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Analysis of the tensile response of a stranded conductor using a 3D finite element model

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ABSTRACT

A 3D finite element modelling approach is proposed to investigate the axial force-elongation behaviour of a stranded conductor used for high voltage overhead lines. An all aluminium alloy conductor (AAAC), a four-layer conductor, is analysed based on the stress-strain response measured for individual wires. The aim of the model is to reproduce the complex deformation mechanisms and non-linearities associated with the helical shape of the wires, their contact interactions and the residual stress state from the manufacturing process. The latter is included in the model through a simulation of the stranding procedure. Simulations of the tensile response are compared to corresponding measurements. The results demonstrate improved predictive capabilities of the finite element model when compared to analytical formulae, and show that inelastic elongation at load levels significantly below the nominal yield strength of the constituent wires can be rationalized when residual stresses from the manufacturing process are included in the calculation.

1. Introduction

An electrical power system mainly comprises of power plants and the electrical grid. The latter connects the producers of electricity with the customers. With market liberalization, power is produced where the costs are low and not necessarily in the vicinity of consumption. The distance between power production and consumption can therefore become large. The superposition of all the power supplies and the increase in demand for electricity [1] result in a highly loaded transmission grid, which hence requires intensive research for its optimal use. The optimum condition lies in exploiting the infrastructure in terms of highest possible transmission capacity while securing the most reliable and safe grid operation. Further, the lifetime of the components such as the conductors (cables carrying the current) can be extended with corresponding maintenance procedures. The short and long term mechanical response of conductors to tensile loads represents,

together with the definition of critical spans [2] and new temperature monitoring approaches [3], an essential input for these tasks, as it is needed for the calculation of the sag and corresponding ground clearance and, in certain cases, for the determination of the required tensile load applied for line retightening [4].

A new modelling approach was developed in this work to predict the axial elongation of a stranded conductor when subjected to tensile loads. The numerical model used for this purpose not only reproduces the 3D geometry of the conductor and the non-linear time dependent stress-strain behaviour of its material, but also accounts for the influence of the manufacturing process and the corresponding residual stress distribution within the wires.

Several analytical models are proposed in the literature to describe the response of stranded conductors to bending or tensile loads, [5–9], accounting for different mechanisms of wire deformation and for geometrical effects influencing the axial stiffness of the conductor. Despite significant progress in the finite element representation of helical structures, cables and stranded conductors [10–12], none of the models proposed so far have focused on the non-linear axial force-elongation behaviour of overhead conductors, the influence of elastic-viscoplastic material behaviour, and the effect of internal stresses generated during manufacture.

Nomenclature

A, A_i	Cross section of a wire, cross section of wire in layer i	r	Wire radius
A_i, A'_i	Constants in creep law	R	Universal gas constant or helix radius of the centre of the wire
E	Elastic modulus	$R_{p0.2}$	0.2% proof strength
F	Axial force	t	Time
G	Shear modulus	T, T_K	Temperature in °C, temperature in K
k	Stiffness geometrical factor	u_r, u_φ, u_z	Displacement in radial, tangential and axial direction
n_i	Stress exponents in creep law	β_i	Helix angle of wire of layer i , zero for wire parallel to the conductor axis
n'	Hardening exponent in Ramberg–Osgood stress-strain equation	ε	Strain
n_L	Number of layers wound around the core in a conductor	ε_{cr}	Creep strain
q_i	Number of wires in layer i	κ_{EE}	Axial stiffness
Q_i, Q^*_i	Activation energy for creep, $Q_i^* = Q_i/R$	ν	Poisson's ratio
		σ	Stress
		σ_0	Stress normalizing constant in creep law

This paper describes the 3D finite element model of a 4 layer Aldrey all aluminium alloy conductor (AAAC). The force-elongation behaviour predicted by the model is compared with the results of corresponding analytical formulae, and with observations from tensile tests. The influence of specific model parameters is then analysed and discussed. Permanent elongations were observed in tensile experiments far below the level of the nominal yield stress for the material. Accounting for internal stresses associated with the manufacturing process allows, in the last step of the present work, to better understand these observations and provides a more accurate description of the mechanical behaviour of the conductor.

2. Material model, conductor geometry and testing

2.1. Constitutive model

In the literature, mechanical and creep properties for materials with similar composition compared to Aldrey are presented, e.g. [13,14]. These data were used for general comparison, but the present model is based on own measurements performed on single wires made from the same batch of wires used for the manufacture of the stranded conductor to be used in the benchmark tests described later (i.e. E-AlMgSi, manufactured from the aluminium alloy AA6101, according to [15,16]). Depending on the objective of the simulation, a purely elastic or an elastic-plastic model was implemented in the FE code. The elastic-plastic model corresponded to a Ramberg–Osgood formulation [17] according to Eq. (1), which was shown to provide an excellent representation of the experimental data. The parameters obtained from the fit on own performed tests at room temperature are given in Table 1.

$$\varepsilon = \frac{\sigma}{E} + 0.002 \cdot \left(\frac{\sigma}{R_{p0.2}} \right)^{n'} \quad (1)$$

The material exhibits non-negligible time dependent deformation, even at room temperature, leading to creep strain accumulation and stress relaxation. In order to account for these inelastic effects, a creep model was developed by three of the authors, as described in detail in [18,19]. Model equations and corresponding parameters are reported in Eq. (2) and Table 2,

respectively. Note that two different parameter sets are used, depending on the stress level, between which a linear interpolation is applied. The creep model was implemented with a strain hardening rule and shown to well represent also the relaxation behaviour of single wires [19].

$$\varepsilon_{cr} = A'_1 \cdot e^{-\frac{Q'_1}{T_K}} \cdot \left(\frac{\sigma}{\sigma_0} \right)^{n_1} \cdot \log \left(1 + A_2 \cdot \left(\frac{\sigma}{\sigma_0} \right)^{n_2} \cdot t \right) + A'_3 \cdot e^{-\frac{Q'_3}{T_K}} \cdot \left(\frac{\sigma}{\sigma_0} \right)^{n_3} \cdot t \quad (2)$$

2.2. Conductor geometry

The conductor analysed in the present work was a four-layer all aluminium alloy conductor defined as 551-AL3 according to [20]. The conductor comprised 61 wires distributed in four layers wound around the core wire. The wires (made of E-AlMgSi) had a diameter of 3.39 mm. The corresponding total cross section was 551 mm². The wires were wound in a helical shape with lay angles of 9.1° (layer 1), 11.3° (layer 2), 13.5° (layer 3) and 14.8° (layer 4) in alternating directions, see Fig. 1.

2.3. Set-up for conductor tensile test

Conductor tensile tests were performed in a specifically designed loading frame which enabled tensile forces of up to 100 kN to be applied to conductor lengths of up to 7 m (Fig. 2). The load line was orientated horizontally. The load was applied by continuous horizontal displacement of the anchoring points using a screw jack arrangement, and monitored using a Class 1 load cell. Elongation was measured over a gauge length of 5 m using a carbon fibre tube arrangement fixed at one end and suspended at three points. The other end of the tube was attached to a linear voltage displacement transducer which was also fixed to the conductor. The carbon fibre tube, acting as rigid body, allowed the extensometer to measure the change in length between the two fixations. The consequent Class 0.5 extensometer arrangement also provided the means for creep tests to be conducted at elevated temperature and for long durations.

The horizontal orientation allowed easier control of the conductor mounting and boundary conditions. In addition, at low tensile forces, the conductor specimen displayed a non-negligible sag (e.g. about 2 cm at 2 kN). The sag was reduced by increasing the axial force which affected the displacement in the horizontal direction and thus the apparent nominal elongation. This effect reduced with increasing load and could be neglected for axial forces higher than 15 kN, as shown through a comparison of

Table 1
Coefficients of the Ramberg–Osgood model for the wire material (Eq. (1)).

E MPa	$R_{p0.2}$ MPa	n' [dimensionless]
63,500	283	46.6

Table 2

Parameter sets for the creep model, see Eq. (2).

Stress [MPa]	A'_1 [%]	Q^*_1 [K]	n_1 [dimensionless]	A_2 [1/h]	n_2 [dimensionless]	A'_3 [%/h]	Q^*_3 [K]	n_3 [dimensionless]	σ_0 [MPa]
< 130	$3.44 \cdot 10^3$	4000	1.1	9.04	0	$1.38 \cdot 10^5$	6600	6.4	280
> 170	$5.21 \cdot 10^3$	3550	2.9	155	4.7	$1.84 \cdot 10^4$	6800	2.7	280

Fig. 1. Structure (left) and whole conductor segment (right) of the analysed four layer AAAC conductor. **Fig. 2.** General view of the test arrangement (left), the carbon fibre tubes for elongation measurement are visible. Right: strain gauges were applied on the external layer of the conductor for local strain measurements.

apparent nominal strain and local strain measured by strain gauges. For this reason, comparison between model prediction and measurement were limited to the force range > 15 kN, and the corresponding strains were based on the reference configuration at 15 kN.

3. Numerical and analytical models

3.1. Finite element model

As evident from Fig. 1, the helical geometry of a conductor was quite complex and its exact representation in a 3D finite element model could lead to very demanding computations. There was a multitude of contacts in the radial and circumferential directions. Every single layer had a different periodicity along the axis of the conductor, and the full structure exhibited a repetition period of > 1 km. It was therefore not possible to implement strict periodicity boundary conditions while keeping the numerical problem within a reasonable size in terms of computational costs. The minimum length of the conductor segment to be represented in the model was provided by the radial contacts, in that an interaction with two different wires of the next layer (below and above) had to be guaranteed for each wire. A model length of 28 mm was selected for the present investigations as a compromise between accuracy and duration of each simulation. This length provided a sufficient number of repeated radial contacts between the

different layers and led to a calculation time of few hours for the simulation of a tensile test. It is noted that the simulation of the production process (see Section 4) could take > 100 hours. Calculation times refer to simulations on clusters using 4 CPUs and the software Abaqus 6.10 [21].

In Fig. 3, the FE model with its mesh is presented. It consists of 51,240 prism elements and 610 brick elements, both with linear interpolation, and a total of 44,652 nodes (732 nodes per wire). The level of mesh refinement was selected to minimize the influence of spatial discretization on the results of all simulations. By comparison, Jiang et al. [11] used 6198 nodes to represent a smaller conductor corresponding roughly to 320 nodes per conductor wire. Contacts could be defined as tied or as sliding with friction. The model and the procedure for simulating the production process were originally presented in [22], and further optimized for the present applications. In contrast to other finite element procedures [7–9], the present modelling approach allows the representation of any conductor size, i.e. with any number of layers, and, for the first time, also consideration of the residual stresses due to the manufacturing process.

The axial periodicity of the model was obtained through equations connecting the displacement of the two opposite faces of each wire. Since these faces were placed at different circumferential positions, this approach could be applied only for axisymmetric load cases. Each wire was fixed in an axial direction at one node in the middle cross sectional plane of the model in order to avoid rigid body displacements. The two faces of each

Fig. 3. FE mesh of a representative segment of a four-layer conductor.

wire were then linked together, node by node, with equations prescribing identical displacements in the radial and circumferential directions. It is noted that in general a coupling between tension and torsion is present in a helical structure, leading to wire rotation in the circumferential direction upon tensile loading. The condition of identical circumferential displacement applied for the following calculations was associated with the constrained rotation present at the wedge clamps of the tensile experiment. The axial elongation was prescribed in that the displacement in the axial direction had to differ by a factor c on the two faces, and this factor increased during the simulation. These conditions were formulated for each corresponding pair of nodes on faces 1 and 2:

$$\begin{aligned} u_r^1 - u_r^2 &= 0 \\ u_\phi^1 - u_\phi^2 &= 0 \\ u_z^1 - u_z^2 &= c \end{aligned} \quad (3)$$

As described in Section 3.4., simulations were performed with different friction coefficients leading to differences in the axial stiffness in the order of magnitude of $< 0.6\%$ between the 'contact tied' condition and the simulation with very low friction (coefficient value: 0.05). Hence, most of the following simulations were performed with tied contact, which led to shorter computation time.

3.2. Analytical models

Ghoreishi et al. [12] compared nine different analytical models with different levels of complexity. Their conclusion was that in the case of small lay angles, as the ones present in the specific conductor analysed in the present work, all the models predicted a similar axial stiffness and provided good agreement with the corresponding FE simulation. The evaluation (analytical formulae and FE model) was performed for a one-layer conductor, thus strongly simplifying the radial interaction, limited to the cylindrical core wire. Based on the analysis in [12], one model was selected and evaluated here for the case of axial stiffness of a 4-layer conductor, i.e. the model of Sathikh et al. [5], considering deformation components due to axial, bending as well as torsional load on each single wire. Furthermore, the model of Feyrer [6], not considered in [12], was analysed since it considered the influence of the lateral contraction (Poisson's effect) on the axial elongation of the conductor.

The axial stiffness of a single layer was calculated in [5] as:

$$\kappa_{\epsilon\epsilon} = E_c A_c + q \left[EA \cos^3(\beta) + \left(G \frac{\pi r^4}{2} \sin^2(\beta) + E \frac{\pi r^4}{4} \cos^2(\beta) \right) \cdot \frac{\sin^4(\beta) \cdot \cos(\beta)}{R^2} \right] \quad (4)$$

Fig. 4. Comparison of measured axial force vs. elongation and corresponding calculations with the (initially stress free) FE model and the analytical models. Measurement performed with a Class 1 load cell and a Class 0.5 extensometer arrangement.

In Eq. (4) q represents the number of wires in the layer, R is the radial position of the wire centre, β is the lay angle between the wire axis and the conductor axis, E is Young's Modulus, G is the shear modulus, A is the cross section surface of the wire and r is the radius of the wire. The subscript c refers to the core. This model was then extended by the authors for the case of a multi-layer conductor (with n_L Layers) by superposition of the stiffness of each layer i . For the present case of identical wires, the total stiffness can be expressed according to Eq. (5):

$$\kappa_{\epsilon\epsilon} = EA + \sum_{i=1}^{n_L} q_i \left[EA \cos^3(\beta_i) + \left(G \frac{\pi r^4}{2} \sin^2(\beta_i) + E \frac{\pi r^4}{4} \cos^2(\beta_i) \right) \cdot \frac{\sin^4(\beta_i) \cdot \cos(\beta_i)}{R_i^2} \right] \quad (5)$$

The model by Feyrer [6] provided the axial stresses σ_z in each single wire when the conductor was loaded in tension with the total force F .

$$\sigma_{zk} = \frac{\frac{\cos^2(\beta_k)}{1 + \nu_k \sin^2(\beta_k)} E_k}{\sum_{i=0}^{n_L} \left(\frac{q_i \cos^3(\beta_i)}{1 + \nu_i \sin^2(\beta_i)} E_i A_i \right)} F \quad (6)$$

In Eq. (6), q_i represents the number of wires in the layer i , E is Young's modulus, ν is Poisson's ratio, β is the lay angle, A is the cross section surface of the wire. The subscripts k and i refer to the specific layer. While the model does not consider wire bending, it accounts for the radial contraction due to the Poisson's effect. The stress in the core wire is:

$$\sigma_{z0} = \frac{E_0}{\sum_{i=0}^{n_L} \left(\frac{q_i \cos^3(\beta_i)}{1 + \nu_i \sin^2(\beta_i)} E_i A_i \right)} F \quad (7)$$

Since the lay angle for the core is 0, the strain of the wire corresponds to the conductor strain. Based on a uniaxial stress elastic response ($\sigma = E \cdot \epsilon$), the relationship between the force F and the conductor strain ϵ can be calculated. For the case of identical wires (same material and geometry) in the whole conductor, the corresponding axial stiffness can be calculated as

$$\kappa_{\epsilon\epsilon} = \sum_{i=0}^{n_L} q_i \frac{\cos^3(\beta_i)}{1 + \nu \sin^2(\beta_i)} EA \quad (8)$$

3.3. Comparison of tensile responses

The analytical models address different aspects of the conductor behaviour but they return very similar axial stiffness values, as

shown in Fig. 4. The corresponding FE calculation leads to a global stiffness lower by about 5% when compared to the analytical models, see Fig. 4. This difference can be attributed to two main factors: (i) the realistic representation of radial contacts in the 3D FE model allows for larger bending deformation of each wire when compared to the analytical models, which assume radial contact between two cylindrical bodies; (ii) radial contraction of the conductor, if considered, is related only to the Poisson's ratio of the material in the analytical model, [3–4], while the 3D FE model accounts for the influence of the radial compression exerted by each layer on the more internal ones. The influence of the latter aspect can be assessed with a simple comparison between two simulations: the first one concerns a single layer conductor and the second a four-layer conductor. In both cases an axial elongation is imposed and the load carried by the first layer is compared. The simulation with a single layer conductor leads to a 5.5% higher load in the first layer as compared to the corresponding case of the four-layer conductor. This indicates that the radial pressure exerted by the outer layers is significantly reducing the axial stress for the same level of elongation. A lower stiffness in the FE calculation compared to the analytical model was also obtained by Jiang et al. [11].

The measured conductor response reveals a lower stiffness compared to analytical models and FE results. The comparison shows that the FE calculation represents the unloading stiffness almost perfectly, but it fails to represent the permanent elongation observed in the experiment. The FE model assumed a stress free initial configuration and no plastic deformation occurred during the simulation. Inelastic effects might be attributed to manufacturing tolerances and corresponding geometrical settlements, as well as to the internal stress distribution generated during the production process. The latter aspect can be included in the finite element analysis, as shown in Section 4.

3.4. Influence of input parameters on the FE model prediction

A conductor model with a length of 28 mm was used for the calculations in Section 3.3 and in Section 4. In order to investigate the influence of the segment length on the calculated axial response, a longer model was created with a total length of 150 mm, see Fig. 5. The value of the friction coefficient for contact interactions, the spatial discretization and the element formulation were included in this analysis. The calculations assumed linear elastic material behaviour and, in order to reduce the duration of the calculations, a two-layer conductor was taken as reference. The parameters of the reference model are indicated in Table 3. The results are compared with respect to the axial stiffness through a representative coefficient k , used to compare the overall stiffness of each calculation with that of the reference model:

$$F = k \cdot E \cdot A \cdot \varepsilon \quad (9)$$

where E is Young's modulus of the material, A is the cross section of the conductor and ε is the nominal axial strain of the conductor. The coefficient k would be unity for the case of straight wires (lay angle = 0).

Fig. 5. FE mesh of a two-layer conductor in the case of the 150 mm long model.

Table 3
Parameter of the reference model.

Model length	Element type	Element length	Friction	Number of layer
28 mm	linear elements (brick and prism)	3 mm	tied	2+ core

Table 4

Influence of friction, on the axial stiffness of a 28 mm long model (2 layer conductor, linear elements with a length of 3 mm).

Friction coefficient μ	k	Difference from reference
0.05	0.9409	–0.57%
0.10	0.9411	–0.55%
0.20	0.9415	–0.45%
tied	0.9463	–

Table 5

Influence of discretization and element formulation (28 mm long model of a 2 layer conductor with a friction coefficient of 0.1).

Element length (mm)	Element formulation (mm)	k	Difference from reference
3	Linear	0.9411	–
1.5	Linear	0.9387	–0.26%
1.5	Quadratic	0.9459	0.50%

For the reference model, $k=0.9463$. The stiffness only changes by less than 1% for a model corresponding to the reference case but with a total length of 150 mm ($k=0.9513$), confirming the validity of the selected model length. This comparison was made also for the case of a four layer conductor and the difference was the same ($< 1\%$).

Regarding the effect of the friction coefficient μ , the results reported in Table 4 demonstrate a rather modest influence of this parameter for the axial load case.

Table 5 shows the influence of spatial discretization (shorter, i.e. 1.5 mm, vs. longer, 3 mm, elements) and element formulation (linear vs. quadratic interpolation function). As expected, shorter elements lead to lower stiffness as compared to the reference case. The shorter quadratic elements lead to a higher stiffness and this effect is attributed to the resulting larger contact surface for these elements thus leading to slightly reduced bending deformation of each wire. However, in all cases the variation in k is less than 1%, thus confirming the reliability of the reference model.

4. Internal stresses from the manufacturing process

The wires received a precipitation hardening heat treatment after being wound on bobbins (typical diameter: 25 cm). Following this heat treatment, the internal stress level in the wires may be assumed to be negligible. During manufacture, the wires experience significant deformation on the path from the circular shape on the bobbin to the helical shape on the conductor. As consequence of this complex deformation history and the associated inelastic strains, residual stresses are present in the conductor after manufacture. Due to room temperature viscoplastic effects, stress relaxation occurs during storage, reducing the magnitude of the residual stresses. When the conductor is ultimately loaded in tension, internal stresses lead to local plastification, even for a

Fig. 6. Sketch and image from the production process of a stranded conductor. (i) production arrangement leading to minimum residual stress case, (ii) production arrangement leading to the maximum residual stress case.

Fig. 7. Axial stress after stranding process (upper) and after storage (lower) for the minimum stress (left) and maximum stress case (right).

nominal stress level far below the yield strength of the material. These effects can be accounted for by 3D FE calculations.

The production process includes complex operations which cannot be directly simulated. As described by Rawlins [23], the wires, wound on spools, are pulled off the bobbin to a straight line and subsequently placed on the conductor through a tortuous path, see Fig. 6. In this process the bobbin rotates around the conductor defining the lay angle with their angular speed. In order to minimize torsional shear deformation of the wires, the bobbins also rotate on their own axis, leading to a variable orientation of the wire with respect to the helix around the conductor.

As a simplified representation of the complex deformation process, in the simulation the wires are first straightened and then either (i) bent back around the existing conductor in a helical manner with a curvature consistent with the original on the bobbin (*minimum residual stress*) or (ii) bent over to a helix with opposite curvature compared to the reference configuration on the bobbin (*maximum residual stress*), see Fig. 6. These two cases may be considered as extreme conditions, limiting the spectrum of actual circumstances (and internal stress states) existing along the length of the conductor. The residual stresses resulting from the minimum and maximum cases can be seen in Fig. 7.

4.1. Prediction of tensile response

Following manufacture, conductors are typically stored on drums at room temperature. As previously stated, Aldrey creeps and residual stresses relax at room temperature. Simulation of the storage phase indicates that residual stresses relax below 200 MPa, as shown in Fig. 7. Calculation of the tensile loading of the conductor, as applied in the performed test, follows as the next step, leading to further inelastic (time dependent and time independent) strain accumulation. The resulting force-strain curves at room temperature are shown in Fig. 8, in which the cases of assumed maximum and minimum internal stresses are compared with the measured tensile response.

The level of permanent elongation measured after unloading is between the predicted values assuming the maximum and minimum internal stress conditions. This result indicates that inelastic effects can be attributed to internal stresses and their influence can be assessed with the proposed finite element model. The case of maximum internal stress reproduces best the loading curve measured in the experiment, while the stiffness is overestimated by simulation of the minimum internal stress case. Interestingly, the latter case (leading to a nearly elastic response) generates a larger stiffness when compared to the stress free FE model (see

Fig. 4). This difference, in the order of 1%, is related to the different geometry obtained after the simulation of the stranding process. In fact, the stress free simulation assumes an ideal geometry where the wires follow the exact helix shape, while the manufacturing process simulations consider that the wires are pulled and radially compressed, see Fig. 6. This way the shape of the wire axis between successive radial contacts follows a straight line, thus reducing the corresponding bending compliance. The precise amount of this radial compression depends on the geometrical tolerances of the components used during the manufacturing process and the effect on the wire shape should be analysed with a corresponding parametric study. The radial conductor geometries associated with the maximum stress condition assumed in Fig. 6 and the stress free model may respectively be considered as limiting cases of maximum and minimum wire straightening.

4.2. Prediction of progressive permanent elongation in cyclic loading

In the CIGRE Green Book on Overhead Lines [4], the typical response of a conductor to increasing cyclic tensile loads is reported. As explained in [4], the conductor was first loaded to 30% of the tensile strength of the conductor and held for 30 min. It was then unloaded and loaded again to 50% of the strength. After 1 h at this level of force, the conductor was unloaded and loaded again. This third load had a target stress of 70% percent of the tensile strength of the conductor material. The load was held for one hour and then the conductor was unloaded. A fourth load application took the conductor to rupture.

It was not possible to quantitatively reproduce these observations with a corresponding finite element model, since the exact

Fig. 8. Strain-force curve of a four-layer conductor compared with the results of corresponding minimum and maximum stress distribution simulations. Measurement performed with a Class 1 load cell and Class 0.5 extensometer arrangement.

geometry and composition of the conductor, as well as the loading rate were not known. A qualitative comparison was therefore proposed in that the present model was loaded in three steps according to the scheme in [4] with respect to the corresponding strength level. Similar to the results reported in [4], each loading step increased the level of permanent elongation. Fig. 9 shows the results of the simulations and the permanent axial strain obtained with the models assuming maximum and minimum residual stress states, and compares these results with the data reported in [4].

The comparison shows that the minimum assumed residual stress case leads to an underestimation of the inelastic deformation. Obviously, a stress free model (neglecting the influence of residual stresses) would predict even smaller permanent deformation and therefore could not explain the observations. The measured inelastic deformations correspond to values between those of the simulations with minimum and maximum assumed residual stresses. In the cases of the second and third load applications, the measurements are closer to the maximum stress case. This might be associated with recovery effects, [24], which increase the amount of primary creep after each unloading phase.

5. Concluding remarks

The comparison between analytical predictions and measurements of axial force-elongation characteristics helps to quantify the reliability of models developed to represent the behaviour of stranded conductors used for high voltage overhead lines. Deviations in the range $< 5\%$ might be interpreted as a confirmation of the good predictive capabilities of analytical models, such as [5] and [6], accounting for relevant mechanisms of deformation of individual wires. The combination of the deformation modes included in [5] with the radial contraction effects represented in [6] might further improve the realism of the analytical calculations. In this respect, a more representative comparison is the one with the “stress-free” FE model, with a corresponding idealized geometry and stress state. In this case, the analytical formulae overestimate the axial stiffness by only 2–3%.

The measured force elongation curve shows a non-linearity associated with a permanent axial elongation, the magnitudes of which lie between the predictions of the FE models considering minimum and maximum assumed residual stresses from the manufacturing process. Consideration of these internal stresses also allows typical measurements of progressive inelastic elongation of a conductor subjected to cyclic axial loading to be rationalised, [4]. These results indicate that local plastification due to residual stresses generated during the manufacturing process offers an effective and convincing explanation to loading-unloading hysteresis and non-linearities observed when subjecting a stranded conductor to axial

Fig. 9. Left: Simulated cyclic loading to progressively larger levels of tension. Right: comparison between measured and predicted permanent axial elongation after the loading sequences specified in [4].

nominal stresses well below the limit of proportionality of the material.

The calculated inelastic axial elongation is in the range of 10^{-4} . This magnitude is small, but significant if compared to corresponding thermal strain: the resulting increase in sag is similar to the one associated with an increase of the conductor temperature by 5 °C. It is noted that, as shown in [19], the corresponding effect of residual stress on long term elongation might be up to an increased nominal axial inelastic strain of $5 \cdot 10^{-4}$.

The proposed 3D finite element model contributes to a better understanding of the complex deformation mechanisms associated with the mechanical response of a stranded conductor, and their influence on the axial force-elongation behaviour. The model provides the opportunity for improved predictions of short and long term conductor sag, and the required axial force for overhead line retightening. The proposed analysis of the influence of the production process opens the possibility to optimize the manufacturing process and so to reduce permanent elongation which could possibly increase the life expectancy of overhead line conductors. It would then be possible to develop further the model to allow a coupled thermal-mechanical simulation, taking also temperature gradients into account [25].

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