TECHNOLOGY WATCH

GAPS IN KNOWLEDGE ABOUT CONDUCTOR FATIGUE

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Presentation outline

AEOLIAN VIBRATIONS AND CONDUCTOR FATIGUE
• Nature of the problem
• Conductor /clamp systems

ENGINEERING DESIGN TOOLS
• Aeolian vibration amplitudes and fatigue of conductors
  - Modelling for prediction of maximum antinode amplitudes
  - Safe design tension of conductors
• Bending model of conductor/clamp systems
• Laboratory determination of fatigue endurance capability
• In-situ measurements of conductor vibrations
• Spectrum loading and cumulative damage

GAPS TO BE FILLED
PROPOSAL FOR A RESEARCH PLAN
AEOLIAN VIBRATIONS AND CONDUCTOR FATIGUE

TRANSMISSION LINES ARE SPECIAL ENGINEERING STRUCTURES

- Spans
- Cantons

EXPOSED TO DIFFERENT CLIMATIC LOADS

- Terrain
- Seasons
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Nature of the problem

Laminar wind on conductors produces aeolian vibrations:

- Small vibration amplitudes exceeding rarely one conductor diameter
- In the frequency range of 3 to 150 Hz
- For winds of 1 to 7 m/s (2 to 15 mph)
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Nature of the problem

Records of natural vibrations show that the phenomenon is far from having a nice sinusoidal form
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Nature of the problem

This motion of the conductor has no detrimental effect along the span.

If the motion is constrained, however, e.g. at suspension clamps, singular points are created.
Nature of the problem

At such a location, conductor curvatures are much larger than in the free span. Interstrand microslip amplitude increases, small cracks are generated and some propagate up to complete strand failures caused by fretting fatigue.

To a lesser extent, a similar phenomenon can occur at damper, marker or spacer clamps.
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Conductor/clamp systems

- **Conductor designs** are not unique, their fatigue performance depends on their configuration.
- Conductor fatigue most often occurs at suspension clamps. Different **conductor supports** are available but a complete study of the impact of their design on the fatigue performance of a conductor has yet to be completed.
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Conductor/clamp systems

CONDUCTORS

• An important component of an overhead power line, it contributes to up to 40% of total capital investment.

• Much attention is given to the selection of a conductor configuration to meet load requirements.

• It thus take different configurations to best meet those requirements.

• Most common types of bare overhead conductors are constructed from commercially pure aluminium e.g. AAC

• For added strength, different alloys are used e.g. AAAC

• For a better strength-to-weight ratio, a strength member such as steel wires may be added in the core e.g. ACSR

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Conductor/clamp systems

TYPICAL CONFIGURATION OF A BARE CONDUCTOR

• Layers of round wires are stranded first around a so-called core
• The stranding takes place in alternating directions from layer to layer
• For conductors with equal diameter wires, each lay has six wires more than the previous to assure a good fit
• To tailor the conductor for various strenght-to-weight ratios, unequal diameter wires are often used.
Conductor/clamp systems

SOME SPECIAL CONDUCTORS

Trapezoidal, Z-shaped compact, Self-damping, Expanded and River crossing conductors:

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Conductor/clamp systems

CLAMPING SYSTEMS (1)

Different designs of suspension clamps
Conductor/clamp systems

CLAMPING SYSTEMS (2)

• Newer design with elastomeric insert

• Special river crossing clamp
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Conductor/clamp systems

CLAMPING SYSTEMS (3)

Some characteristics of the design:

• The profile of the body should theoretically follow the natural curvature of the conductor
• In practice an optimum profile design is found taking into account the different load assumptions
• The main profile of the body (and keeper) must be rounded and curved into a bell mouth to avoid damaging the conductor in case of exceptional overloads
• The clamp should be able to rotate in a longitudinal vertical plane to accommodate asymmetrical loads
• The rotation is assured by a pivot either below, above or at the conductor axis
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Conductor/clamp systems

FATIGUE ENDURANCE OF CONDUCTOR/CLAMP SYSTEMS

- Fatigue of conductors is due to microslip movements of wires inducing fretting fatigue
- The phenomenon is complex and its exact modelling has yet to be completed
- The knowledge on fatigue performance of conductors mostly relies on results of laboratory tests made on conductors in fixed short metallic clamps
- The determination of the fatigue endurance of a conductor alone is not possible with the present knowledge of the phenomenon
- The above review of conductors and supports illustrated their diversity of design and geometry
- The direct extrapolation of fatigue data available to other types of conductors or to different types of supports is not recommended
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ENGINEERING DESIGN TOOLS

Aeolian vibration amplitudes and fatigue of conductors

• After more than 80 years of active work, the complexity of both phenomena did not permit to propose complete solutions supported by thorough analysis taking into account the numerous parameters varying both in space and time

• Engineering solutions were sought concurrently. Through the years they became reliable design tools

• When applied correctly, within the limits inherent to their definitions, they permit to assure an acceptable control of the situation pending the completion of more complete analytical tools

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Aeolian vibration amplitudes and fatigue of conductors

- Both aspects were studied concurrently
- Emphasis was first put on the elimination conductor vibrations
- Hence *fatigue* was often retained *as one of the parameters*
- Two examples of such engineering design tools:
  - *Modelling for prediction of maximum antinode amplitudes*
  - *Overhead conductor safe design tension*
- Both approaches make use of the Energy Balance Principle (EBP)
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Aeolian vibration amplitudes and fatigue of conductors

Modelling for prediction of maximum antinode amplitudes

Outline of the technology applied to the case of a single conductor plus damper making use of the Energy Balance Principle (EBP)

CIGRE TF B2.11.01
ELECTRA # 223 DEC. 2005

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Aeolian vibration amplitudes and fatigue of conductors

Energy Balance Principle (EPB)

• The EBP works in the frequency domain, one mode of vibration at a time

• The steady state solutions computed correspond to the maximum amplitude which could be excited on a conductor at that frequency

• Transient effects (e.g. wind turbulence) cannot be taken into account

• Energy input is evaluated in a condition of laminar wind

• Conductor self-damping is the sole energy dissipator in the simplest case

• The presence of damper(s) requires an adequate modelling of its interaction with the conductor
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Aeolian vibration amplitudes and fatigue of conductors

PREDICTION OF MAXIMUM ANTINODE AMPLITUDES

• The Energy Balance Principle (EBP) is an analytical approach that can be usefully used to investigate alternatives in the design or redesign process

• *Being aware of its limits*, the EBP can also be used for the direct design of the damping system for a new line

• EBP permits to determine an estimate of an *upper bound* to the expected vibratory motions

• The acceptable *upper bound* value entirely depends on the choice of a *fatigue parameter* for the conductor/clamp system under evaluation

• The straightforward EBP is considered acceptable for use for engineering applications

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Aeolian vibration amplitudes and fatigue of conductors

Limitations regarding the EBP for prediction of maximum antinode amplitudes of vibration


« The strains predicted by the different researchers exhibit considerable variability. Nevertheless analytical methods based on the EBP and shaker-based technology can provide a useful tool for use in design of damping systems for the protection of single conductors against aeolian vibrations. It should be used with circumspection and be supplemented by references to field experience. Greater accuracy can be obtained by evaluating damper dissipation on laboratory span rather than on the shaker. »
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Aeolian vibration amplitudes and fatigue of conductors

OVERHEAD CONDUCTOR SAFE DESIGN TENSION

• Approaches to guide an assessment of the severity of vibrations can be pragmatic, through design rules based on passed experience

• Conditions can also be assessed through measurements on existing lines

• The mechanical tension of the conductors was reckoned at the early stage as an important parameter related to the presence of conductor vibrations

• Recently, CIGRE TF B2.11.04 proposed an engineering design tool: « Overhead conductor safe design tension with respect to aeolian vibrations »
  CIGRE TB # 273 June 2005
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Aeolian vibration amplitudes and fatigue of conductors

OVERHEAD CONDUCTOR SAFE DESIGN TENSION

Conductor tension design guide - modelling approach
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### Aeolian vibration amplitudes and fatigue of conductors

#### OVERHEAD CONDUCTOR SAFE DESIGN TENSION

Basic assumptions underlying model calculations

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>IREQ / Leblond &amp; Hardy [25]</td>
<td>Endurance Limit</td>
</tr>
<tr>
<td>Alcoa Fujikura / Rawlins [26]</td>
<td>Endurance Limit</td>
</tr>
</tbody>
</table>

### Conductor damping capacity

Calculated on the basis of similarity laws calibrated by means of measured data (ISWR method).

Measured (ISWR method)

### Span-end damping

Travelling wave approach using complex damper stiffness measured on shaker.

Measured efficiency of span-end damping arrangement.

### Wind power input

Laminar or reduced for normally-distributed turbulence.

Laminar or reduced for turbulence.

### Vibration mode shape

Narrow band random vibration (peak amplitudes Rayleigh-distributed, maximum amplitude limited to 3.5 times RMS-value at each frequency).

Sinusoidal

### Conductor tolerance to vibration

Fatigue endurance as per [13]

Fatigue endurance as per [13]

### Clamping system

Fixed metal to metal clamps

Fixed metal to metal clamps


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Aeolian vibration amplitudes and fatigue of conductors

OVERHEAD CONDUCTOR SAFE DESIGN TENSION
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Aeolian vibration amplitudes and fatigue of conductors

OVERHEAD CONDUCTOR SAFE DESIGN TENSION

- The CIGRE guide for conductor safe design tension with respect to aeolian vibrations is based on calculations making use of the EBP
- The limitations expressed previously for the use of EPB to evaluate the maximum antinode amplitudes of vibration are thus also inherent in this engineering design tool
- Cases calculated to draw the safe zones are based on conservative conditions of conductors supported in fixed short metallic clamps
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Bending model of the conductor /clamp system

- The conductor/clamp system is represented as a cantilever beam in bending
- The bending amplitude $Y_b$ is defined at 89 mm from LPC

- Bending amplitude method is valid only for conductors fitted with solid metallic clamps where LPC can be reached (armored or unarmored)

- Cushioned clamps (armored or unarmored) need special treatment.
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Simplified Analytical Representation of the Fatigue Phenomenon (1)

An idealized bending stress (Poffenberger-Swart formula) is calculated at the outer-layer strand in the plane of the last point of contact (LPC) as function of $Y_b$

$$\sigma_a = \frac{E_a \cdot d \cdot p^2}{4 \left( e^{-px} - 1 + px \right)} \cdot Y_b$$

$E_a$: modulus of elasticity of outer wire material (N/mm2)
$d$: diameter of outer-layer wire (mm)
$p = (H/El)^{\frac{1}{2}}$
$H$: conductor tension at average temperature during test period (N)
$El$: sum of flexural rigidities of individual wires in the cable (N mm2)
$x$: distance from the point of measurement to the last point of contact
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Simplified Analytical Representation of the Fatigue Phenomenon (2)

The antinode amplitude of vibration, $y_{max}$, is also a useful parameter

The stress formula becomes:

$$\sigma_a = \pi d E_a \sqrt{\frac{m}{EI}} f y_{max}$$

$E_a$: Young’s modulus for the outer-layer strand material (N/mm2)
$d$: diameter of outer-layer wire (mm)
$f$: frequency of the motion (Hz)
$m$: conductor mass per unit length (kg/m)
$EI$: sum of flexural rigidities of individual wires in the cable (N mm2)
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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Laboratory fatigue tests — Resonant type test benches

Important test parameters:

• Constant amplitude excitation
• Most tests done with conductors supported in short metallic clamps
• Clamps usually held in a fixed position on the test bench
• Measurement of the bending amplitude $Y_b$ and the free loop amplitude $f_{y_{max}}$
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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Characterization of the fatigue behaviour of a conductor

- The results of such tests ultimately lead to the presentation of a fatigue (S-N) curve
- Idealized bending stress at conductor surface vs megacycles to failure
- The endurance limit is determined at 500 megacycles
- Stress expressed as function of $Y_b$ or $f_{y\text{max}}$,

Endurance limits:

- stress as function of $Y_b$:
  - 22.5 MPa for single-layer ACSR
  - 8.5 MPa for multi-layer ACSR

- stress as function of $f_{y\text{max}}$:
  - 22 MPa for ACSR

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Figure 3.2-23 Fatigue tests of single-layer ACSR.

EPRI 2007

ALCOA (1979) 1/0 (6/1) Susp
ALCOA (1979) 1/0 (6/1) Susp; run out
ALCOA (1979) No. 4 (7/1) BM
ALCOA (1979) 3/0 (6/1) BM
ALCOA (1979) No. 4 (6/1) BM; Log mean

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Figure 3.2-24 Fatigue tests of two-layer ACSR

EPRI 2007

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Figure 3.2-25 Fatigue tests of three-layer ACSR

EPRI 2007

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Figure 3.2-13a Fatigue tests of two-layer ACSR

- Seppä (1969) 397.5 lbs 26/7 Susp
- EPRI (1987) 795 Drake 26/7 Susp; run out
- ALCOA (1979) 397.5 Lark Susp; run out

EPRI 2007

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Figure 3.2-13b Fatigue tests of three-layer ACSR

EPRI 2007

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Conversion of $f_{y_{\max}}$ to $Y_b$ endurance limits

Ratio $Y_b/f_{y_{\max}}$ should be obtained experimentally for given axial load and conductor/clamp system. The values of stresses at the outer layer strand are different surrogates for the actual fatigue–initiating stress at the strand contacts where failures originate.

Endurance limits that have been established in terms of $f_{y_{\max}}$ may be converted to $Y_b$ endurance limits by experimental determination in a laboratory span of the value of $Y_b$ that corresponds to the $f_{y_{\max}}$ endurance limit. This should be done at the $f_{y_{\max}}$ endurance limit. $Y_b$ does not always vary linearly with $f_{y_{\max}}$. 
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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Statistical representation of two S-N curves:

- Average (50 %)
- 95% probability of survival

![Graph showing statistical representation of two S-N curves: average (50%) and 95% probability of survival.](image)
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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

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**Estimated bending amplitude endurance limits for ACSR**

<table>
<thead>
<tr>
<th>Conductor Name</th>
<th>Size (kcmils)</th>
<th>Stranding</th>
<th>Tension in Percent of Rated Strength*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$Y_b$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Ruddy</td>
<td>900.0</td>
<td>45 / 7</td>
<td>0.30</td>
</tr>
<tr>
<td>Canary</td>
<td>900.0</td>
<td>54 / 7</td>
<td>0.31</td>
</tr>
<tr>
<td>Catbird</td>
<td>954.0</td>
<td>46 / 1</td>
<td>0.29</td>
</tr>
<tr>
<td>Rail</td>
<td>954.0</td>
<td>45 / 7</td>
<td>0.29</td>
</tr>
<tr>
<td>Cardinal</td>
<td>954.0</td>
<td>54 / 7</td>
<td>0.30</td>
</tr>
<tr>
<td>Ortolan</td>
<td>1033.5</td>
<td>45 / 7</td>
<td>0.29</td>
</tr>
<tr>
<td>Curlew</td>
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<td>54 / 7</td>
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<td>Bluejay</td>
<td>1113.0</td>
<td>45 / 7</td>
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<td>Finch</td>
<td>1113.0</td>
<td>54 / 19</td>
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</tr>
<tr>
<td>Bunting</td>
<td>1192.5</td>
<td>45 / 7</td>
<td>0.28</td>
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<td>Grackle</td>
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<td>Esterh</td>
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<tr>
<td>Dripper</td>
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<tr>
<td>Martin</td>
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<td>54 / 19</td>
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<td>Bobolink</td>
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<td>45 / 7</td>
<td>0.26</td>
</tr>
<tr>
<td>Plover</td>
<td>1431.0</td>
<td>54 / 19</td>
<td>0.26</td>
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<tr>
<td>Nutthatch</td>
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<tr>
<td>Thrush</td>
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</tr>
<tr>
<td>Jocie</td>
<td>2515.0</td>
<td>76 / 19</td>
<td>0.26</td>
</tr>
</tbody>
</table>

*For other tensions, interpolate between values given*
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In-situ measurement of conductor vibration

Bending Amplitude Recorders

Vibrec 400

Pavica

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Spectrum loading and cumulative damage

• When S/N curves are available, it is possible to determine an endurance limit applicable to the cases studied.

• The systematic use of the endurance limit as the maximum value of bending amplitude acceptable represents a safe design choice, but could imply an unnecessary margin of overdesign.

• To go from the constant to the variable amplitude situation, the usual approach is to use a cumulative damage law.

• Miner’s rule is widely used because of its simplicity despite the following two limitations:

  *It is independent of the cycle sequence.*

  *Stress levels below the endurance limit are ignored.*
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Spectrum loading and cumulative damage

Constant Amplitude Data and Variable Amplitudes Vibrations

Usually based on cumulative damage theory (Miner’s rule) with the following hypotheses:

Total damage $D$ at several stress levels $\sigma_i$ cumulates linearly:

$$D = \sum \frac{n_i}{N_i}$$

Failure is predicted when:

$$D = \sum \frac{n_i}{N_i} = 1$$

Note: the use of $D=1$ has not been confirmed experimentally for conductors.
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GAPS TO BE FILLED (1)

Two of the engineering design tools available are aimed at limiting the amplitudes of vibration

1. Model to predict acceptable antinode vibration amplitudes
2. Model to evaluate tension to avoid detrimental vibrations

Both approaches are based on some empirical knowledge or some simplified models.

e.g. both use EBP where wind input, conductor self damping, damper characteristics and damper/conductor interaction are complex situations that are difficult to model accurately.

In both cases, the limit for the calculations is a criterion related to the fatigue of conductors.

For the moment, the only reliable criterion for conductor fatigue is the bending amplitude method applied to the case of a conductor supported in a short metallic clamp.

It severely limits their application to cases with different supports.
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GAPS TO BE FILLED (2)

Influence of clamp design

Although the present conductor fatigue criterion, related to bending amplitudes, presents severe limitations it has been a useful tool until now because of the frequent choice of short metallic supension clamps to support a conductor.

The laboratory fatigue results available when the first EPRI Orange Book was published (1979) was limited to cases with short support clamps. It did not permit to consider the influence of the clamp geometry as an important parameter.

More recent work rather lead towards the consideration of the clamp design as an important parameter for the fatigue performance of the conductor.

• Incorporated elastomeric inserts, are good examples.
• The clamp design (geometry) should be part of the study.
GAPS TO BE FILLED (3)

Conductor configuration

The results of laboratory fatigue tests that were made until now mostly refer to ACSR conductors supported in a short metallic clamp. It is important to conduct similar tests on conductor of different configurations and to take advantage of the present data available to assess the importance of the strand geometry, size and material, the importance of the choice of the number of layers on the fatigue endurance of the conductor.

Armour rods

With the advantage of measuring $Y_b$ and $f_{y_{\text{max}}}$ in a fatigue test, the influence of the presence of armour rods could be evaluated. Armour rods, for a given $f_{y_{\text{max}}}$, will affect the value of $Y_b$ at the clamp. (They could also reduce $f_{y_{\text{max}}}$ at given wind conditions)
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GAPS TO BE FILLED (4)

*Spectrum loading and cumulative damage*

Laboratory tests at variable amplitudes are necessary to determine an appropriate cumulative law and to indicate its limits. e.g. Miner’s Law

N.b.. Amplitudes of conductor vibrations are not constant values and design with endurance limits is a very conservative when the S/N curve is known.

*Fatigue tests with large amplitudes*

The occurrence of galop on the lines indicated that in some occasion that phenomenon may have been the cause of strand failures. Tests at large amplitudes are necessary to identify the nature of the strand failures.
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GAPS TO BE FILLED (5)

*In situ measurements*

- Instruments to detect strand failures
- Instruments (in span) to measure antinode amplitudes (present recorders measure a *curvature parameter* at the clamps)
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GAPS TO BE FILLED (6)

Limitations to present methods for the characterization of fatigue performance

• Dispersion of fatigue results, use of statistical approach

• Detection of broken strands, relation between first and subsequent breaks

• Criteria for test termination

• Modification to laboratory test bench to better evaluate special supports
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GAPS TO BE FILLED (7)

- Definition of an adequate model related to the cause of the strand failures: *fretting fatigue*.
  - contact mechanics for the analysis of crack initiation
  - fracture mechanics for the analysis of crack propagation

Note: It is of *paramount importance* that such work takes into account the knowledge already available through studies related to the simplified flexion model, in order to keep making good use of the data bank presently developed.
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PROPOSAL FOR A RESEARCH PLAN
With reference to actual bending model

Laboratory tests, constant amplitudes:

- **Conductor configuration**: strand geometry, size, material, and # of layers.
- **Presence of armored rods**
- **Influence of clamp design**:
  - elastomeric inserts (continuous or at the ends),
  - inserts and armored rods (AGS)
  - geometry of metallic clamps (length, curvature)
- **Large amplitudes (conditions of galop)**

Laboratory tests, **spectrum loading** (for evaluation of cumulative damage laws)

Note: *Labo tests* are the 1st avenue to explore before trying to define links to the flexion model
PROPOSAL FOR A RESEARCH PLAN

2. Other aspects related to laboratory tests

• Detection of strand failures, relationship between first and subsequent
• Dispersion of results, statistical approach
• Criteria for test termination
• Modification to test bench to accommodate special supports e.g. symmetric excitation

3. In situ measurements

• Instrument to detect strand failure(s)
• In span instrument to measure antinode amplitudes (present recorders measure a curvature parameter at clamps)
4. More fundamental work

Definition of a new fatigue criterion (index) related to fretting (still related to $Y_b$ via interstrand micro slip)

The avenues for such a modelisation are:

• contact mechanics, to identify conditions of micro cracks initiation

• fracture mechanics, to define conditions of cracks propagation
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DISCUSSION