carried out the generalization of the method. As a result, the method is valid not only for gap-type conductors but for any type of conductor, including the high temperature low sag (HTLS) conductors [9-12] and the conventional conductors such as the ACSR. The main advantage of the method is the flexibility for the consideration of several creep stages and the ability to take into account the influence of previous creep stages.

This paper gives a detailed description of the method and it includes diagrams that relate all the parts of the calculation algorithm. The relation between the outputs and the inputs of the algorithm parts are clearly defined from the installation of the conductor to the end of the line lifetime. The creep calculation during the installation is fully described as a function of the type of conductor (gap-type or non gap-type) and taking into account the time the conductor is at rest and whether there is pretensioning or not. The calculation of creep developed during the operation is also described.

III. Sag-Tension Calculation Algorithm

The creep developed in previous stages influences the creep developed in subsequent stages [13,14]. For this reason, the algorithm makes a sequential calculation of the creep. Two periods are differenced in the creep development: the installation period and the operation period (Fig. 1). The creep developed during the operation depends on the creep previously developed during the installation. The creep developed during each operation stage is calculated taking into account the creep developed so far.

In each stage, the metallurgical creep ε^{mc} and the creep due to geometrical settlement ε^{gs} are calculated separately. The metallurgical creep is calculated as a function of the conductor tension T, the conductor temperature θ and the duration t of the stage. The strain due to geometrical settlement is assumed to be independent of time. It is only dependent on the conductor construction and the historical maximum tension T^{max} experienced. This calculation process is carried out for the aluminium and the core separately.

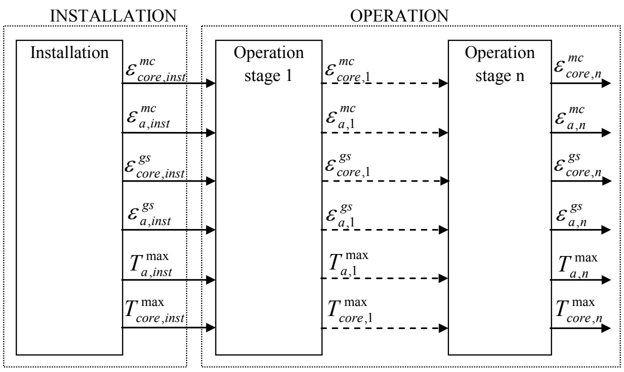


Fig. 1. Creep and maximum tension evolution in time

When the method characterises the conductor installation it differentiates between the gap-type conductors and the rest of conductors.

The conductor temperature and the wind and ice loads are assumed to be constant during each operation stage. Thus, the parameters that characterise each stage i are the following:

- Conductor temperature θ_i
- Load conditions (ice and wind)
- Duration t_i

From the creep strain values calculated for the operation stages, the tension values related to the maximum tension conditions are calculated by the state calculation algorithm described in section IV. The maximum tension conditions are characterised by the conductor temperature and the ice and wind load values. The tension limit values are defined for these conditions. The conditions are related to specific stages (after the installation, 10 year operation, etc.). Thus, from the installation tension T_{inst}, the algorithm calculates the conductor tension in the defined maximum tension conditions. The installation tension value T_{inst} is iterated until one of the maximum tension conditions does not allow increasing its value. The state calculation algorithm determines the conductor tension value calculating separately the core tension T_{core} and the aluminium tension T_a from the conductor temperature θ_i, the wind and ice load and the creep $\varepsilon^{mc}_{core,i}$, $\varepsilon^{mc}_{a,i}$, $\varepsilon^{gs}_{core,i}$ and $\varepsilon^{gs}_{a,i}$ of the corresponding stage (installation, stage 1, stage 2, etc.).

IV. State Calculation Algorithm

The state calculation algorithm is shown in Fig. 2. The core tension T_{core} is iterated until the difference between the span geometry length L_g and the conductor length L_c is below a threshold value. The aluminium tension T_a cannot go below its minimum value. This minimum value is zero or a negative value if aluminium compression is considered [15]. This is taken into account in the algorithm when aluminium tension T_a is evaluated.

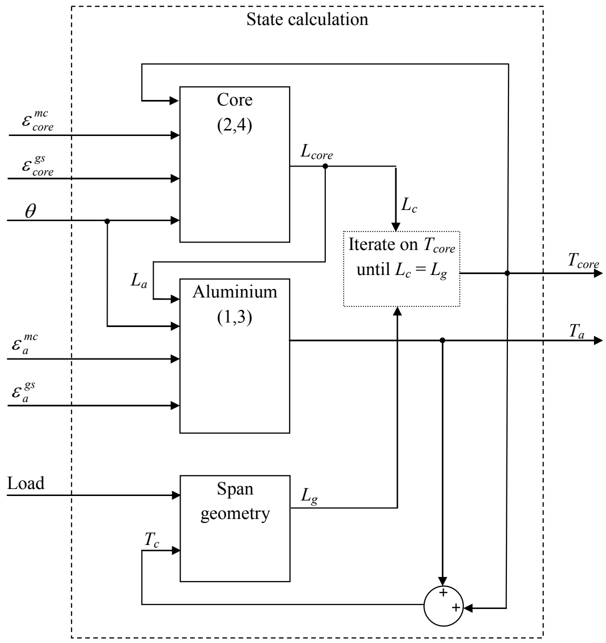


Fig. 2. State calculation algorithm

The state calculation algorithm is based in the dependence of the core and aluminium lengths L_{core} and L_a on the strain values due to tension ε^{T}_{core}, ε^{T}_{a}, temperature $\varepsilon^{\theta}_{core}$, ε^{θ}_{a}, and creep ε^{mc}_{core}, ε^{mc}_{a}, ε^{gs}_{core}, ε^{gs}_{a}, and the core and aluminium reference lengths L_o^{core} and L_o^{a} (1,2).

$$L_a = L_o^a \cdot \left(\varepsilon_a^T + \varepsilon_a^\theta + \varepsilon_a^{mc} + \varepsilon_a^{gs}\right) \quad (1)$$

$$L_{core} = L_o^{core} \cdot \left(\varepsilon_{core}^T + \varepsilon_{core}^\theta + \varepsilon_{core}^{mc} + \varepsilon_{core}^{gs}\right) \quad (2)$$

As described in [8], the core and aluminium reference lengths L_o^{core} and L_o^{a} correspond to the reference condition with no tension and no creep. They are obtained from the installation condition, where the temperature and the tension values are known and the creep strain is estimated from the installation process (3,4). The span geometry is characterised by the catenary equation. The catenary equation is a function of the conductor tension T and the weight ω. The weight value ω depends on the conductor weight ω_c and the wind and ice load. The catenary length $L_{g,inst}$ is obtained from the installation tension T_{inst} and the conductor weight ω_c (5).

$$L_o^a = \frac{L_{g,inst}}{\left(1 + \varepsilon_{a,inst}^T + \varepsilon_{a,inst}^\theta + \varepsilon_{a,inst}^{mc} + \varepsilon_{a,inst}^{gs}\right)} \quad (3)$$

$$L_o^{core} = \frac{L_{g,inst}}{\left(1 + \varepsilon_{core,inst}^T + \varepsilon_{core,inst}^\theta + \varepsilon_{core,inst}^{mc} + \varepsilon_{core,inst}^{gs}\right)} \quad (4)$$

$$L_{g,inst} = 2 \cdot \frac{T_{inst}}{\omega_c} \cdot \sinh\left(\frac{s \cdot \omega_c}{2 \cdot T_{inst}}\right) \quad (5)$$

V. Creep Developed during the Installation

V.1. Gap-type Conductors

The gap-type conductors allow a relative displacement between the core and the aluminium during the installation of the conductor. In this way, the aluminium gets slack during the installation and the knee-point temperature is forced to be the temperature of installation. Thus, the installation process of the gap-type conductors is special and comprises several steps. For a few minutes, during the pre-sagging step, around 70 % of the sagging tension is applied only to the aluminium. In the final installation step, the whole sagging tension is applied only to the steel for a few hours, between 2 and 24 hours depending on the span. Due to this special installation process, the total strains of the aluminium ε_a and the core ε_{core} have different values.

Fig. 3 shows a diagram of the algorithm that calculates the creep developed by the aluminium during the installation of the gap-type conductors. The input values of the algorithm are the installation temperature θ_{inst}, the installation sagging tension T_{inst}, the percentage of the sagging tension $T_{a,inst}$ (%) the aluminium is expected to support during the pre-sagging step (usually 70 %) and the duration $t_{pre\text{-}sagging}$ of the pre-sagging step. The outputs of the algorithm are the maximum tension $T_{a,inst}^{\max}$ experienced and the deformation due to metallurgical creep $\varepsilon_{a,inst}^{mc}$ and geometrical settlement $\varepsilon_{a,inst}^{gs}$.

From the installation sagging tension T_{inst} and the percentage of the sagging tension $T_{a,inst}$(%), the aluminium tension $T_{a,inst}$ is calculated.

The metallurgical creep $\varepsilon_{a,inst}^{mc}$ is calculated as a function of the aluminium tension $T_{a,inst}$ the installation temperature θ_{inst} and the duration $t_{pre\text{-}sagging}$ of the pre-sagging step. The metallurgical creep in the aluminium follows the law given in (6), where K, Φ, β and μ are constant coefficients that represent the behaviour of the aluminium [14].

$$\varepsilon^{mc} = K \cdot e^{\Phi\theta} \cdot \sigma^\beta \cdot t^\mu \quad (6)$$

The deformation due to geometrical settlement $\varepsilon_{a,inst}^{gs}$ is obtained from the modified stress-strain curves of the aluminium. The strain in the stress-strain curve [16] is composed of three components related to the stress, the geometrical settlement and the metallurgical creep developed during one hour. To obtain directly the value of the geometrical settlement from the curve, this is modified removing the strain related to the metallurgical creep. For this purpose, the metallurgical creep at the stress-strain test temperature $\theta_{s\text{-}s}$ and different stress values σ is calculated by (6). Thus, a modified curve is obtained as it is shown in Fig. 4.

The total strain ε_a corresponding to the tension T_a at the installation temperature θ_{inst} is obtained from the modified aluminium stress-strain curve. The modified stress-strain curve corresponding to the stress-strain test carried out at the temperature $\theta_{s\text{-}s}$ is displaced in the strain axis in order to model the deformation $\varepsilon_{a,inst}^\theta$ due to thermal expansion (Fig. 5). This deformation $\varepsilon_{a,inst}^\theta$ is a function of the installation temperature θ_{inst}, the temperature $\theta_{s\text{-}s}$ of the stress-strain test and the coefficient of thermal expansion α_a of the aluminium (7). From the tension $T_{a,inst}$ and the area of the aluminium A_a, the aluminium stress $\sigma_{a,inst}$ is calculated and the strain ε_a is obtained from the aluminium stress-strain curve (Fig. 5). The strain due to tension $\varepsilon_{a,inst}^T$ is obtained from the aluminium stress $\sigma_{a,inst}$ and the elastic modulus of the aluminium E_a (8). The deformation due to geometrical settlement $\varepsilon_{a,inst}^{gs}$ is then calculated subtracting from the total strain ε_a the strain due to tension $\varepsilon_{a,inst}^T$ and the strain due to thermal expansion $\varepsilon_{a,inst}^\theta$ (9).

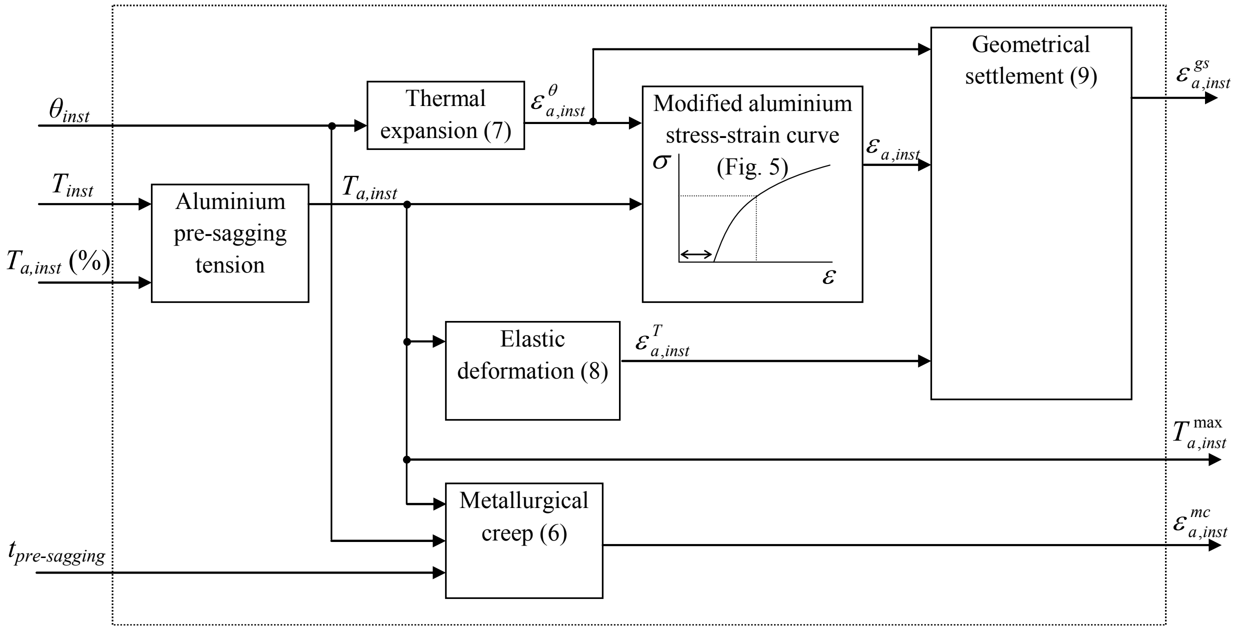


Fig. 3. Creep developed in the aluminium of a gap-type conductor during the installation

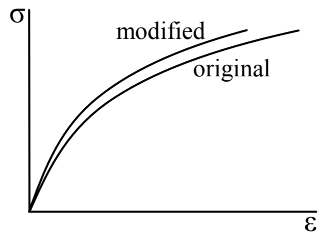


Fig. 4. Modified (1 h metallurgical creep removed) stress-strain curve

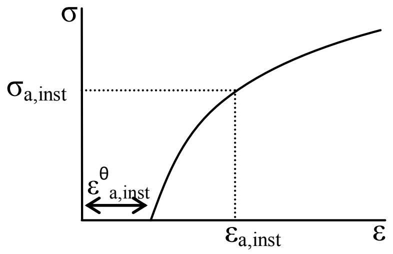


Fig. 5. Modified (1 h metallurgical creep removed) aluminium stress-strain curve

$$\varepsilon^{\theta}_{a,inst} = \alpha_a \cdot \left(\theta_{inst} - \theta_{s-s}\right) \tag{7}$$

$$\varepsilon^{T}_{a,inst} = \sigma_{a,inst} / E_a \tag{8}$$

$$\varepsilon^{gs}_{a,inst} = \varepsilon_{a,inst} - \varepsilon^{T}_{a,inst} - \varepsilon^{\theta}_{a,inst} \tag{9}$$

Fig. 6 shows a diagram of the algorithm that calculates the creep developed by the core during the installation of the gap-type conductors. The input values of the algorithm are the installation temperature θ_{inst}, the installation sagging tension T_{inst} and the time the core is at rest under installation sagging tension t_{rest}. The outputs of the algorithm are the maximum tension $T^{\max}_{core,inst}$ experienced and the deformation due to metallurgical creep $\varepsilon^{mc}_{core,inst}$ and geometrical settlement $\varepsilon^{gs}_{core,inst}$.

The metallurgical creep $\varepsilon^{mc}_{core,inst}$ is calculated as a function of the core tension T_{inst}, the installation temperature θ_{inst} and the time the core is at rest t_{rest}. The metallurgical creep in the core follows the law given in (6), where K, Φ, β and μ are constant coefficients that represent the behaviour of the core steel. These coefficients are different from those previously given for the aluminium.

The deformation due to geometrical settlement $\varepsilon^{gs}_{core,inst}$ is obtained from the stress-strain curves in a similar way to the aluminium (10-12). This process has been described above.

$$\varepsilon^{\theta}_{core,inst} = \alpha_{core} \cdot \left(\theta_{inst} - \theta_{s-s}\right) \tag{10}$$

$$\varepsilon^{T}_{core,inst} = \sigma_{core,inst} / E_{core} \tag{11}$$

$$\varepsilon^{gs}_{core,inst} = \varepsilon_{core} - \varepsilon^{T}_{core,inst} - \varepsilon^{\theta}_{core,inst} \tag{12}$$

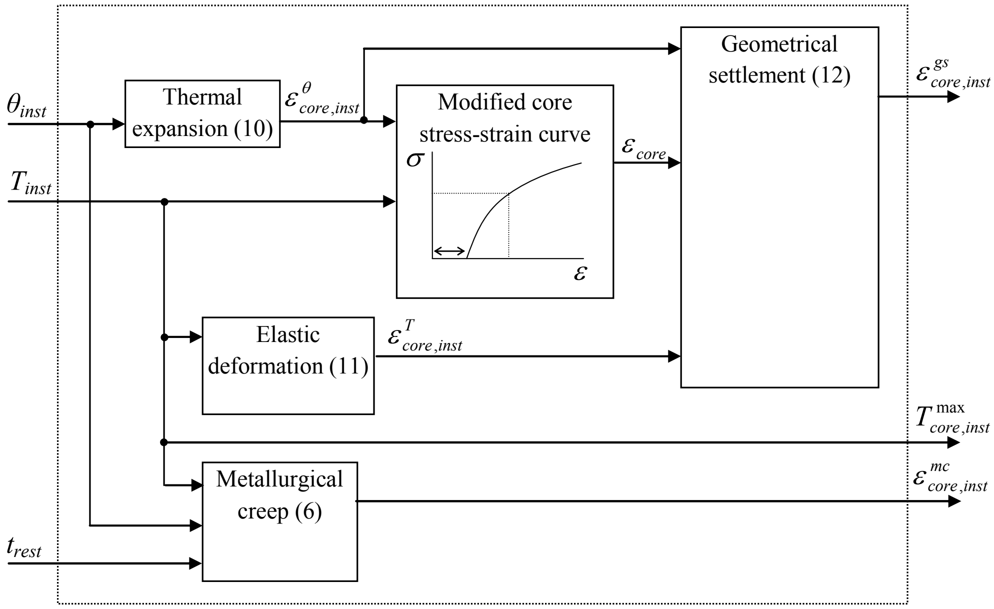


Fig. 6. Creep developed in the core of a gap-type conductor during the installation

V.2. Non gap-type Conductors

In the case of non gap-type conductors there is no relative displacement between the core and the aluminium during the installation of the conductor. Hence, the total strains of the conductor ε_c, the aluminium ε_a and the core ε_{core} have the same values. For this reason, the reference lengths of the core L_o^{core} and the aluminium L_o^a have the same values.

It is recommended to maintain the conductors at rest under the sagging tension T_{inst} for some hours in order to reduce the metallurgical creep during line operation. 12 hours is recommended and 48 hours is desirable.

The deformation due to geometrical settlement is independent from the duration of the period at rest. It depends on the sagging tension T_{inst} and the installation temperature θ_{inst}. Fig. 7 shows a diagram of the algorithm that calculates the geometrical settlement creep developed in the core $\varepsilon^{gs}_{core,inst}$ and the aluminium $\varepsilon^{gs}_{a,inst}$ during the installation. The deformation due to geometrical settlement is obtained from the stress-strain curves of the conductor. In this case, the total strains of the aluminium ε_a and the core ε_{core} have the same values. Fig. 8 shows the way these strains are obtained. Firstly, the core and aluminium curves are displaced in the strain axis to take into account the strain due to temperature $\varepsilon^{\theta}_{core,inst}$ and $\varepsilon^{\theta}_{a,inst}$. Then, from the tension T_{inst} and the area of the conductor *A,* the conductor stress σ_{inst} is calculated and the total strain ε_c is obtained from the conductor stress-strain curve. This strain value is the same as the aluminium ε_a and the core ε_{core} strains. Besides, the stress values of the aluminium σ_a and the core σ_{core} are calculated (13,14) from the virtual stress values $\sigma_a^{virtual}$ and $\sigma_{core}^{virtual}$ obtained from the virtual stress-strain curves of the aluminium and the core as it is shown in Fig. 8. From the stress values, the tension values are obtained (15,16).

$$\sigma_{a,inst} = \sigma^{virtual}_{a,inst} \cdot \frac{A}{A_a} \tag{13}$$

$$\sigma_{core,inst} = \sigma^{virtual}_{core,inst} \cdot \frac{A}{A_{core}} \tag{14}$$

$$T^{\max}_{a,inst} = \sigma_{a,inst} \cdot A_a \tag{15}$$

$$T^{\max}_{core,inst} = \sigma_{core,inst} \cdot A_{core} \tag{16}$$

While the conductor is at rest during the period t_{rest}, the deformation due to creep develops, the conductor stress value decreases and as a consequence the creep deformation developed afterwards decreases too. In other words, the creep that results from a constant stress value equal to the initial stress of the period is higher than the creep that actually develops. To take into account this fact, the calculation method follows the following steps.

Firstly, the initial reference length $L_{o,ini}$ is calculated taking into account the catenary conductor length L_g related to the installation tension T_{inst}, the creep strain due to geometrical settlement $\varepsilon^{gs}_{a,inst}$ calculated previously, the strain due to tension $\varepsilon^{T}_{a,inst}$ and the strain due to temperature $\varepsilon^{\theta}_{a,inst}$ (17). The metallurgical creep is not taken into account because it has not started developing yet.

$$L_{o,ini} = L^{core}_{o,ini} = L^{a}_{o,ini} = \frac{L_g}{\left(1 + \varepsilon^{T}_{a,inst} + \varepsilon^{\theta}_{a,inst} + \varepsilon^{gs}_{a,inst}\right)} \tag{17}$$

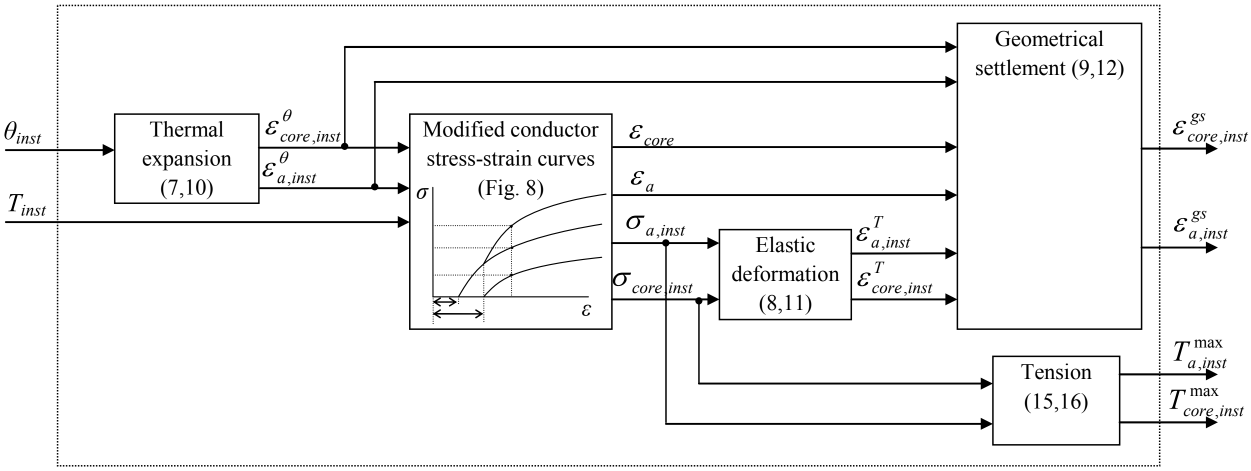


Fig. 7. Geometrical settlement creep developed in the core and the aluminium during the installation

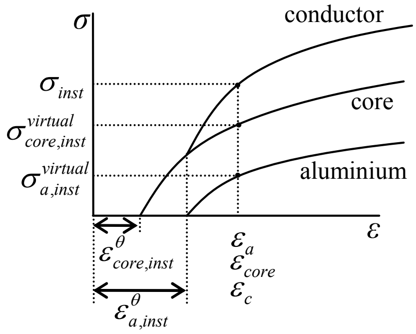


Fig. 8. Modified conductor stress-strain curve

Then, to calculate the metallurgical creep developed during the rest period t_{rest}, the method proposed by CIGRE [14] is used. This method divides the period of time t_{rest} in short sub-periods in which the change in stress and creep strain is small enough. Sub-periods in which the change in strain is around 20 μm/m are considered. The initial tension of the first sub-period is the installation tension T_{inst}. At the end of each sub-period, with the new creep values, the core and aluminium tension values are updated by the state calculation algorithm and these are used to evaluate the creep in the following sub-period. This process is carried out until the period is completed. As a result, the metallurgical creep developed by the core $\varepsilon^{mc}_{core,inst}$ and the aluminium $\varepsilon^{mc}_{a,inst}$, and the tension value T' at the end of the period are obtained.

At the end of the period, the conductor catenary length L_g' related to the final tension T' is higher than the initial conductor catenary length L_g related to T_{inst}, and for this reason the conductor is retensioned to the initial value. Hence, a portion of the conductor is removed. Thus, the new reference value L_o is lower than the initial reference value $L_{o,ini}$ and it is given by (18) taking into account the metallurgical creep $\varepsilon^{mc}_{a,inst}$ developed during this period.

$$L_o = L_o^{core} = L_o^a = \frac{L_g}{\left(1+\varepsilon^T_{a,inst}+\varepsilon^\theta_{a,inst}+\varepsilon^{gs}_{a,inst}+\varepsilon^{mc}_{a,inst}\right)} \quad (18)$$

The conductor can be pretensioned during the installation process causing the geometrical settlement of the conductor and decreasing the deformation developed during the operation. During the pretensioning period, the conductor is under a tension T_{pret} that is higher than the installation tension T_{inst}.

The calculation of the deformation due to geometrical settlement is carried out in a similar way to the calculation when there is no pretensioning. The only difference is the value of the tension. Thus, the calculation algorithm is that given in Fig. 7 but with T_{pret} instead of T_{inst}.

The calculation of the metallurgical creep is also carried out in a similar way to the calculation when there is no pretensioning. The only difference is that when the initial reference length $L_{o,ini}$ corresponding to the beginning of the period at rest is calculated, the creep developed during the pretensioning period is taken into account (19).

$$L_{o,ini} = \frac{L_g}{\left(1+\varepsilon^T_{a,inst}+\varepsilon^\theta_{a,inst}+\varepsilon^{gs}_{a,pret}+\varepsilon^{mc}_{a,pret}\right)} \quad (19)$$

VI. Creep Developed during the Operation

To calculate the creep developed during the operation, the line lifetime is divided in operation stages where the conductor temperature and the wind and ice loads are assumed to be constant. The method calculates sequentially each of the operation stages.

Fig. 9 shows the calculation of the creep in the operation stage i. The input values are the creep strain values $\varepsilon^{mc}_{core,i-1}$, $\varepsilon^{mc}_{a,i-1}$, $\varepsilon^{gs}_{core,i-1}$ and $\varepsilon^{gs}_{a,i-1}$ and the historical maximum tension values $T^{\max}_{core,i-1}$ and $T^{\max}_{a,i-1}$ at the end of the stage (i-1). The output values are the same but at the end of the stage *i*.

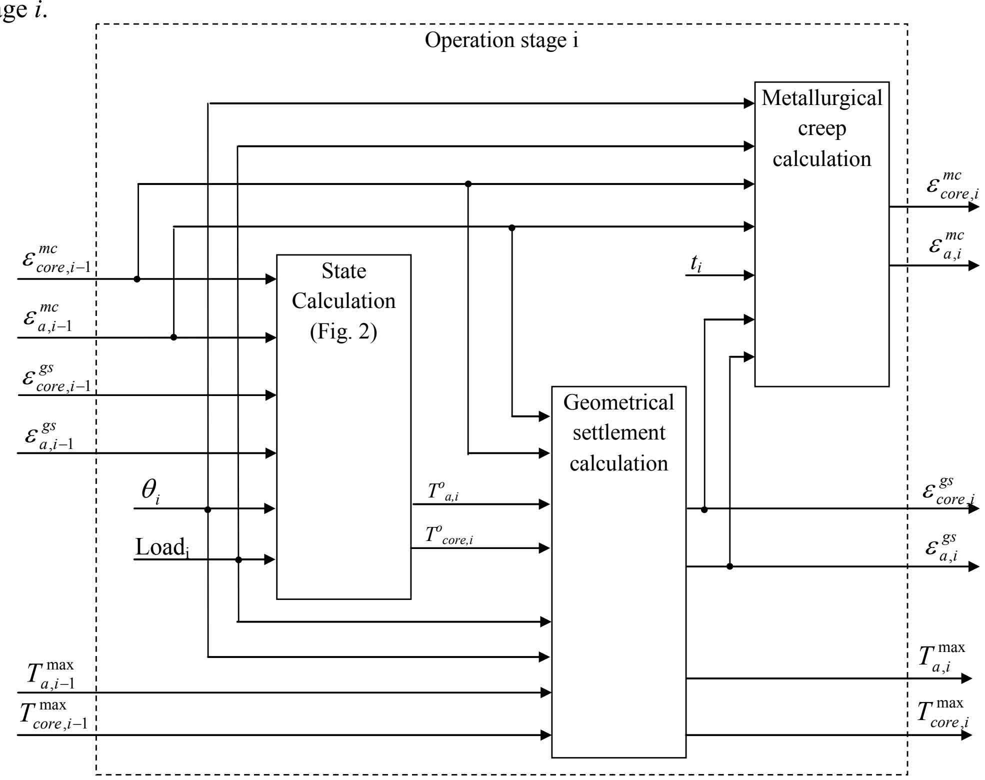


Fig. 9. Creep calculation in the operation stage i

In a first step, the initial tension values $T^{o}_{a,i}$ and $T^{o}_{core,i}$ corresponding to the creep at the end of the stage (*i*-1) and the temperature and the load of the stage *i* are calculated by the state calculation algorithm. From these tension values the geometrical settlement is calculated first and the metallurgical creep is calculated afterwards.

The initial tension values $T^{o}_{a,i}$ and $T^{o}_{core,i}$ of the stage *i* are compared with the historical maximum tension values $T^{\max}_{core,i-1}$ and $T^{\max}_{a,i-1}$. If they are lower, the creep strain due to geometrical settlement and the maximum historical tension values do not change. If the initial tension value is higher, the creep strain due to geometrical settlement and the maximum historical tension values are recalculated. Fig. 10 shows the calculation of the geometrical settlement of the aluminium $\varepsilon^{gs}_{a,i}$. The total strain $\varepsilon_{a,i}$ is given by (20) and the geometrical settlement of the aluminium $\varepsilon^{gs}_{a,i}$ is calculated by the equation (21). The calculation for the core is carried out in a similar way.

$$\varepsilon_{a,i} = \frac{L_a}{L^a_o} \tag{20}$$

$$\varepsilon^{gs}_{a,i} = \varepsilon_{a,i} - \varepsilon^{T}_{a,i} - \varepsilon^{\theta}_{a,i} - \varepsilon^{mc}_{a,i-1} \tag{21}$$

The load due to wind or ice affects the span geometry whereas the conductor behaviour is affected by the conductor temperature θ_i. The algorithm iterates the tension value T_c until the difference between the span geometry length L_g and the conductor length L_c is below a threshold value. The conductor is characterised from the stress-strain curves of the core and the aluminium. These curves have been modified as it has been described above (Fig. 4). Besides, below the maximum historical tension value, the behaviour of the aluminium and the core is linear and is a function of the elastic modulus (Fig. 11).

To make the calculation of the metallurgical creep developed during the stage *i*, the period t_i is divided in several sub-periods where stress and temperature values are considered to be constant. As it has been mentioned before, sub-periods in which the change in strain is around 20 μm/m are considered. To evaluate the creep during the first sup-period, the core and aluminium stress values are calculated by the state calculation algorithm from the geometrical settlement calculated for the stage *i*, the metallurgical creep at the end of the stage (*i*-1) and the temperature θ_i. At the end of each sub-period, the core and aluminium tension values are updated. As a result, the metallurgical creep developed by the core $\varepsilon^{mc}_{core,i}$ and the aluminium $\varepsilon^{mc}_{a,i}$ are obtained.

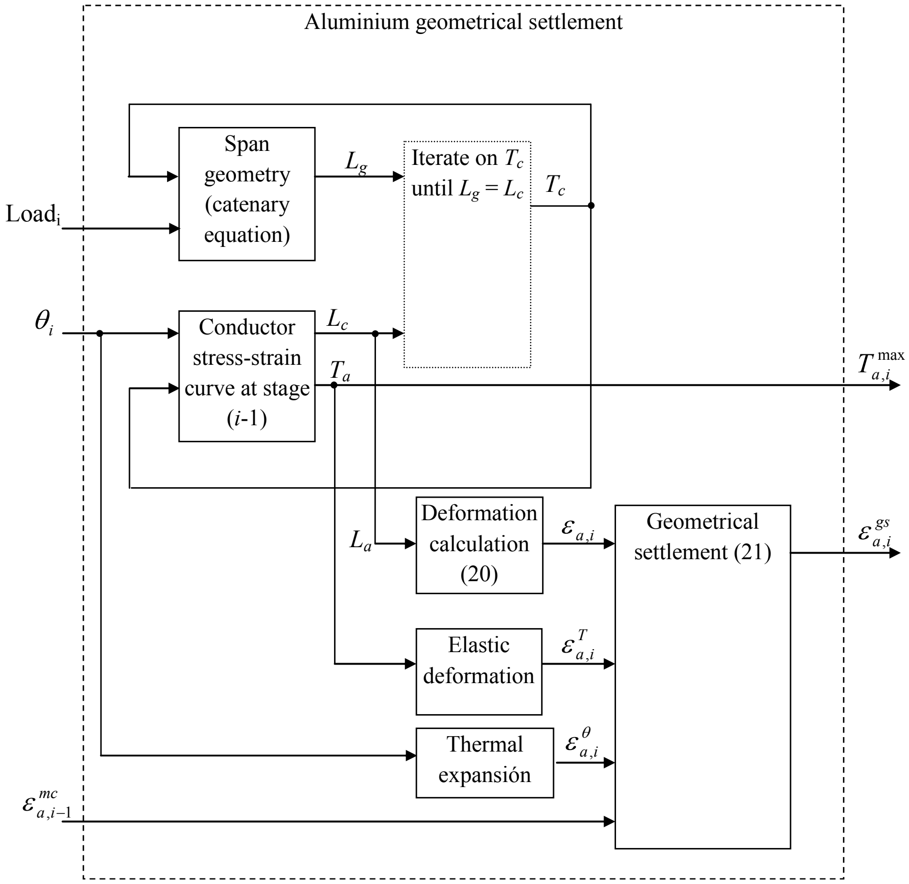


Fig. 10. Aluminium geometrical settlement calculation in the operation stage *i*

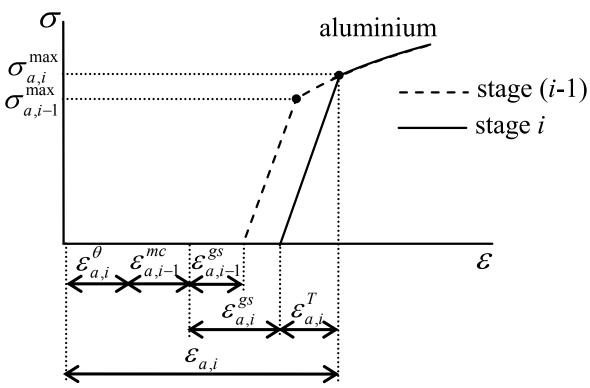


Fig. 11. Stress-strain curve of the aluminium at the end of the stages (i-1) and i

VII. Application Example

The described method is applied in an application example. The span length is 350 m and the conductor is the ZTACIR Hen. The installation tension is 1681 kg (15 % RTS) and it has been carried out at 15 ºC.

The maximum tension conditions evaluated are those established in the Spanish regulation. The maximum tension condition in Spanish lines considers ice load at -20 ºC. Besides, a high temperature operation of the line is expected. In order to model the effect of different operation temperatures, the conductor temperature is assumed to be 15 ºC for 6 months, 30 ºC for 3 months, 60 ºC for 2 months and 120 ºC for one month every year.

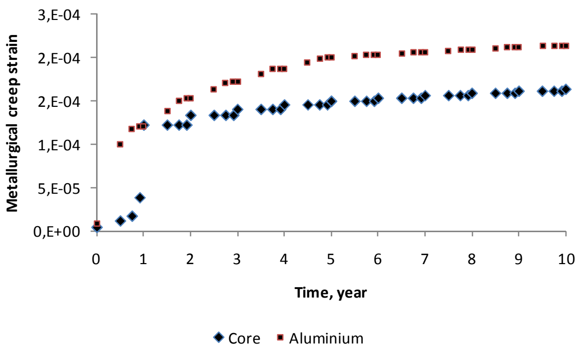
VII.1. Creep Developed during the Installation

The ZTACIR conductor is a non gap-type conductor and for this reason the algorithm described in sub-section V.2 is applied. Thus, the geometrical settlement is calculated with the algorithm given in Fig. 7 The inputs are the installation temperature θ_{inst} (15 ºC) and tension T_{inst} (1681 kg). The obtained results are the geometrical settlement of the core $\varepsilon_{core,inst}^{gs}$ ($6.54\cdot10^{-6}$) and the aluminium $\varepsilon_{a,inst}^{gs}$ ($1.7\cdot10^{-4}$), and the historical maximum tension of the core $T_{core,inst}^{\max}$ (812 kg) and the aluminium $T_{a,inst}^{\max}$ (869 kg). For the metallurgical creep calculation, the period the conductor is at rest t_{rest} is assumed to be one hour. The obtained results are the metallurgical creep developed by the core $\varepsilon_{core,inst}^{mc}$ ($3.55\cdot10^{-6}$) and the aluminium $\varepsilon_{a,inst}^{mc}$ ($8.5\cdot10^{-6}$). As the ZTACIR is a non gap-type conductor, the reference lengths L_o^{core} and L_o^{a} given by the equation (18) have the same value (350.65 m). They are obtained from the catenary length of the installed conductor L_g (350.89 m).

VII.2. Creep Developed during the Operation

The creep developed for 10 years is calculated. The first step is the definition of the operation stages. For this purpose, in addition to the duration of the stage, the conductor temperature and the wind and ice loads have been defined. Each year is divided in 4 stages of different length (6, 3, 2 and 1 month) where different conductor temperatures are assumed (15 ºC, 30 ºC, 60 ºC, 120 ºC). Besides, after 5 years in operation an ice load condition is assumed at -20 ºC. Hence, 41 stages are calculated. The algorithm described in Fig. 9 is applied to each of the stages.

Fig. 12 shows the evolution of the creep during the 10 year period. The first 5 years there is an increase of the metallurgical creep that decreases the tension value. As a consequence, the tension values are below the historical tension values and no geometrical settlement is developed. When the ice load occurs new historical tension values are obtained for the core $T_{core}^{\max}$ (1494 kg) and the aluminium $T_{a,inst}^{\max}$ (2109 kg). Hence, geometrical settlement is developed and it mainly affects the aluminium. During the last 5 years the metallurgical creep develops but much slower than at the beginning.



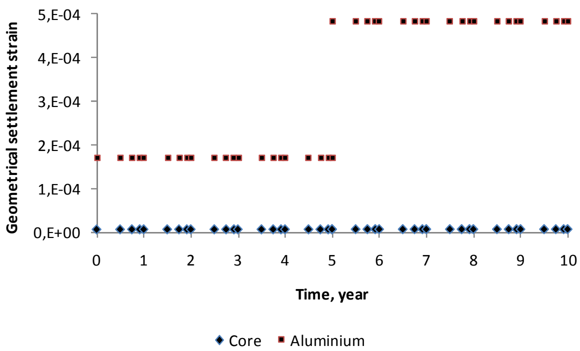


Fig. 12. Creep developed during the operation

VIII. Conclusion

A complete description of a sag-tension calculation algorithm developed by the authors has been presented including a calculation example. The relation between the creep development and the factors that influence it such as the installation process and the operation conditions during the line lifetime is described step by step. The algorithm is characterised by the creep sequential calculation. Thus, the creep developed in previous stages influences the creep developed in subsequent stages. Two periods are differenced in the creep development: the installation period and the operation period.

The method is suitable for modelling the conductor behaviour including the multiple stages during the line lifetime. Besides, it allows a detailed modelling of the installation process. The described algorithm takes into account the interaction between the metallurgical creep and the geometrical settlement. Thus, the method calculates the installation tension for new lines taking into account the expected conditions during the line lifetime. Furthermore, the method is also useful for the calculation of the current state of lines in operation whose historical operation conditions are known.

The method has several advantages over other methods proposed in literature. Some advantages of the developed method over the graphical method are related to the creep stages (several stages are calculated sequentially and there is interaction between metallurgical creep and creep due to wind or ice loads), the gap-type conductor installation (the aluminium creep is modelled and the steel is assumed to be at rest during a configurable duration), the high temperature metallurgical creep (independent core and aluminium creep calculation and coefficients as a function of the conductor type) and the pretensioning during the installation (it is included in the calculation method). Some advantages over the strain summation method are the independent core and aluminium reference lengths for gap-type conductors and the detailed calculation of the creep developed during the installation.

Acknowledgements

This work is financially supported by the University of the Basque Country UPV/EHU under project EHU09/18, the Ministerio of Ciencia e Innovación under project DPI2009-08454 and the Eusko Jaurlaritzako Hezkuntza, Unibertsitate eta Ikerketa Saila (Euskal unibertsitate-sistemako ikerketa-taldeak Ref. IT532-10).

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