Mechanical Failure of Overhead Power line Conductors

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Recently in France (due to extreme climate changes)

The goal of the electric system operators:
- to ensure power transportation in overhed power lines
- maintenance and replacement of the conductors due to aging effects

Understanding the phenomena of aging and failure of conductors
Main causes of mechanical failure

Mechanical failure is caused by continuous and **progressive fretting fatigue** of the conductor’s strands induced by:

- **wind** (Aeolian vibrations or sub-conductor oscillations)
- fall of the tree branch on the conductor (**concentrated force**)
- **compressive forces** produced by the clamping device
- **sliding of the strands** between each other
- **contact** between strand and the clamping device
- **torque** due to tension force and twisting of the cable inside the clamping device

**Aeolian vibrations** are followed by high frequency vibrations (10-40 Hz) positioned normal to the transmission conductor

**Sub-conductor oscillations** are characterized by low frequencies at around 1Hz which cause Flexing of the conductor’s – failure after tens of millions of cycles
Traditional approach for conductor design

Usually based on empirical formulae for stress in the outer layer of conductor such as P-S (Poffenberger-Swart) and S-N curves for fatigue

Major drawbacks of this approach:
- Cannot consider progressive degradation of the conductor strands and inner failure mechanisms
- Cannot correctly take into account complexities in inner conductor mechanics (plasticity, wear due to slip of the strands...)
- Cannot distinguish between the state when 1, 2, 3 or more strands are broken

Powerful numerical models needed

Source: Azevedo et al: Fretting fatigue in overhead conductors...(2009)
The experiments have detected the failure mechanisms in ACSR conductor...

Experiments have shown that final failure is influenced by fretting fatigue and followed by shear failure mechanism in the close neighbourhood of the clamp.

Source: Azevedo et al: [Fretting fatigue in overhead conductors](http://example.com)...(2009)
Numerical approach for large conductors

Multi-scale problem

High heterogeneity of the transmission lines, tens of wires twisted together.

Modelling: large displacements, small strains, plasticity, damage

Meso scale: contact between the strands, sliding between the strands.
Numerical approach for large conductors

Macroscopic model

Beam elements to capture shear forces and to model shear failure mechanisms in the clamp
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...experiments have shown that final failure is influenced by **fretting fatigue** and followed by shear failure mechanism in the close neighbourhood of the clamp.

**Enhanced Timoshenko beam** to simulate the conductor in the clamping region can account for fretting and shear failure.

**Kinematics:**

\[
\begin{align*}
\epsilon(x) &= \frac{du(x)}{dx}, \\
\gamma(x) &= \frac{dv(x)}{dx} - \theta(x), \\
\kappa(x) &= \frac{d\theta(x)}{dx}
\end{align*}
\]

**Enhanced displacement field:**

\[
u(x) = \overline{u}(x) + \alpha^{(u)} H_{x_c}, 
\]

**Enhanced strain field:**

\[
\begin{align*}
\epsilon(x) &= \overline{\epsilon}(x) + \alpha^{(u)} \delta_{x_c}, \\
\gamma(x) &= \overline{\gamma}(x) + \alpha^{(v)} \delta_{x_c}
\end{align*}
\]

**mode I**

**mode II**
Numerical approach for large conductors

Enhanced Timoshenko beam response

fretting  final failure

Static response

Dynamic response
Numerical approach for large conductors

Large displacement cable for cable span

The capabilities of the proposed model (cable):
- Large displacements (geometric nonlinearity)
- Large strains (geometric nonlinearity)
- Plasticity hardening formulation (material nonlinearity)
- Localized failure of the cable + softening with embedded discontinuity (material nonlinearity)

The global computation is performed using the **Total Lagrangian formulation** with corresponding stress and strain measures:

**Green Lagrange strain:**

\[ E = \frac{dx^T}{dt} \frac{du}{ds} + \frac{1}{2} \frac{du^T}{ds} \frac{du}{ds} \]

**2nd Piola-Kirchoff stress**

\[ S = CE \]

For linear elasticity: St Venant’s material:

\[ W(x, E) = \frac{1}{2} CE^2 \]
Numerical approach for large conductors

We use 3-node elements...and corresponding high order polynomials:

\[ \xi_1 = -1 \quad \xi_2 = 0 \quad \xi_3 = +1 \]

High order polynomials for \( n_{en}=3 \)

\[ N_1(\xi) = \frac{1}{2} \xi (\xi - 1) \]
\[ N_2(\xi) = (1 + \xi)(1 - \xi) \]
\[ N_3(\xi) = \frac{1}{2} \xi (\xi + 1) \]

3 Gauss points are used to obtain the proper convergence of the element

\[ \xi_1 = -1 \quad \xi_2 = 0 \quad \xi_3 = +1 \]
Numerical approach for large conductors

Nonlinear elastic cable
- Large displacement theory
- Total Lagr. Form.

Material and geometric character.
- $L = 100 \text{ m}$
- $A = 2.88 \times 10^{-4} \text{ m}^2$
- $E = 7.75 \times 10^7 \text{ kN/m}^2$
- $\rho = 3721 \text{ kg/m}^3$
- $N_{u,t} = 1.14 \times 10^2 \text{ kN}$
- $\sigma_{u,t} = 3.96 \times 10^5 \text{ kN/m}^2$

Pre applied tension force: $1.05 \text{ kN}$

Deformed line from FEAP

For $P = 23 \text{ kN}$

**Final Displacement** = $5.04 \text{ m}$

**Cauchy (true) stress**: $3.96 \times 10^5 \text{ kN/m}^2$

**Ax. force**: $1.14 \times 10^2 \text{ kN}$
Numerical approach for large conductors

Nonlinear elastic 2D BEAM (Ibrahimbegovic & Frey [1993] IJNME)

- Large displacement theory
- Total Lagr. Form.

Material and geometric charact.:

$L = 100m$
$A = 2.88E-04m^2 \rightarrow I = 0.66-07m^4$
$E = 7.75E+07kN/m^2$
$\rho = 3721kg/m^3$
$N_{u,t} = 1.14E+02kN$
$\sigma_{u,t} = 3.96E+05kN/m^2$

Ultimate stress and stress resultant

For $P = 23$ kN

**Final Displacement** = $4.64m$ \( \rightarrow \) (smaller than : $5.04m$)

**Cauchy (true) stress**: $3.96E+05kN/m^2$ \( \rightarrow \) Ultimate stress

**Ax. force**: $1.14E+02kN$
Numerical approach for large conductors

Nonlinear plastic cable (hardening plasticity)
(The same example like in previous slide – with plasticity hardening)

Yield stress: \( \sigma_y = 3.0 \times 10^5 \text{kN/m}^2 \)

Hardening modulus: \( K_y = 1 \times 10^7 \text{kN/m}^2 \)

For \( P = 23 \text{kN} \)

**Final Displacement** = 6.03 m

**Cauchy (true) stress**: 3.31E+05 kN/m²

**Ax. force**: 9.53E+01 kN

Convergence file from FEAP

Hardening triggered (Wearing of the material)

Displacement in the middle of the cable vs time step for elastic and plastic cable
Numerical approach for large conductors
Nonlinear elastic cable + Timoshenko beam

(The same example but with cable + beam)

<table>
<thead>
<tr>
<th>lp</th>
<th>M (kNm)</th>
<th>T (kN)</th>
<th>N (kN)</th>
<th>Final disp. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1m</td>
<td>0.86</td>
<td>11.5</td>
<td>114</td>
<td>5.04</td>
</tr>
<tr>
<td>0.5m</td>
<td>4.31</td>
<td>11.5</td>
<td>114</td>
<td>5.08</td>
</tr>
<tr>
<td>1m</td>
<td>8.62</td>
<td>11.5</td>
<td>114</td>
<td>5.56</td>
</tr>
</tbody>
</table>

A=2.88E-04m²
I=8E-08m⁴

Two loading phases through 20 time steps:
Phase I: H=1.05 kN, Phase II: P=23kN

- Normal force at its ultimate value
- But shear force is large 11.5 kN and shear failure happened earlier

The beam zone length should be in a very close neighbourhood of the clamp
Numerical approach for large conductors
Nonlinear elastic cable + Timoshenko beam in dynamics (1)

**Loads:**
- **Phase I:** pretension 17 kN + selfweight of the cable
- **Phase II:** force $P (P=P\sin2\omega t)$, amplitude 150 N, $f=28.6$ Hz

Simulation time 20 seconds, time step $10^{-4}$ sec

Elastoplastic material behaviour (obtained with meso scale):

Axial force  
Shear force  
Moment
Numerical approach for large conductors
Nonlinear elastic cable + Timoshenko beam in dynamics (2)

Elastoplastic material behaviour:

- \( EA = 25 \times 10^6 \text{N} \)
- \( GA = 15 \times 10^3 \text{N} \)
- \( EI = 3.3 \times 10^6 \text{N cm}^2 \)
- \( K_s = 3 \times 10^3 \text{N} \)
- \( K_r = 417 \times 10^3 \text{N cm}^2 \)

Shear force at the clamp is monitored during 20 seconds

Shear force

Moment

Hardening moduli:
Numerical approach for large conductors

**DRAKE** cable of 100m length in **DYNAMICS** regime:

<table>
<thead>
<tr>
<th>Table 1: Characteristics of Drake cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section [mm$^2$]</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>465.5</td>
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<td></td>
</tr>
</tbody>
</table>

**Geometry setup:**
1 Timoshenko beam element (homogenization!!!) – 5cm clamp

We want to show the possibility to represent **FREE VIBRATIONS** with our model developed for **NONLINEAR DYNAMIC ANALYSIS FOR FAILURE** in **LINEAR ELASTIC REGIME**

By comparing it with **MODAL ANALYSIS**
Numerical approach for large conductors

DRAKE cable of 100m length in DYNAMICS regime:

Modal analysis requires: **EIGENVALUES** and **EIGENVECTORS** by solving the system

$$K - \lambda M = 0$$

for DRAKE of 100m represented by BEAM + CABLE elements

**EIGENVECTORS:**

1. $1.47 \times 10^{-2} \text{Hz}$
2. $2.93 \times 10^{-2} \text{Hz}$
3. $4.40 \times 10^{-2} \text{Hz}$
4. $5.86 \times 10^{-2} \text{Hz}$
5. $7.33 \times 10^{-2} \text{Hz}$

8. $8.97 \times 10^{-2} \text{Hz}$
9. $1.03 \times 10^{-1} \text{Hz}$
10. $1.17 \times 10^{-1} \text{Hz}$
11. $1.32 \times 10^{-1} \text{Hz}$
12. $1.47 \times 10^{-1} \text{Hz}$

......
Numerical approach for large conductors

We apply the force $F$ during the full simulation time and monitor the \textbf{VERTICAL DISPLACEMENT} and \textbf{SHEAR FORCE} AT THE CLAMP during 30 sec

\[ F = F_0 \sin \omega t \quad F_0 = 300 N \]

Two loads with frequencies $1.47 \times 10^{-2} \text{Hz}$ (corresponding to cable 1st mode) and $7.35 \times 10^{-2} \text{Hz}$

\[ 1.47 \times 10^{-2} \text{Hz} \]

\[ 7.35 \times 10^{-2} \text{Hz} \]

Rayleigh damping included with damping matrix defined as

\[ C = a_0 M + a_1 K \]

We choose

\[ a_0 = 0.001 \quad a_1 = 0.001 \]
Numerical approach for large conductors

Results for frequency $1.47 \times 10^{-2} \, Hz$
Numerical approach for large conductors

Results for frequency $7.35 \times 10^{-2} \text{Hz}$
Numerical approach for large conductors

BAUSCHINGER EFFECT

For representation of yield limit change during cyclic loadings

The model can be constructed as a combination of ISOTROPIC and KINEMATIC hardening

\[ L = 6 \]
\[ EA = 20000 \]
\[ \sigma_y = 30 \]
\[ K(\text{isotropic}) = 500 \]
\[ K(\text{kinematic}) = 10000 \]
Numerical approach for large conductors

How to evaluate damping for dynamics behaviour?

To provide reliable meso-scale model which can take into account the failure of individual strands

The figure shows behaviour of the conductors when strands are driven to failure progressively.
Thank you for your attention!!!!