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

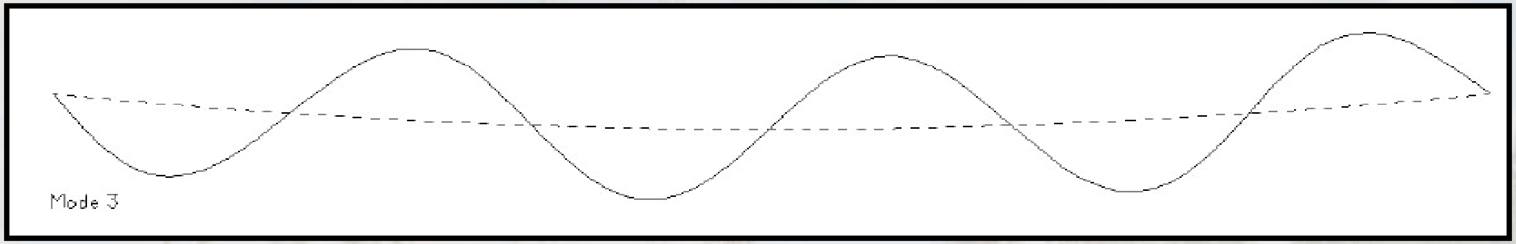
- Spans
- Cantons

EXPOSED TO DIFFERENT CLIMATIC LOADS

- Terrain
- Seasons

Nature of the problem

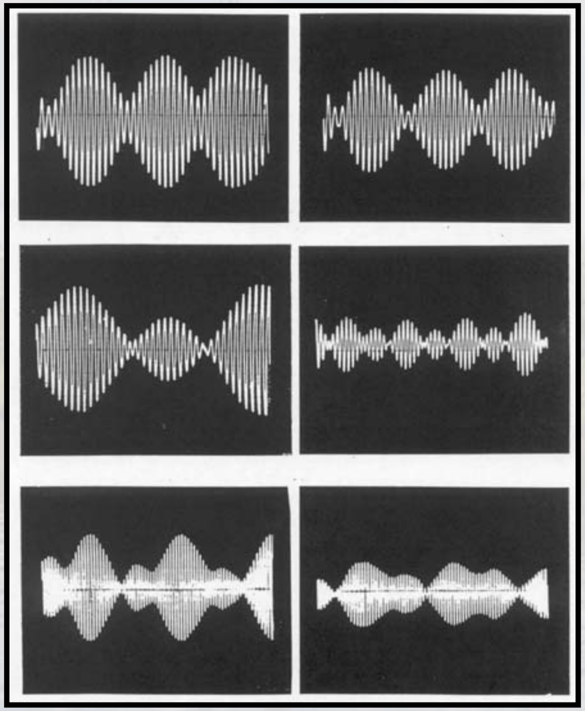
Laminar wind on conductors produces aeolian vibrations:



- 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)

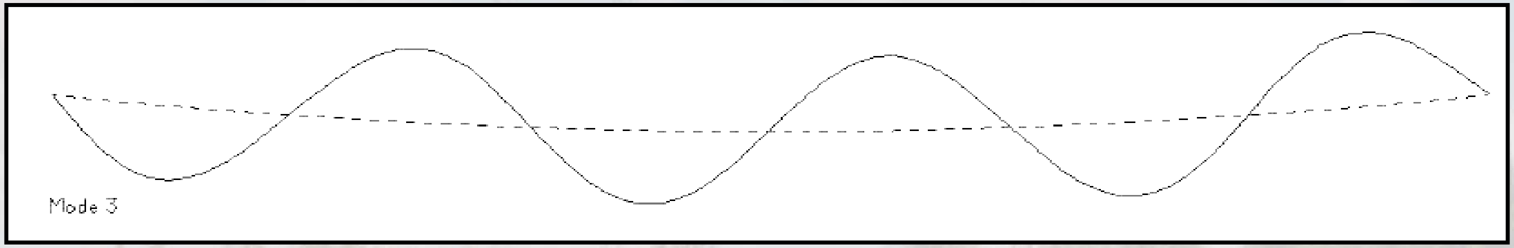
Nature of the problem

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

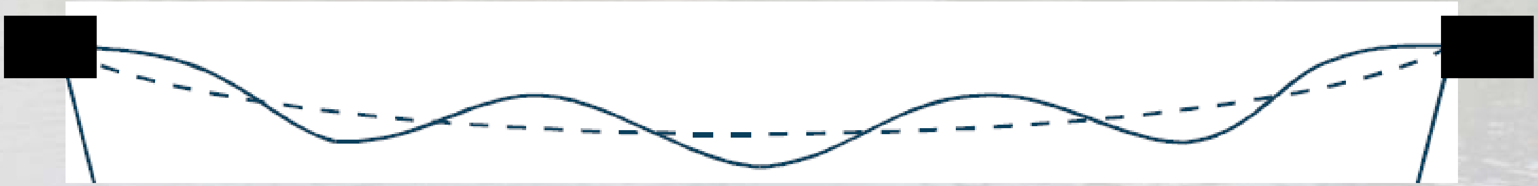


Nature of the problem

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

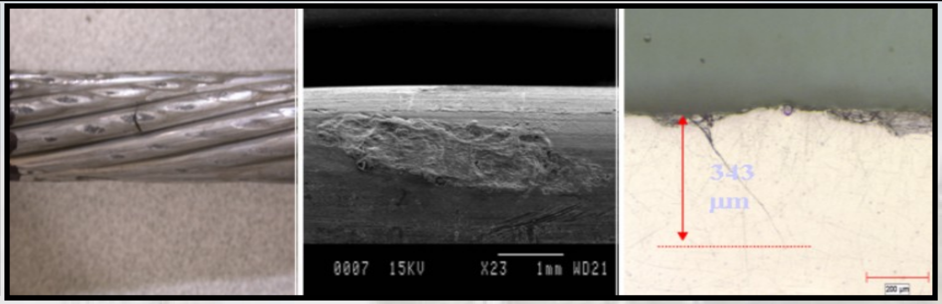


If the motion is constrained, however, e.g. at suspension clamps, singular points are created

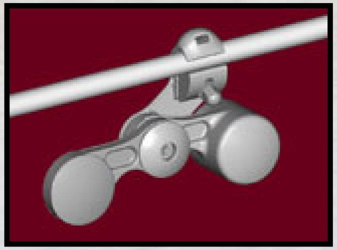


Nature of the problem

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.



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*.

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

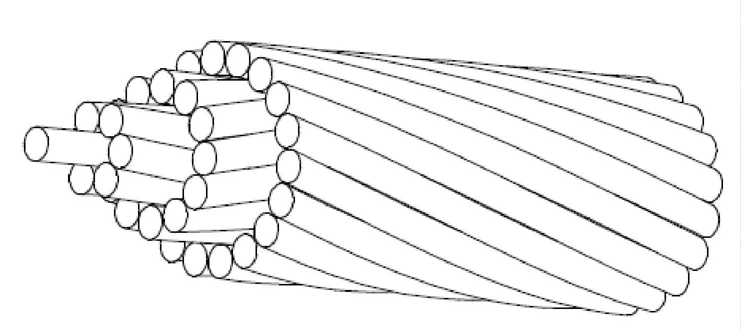
• For added strength, different alloys are used e.g. AAAC

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

Conductor/clamp systems

TYPICAL CONFIGURATION OF A BARE CONDUCTOR

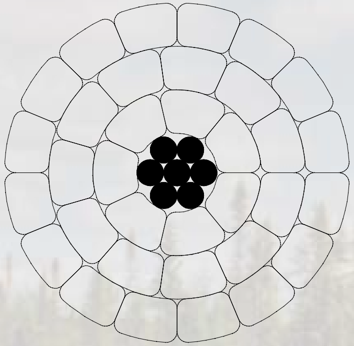
- Layers of round wires are stranded first around a so-called core
- The stranding takes place in alternating directions from layer to layer
- For conductors with equal diameter wires, each lay has six wires more than the previous to assure a good fit
- To tailor the conductor for various strenght-to-weight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

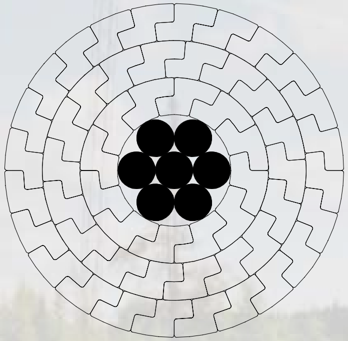


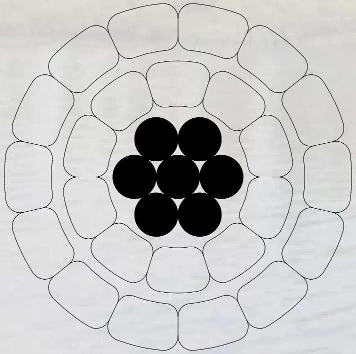
Conductor/clamp systems

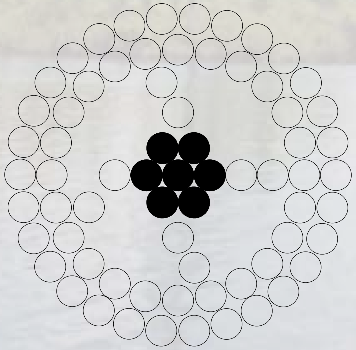
SOME SPECIAL CONDUCTORS

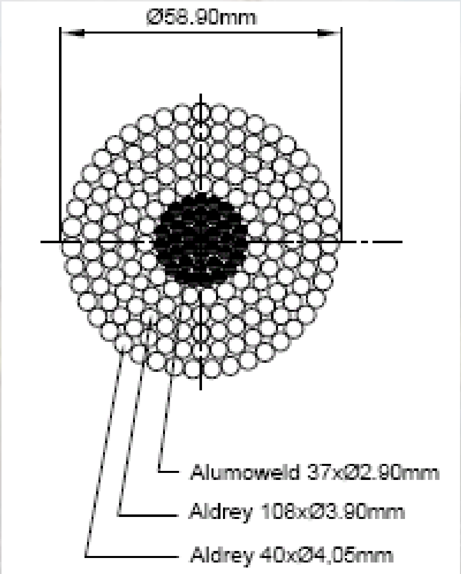
Trapezoidal, Z-shaped compact, Self-damping, Expanded and River crossing conductors:







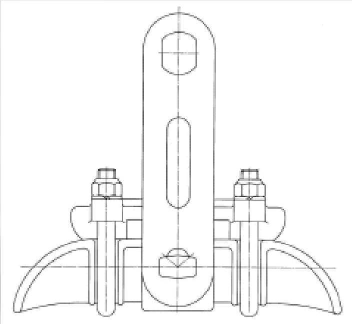
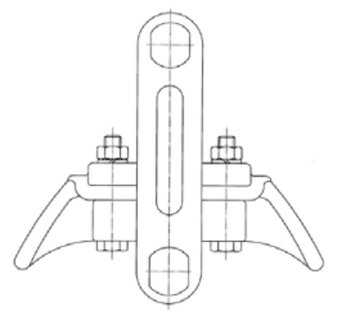
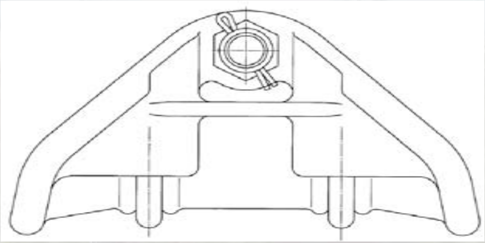
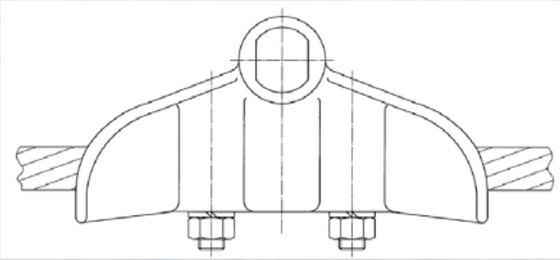
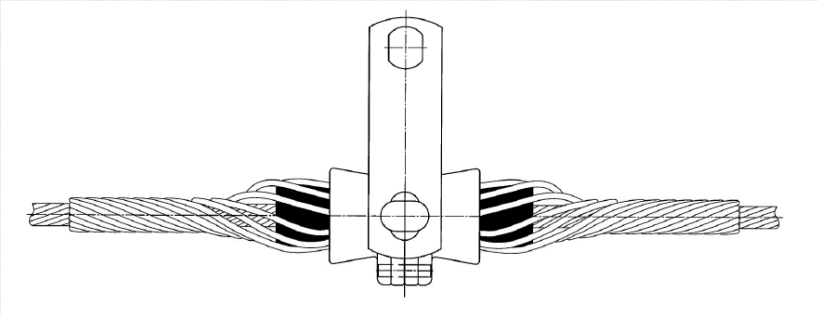




Conductor/clamp systems

CLAMPING SYSTEMS (1)

Different designs of suspension clamps

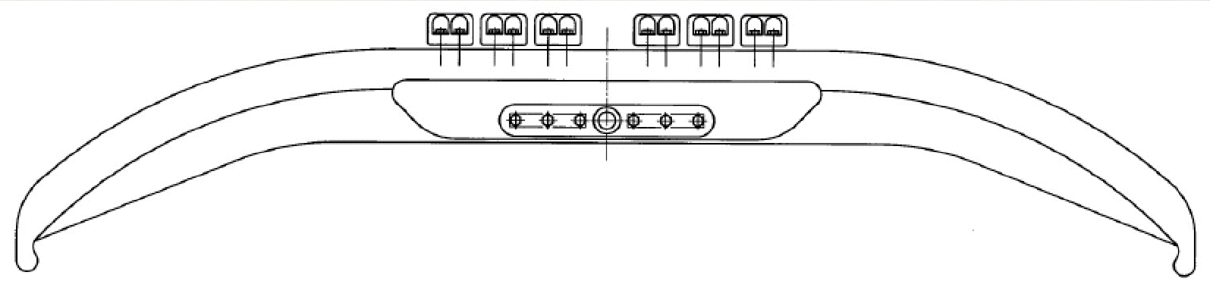






Conductor/clamp systems

CLAMPING SYSTEMS (2)

•Newer design with elastomeric insert

•Special river crossing clamp



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 accomodate asymmetrical loads
- The rotation is assured by a pivot either below, above or at the conductor axis

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

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

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)**

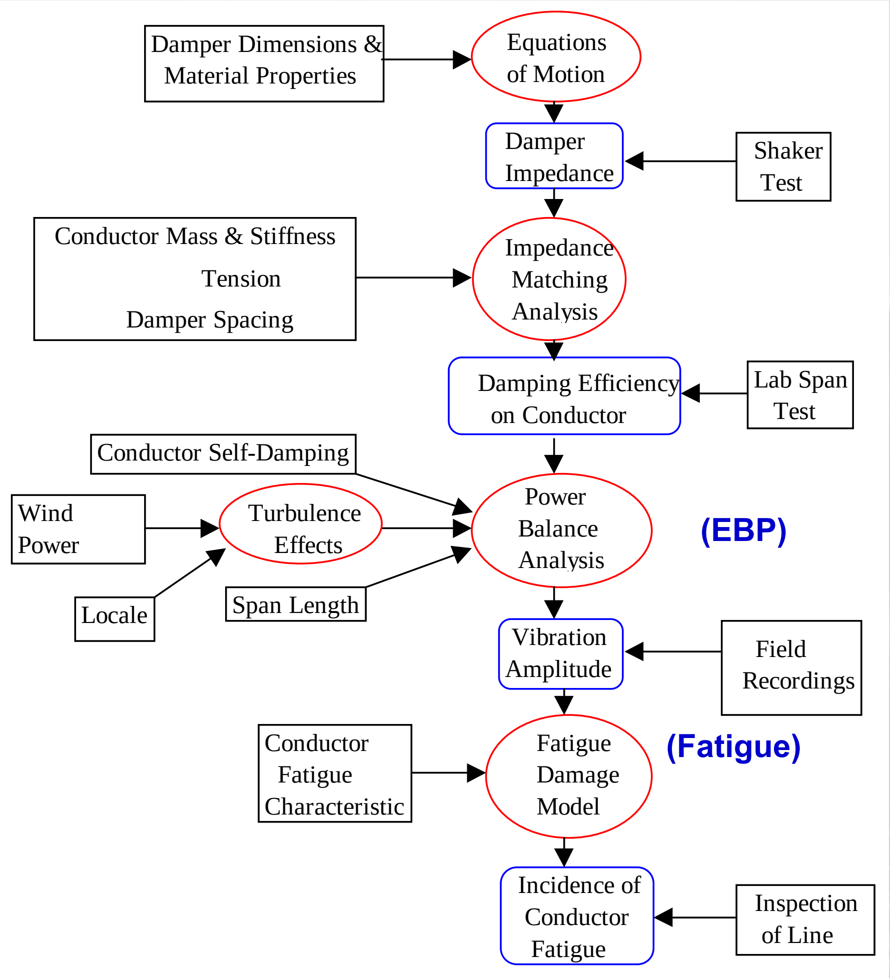
Technology Watch for Gaps in Knowledge about Conductor Fatigue

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



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

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

Aeolian vibration amplitudes and fatigue of conductors

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

ref: Conclusion of paper **« Modelling of aeolian vibrations of a single conductor plus damper: assessment of technology »,**
CIGRE TF B2.11.01, Electra, No 223, December 2005 pp.28-36

« 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. »

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

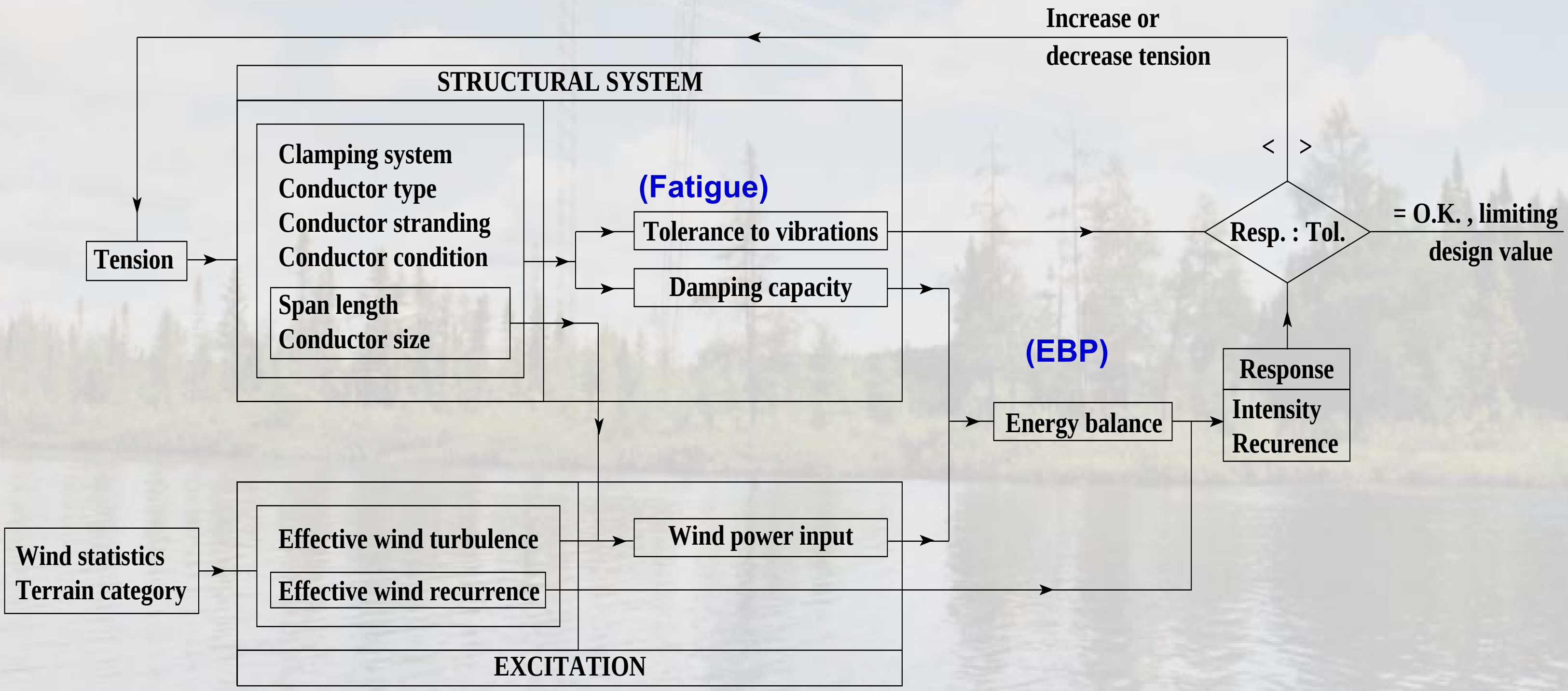
- The mechanical tension of the conductors was reckoned at the early stage as an important parameter related to the presence of conductor vibrations

- 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

Aeolian vibration amplitudes and fatigue of conductors

OVERHEAD CONDUCTOR SAFE DESIGN TENSION

Conductor tension design guide - modelling approach



Aeolian vibration amplitudes and fatigue of conductors

OVERHEAD CONDUCTOR SAFE DESIGN TENSION

Basic assumptions underlaying model calculations

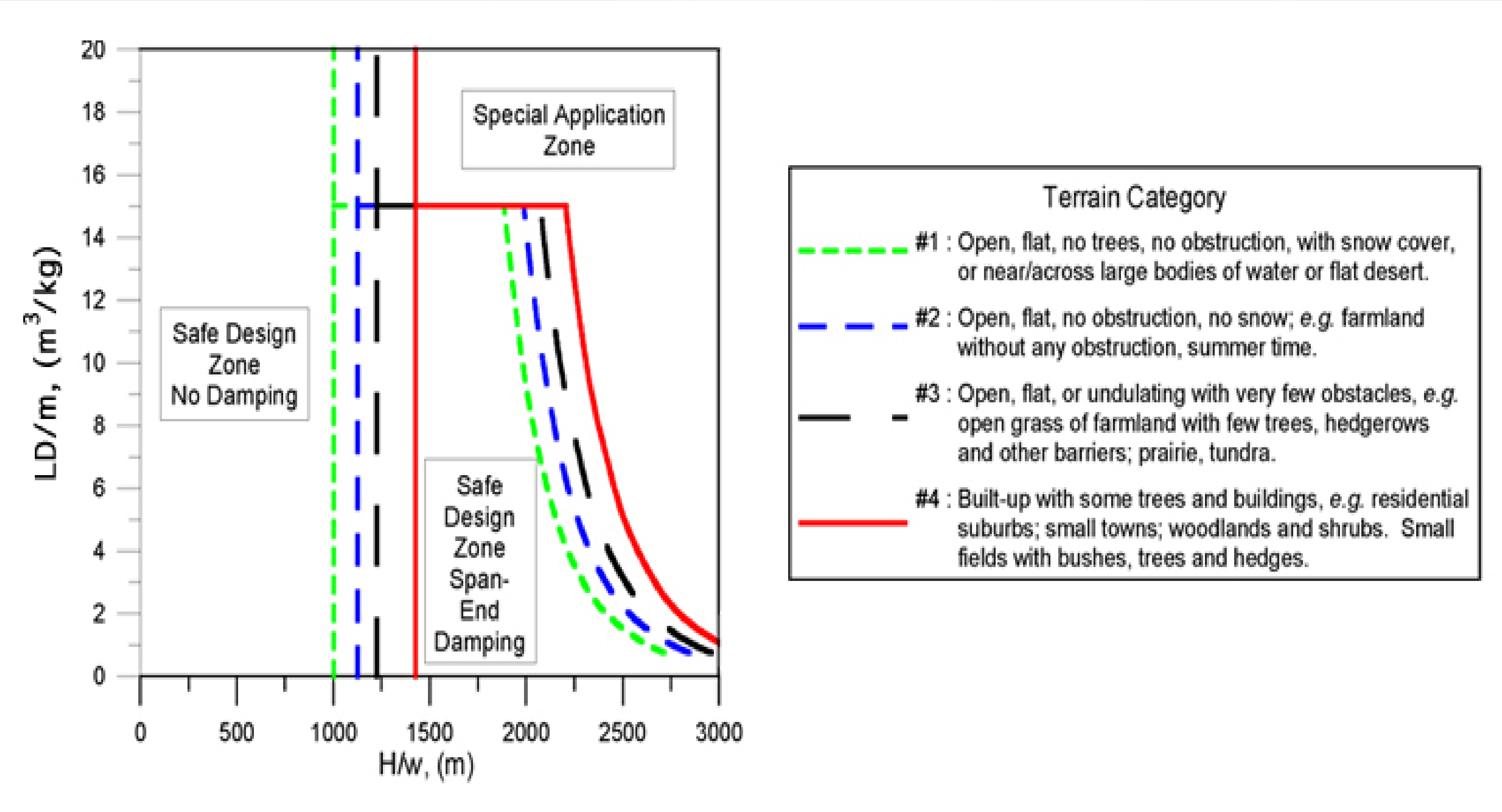
Organisation	IREQ / Leblond & Hardy [25]	Alcoa Fujikura / Rawlins [26]
Approach	Endurance Limit	Endurance Limit
Conductor damping capacity	Calculated on the basis of similarity laws calibrated by means of measured data (ISWR method).	Measured (ISWR method)
Span-end damping	Travelling wave approach using 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

(Fatigue)

(13) Chapter 2 of « Wind induced Conductor motion » EPRI Transmission Line Reference Book,1979

Aeolian vibration amplitudes and fatigue of conductors

OVERHEAD CONDUCTOR SAFE DESIGN TENSION



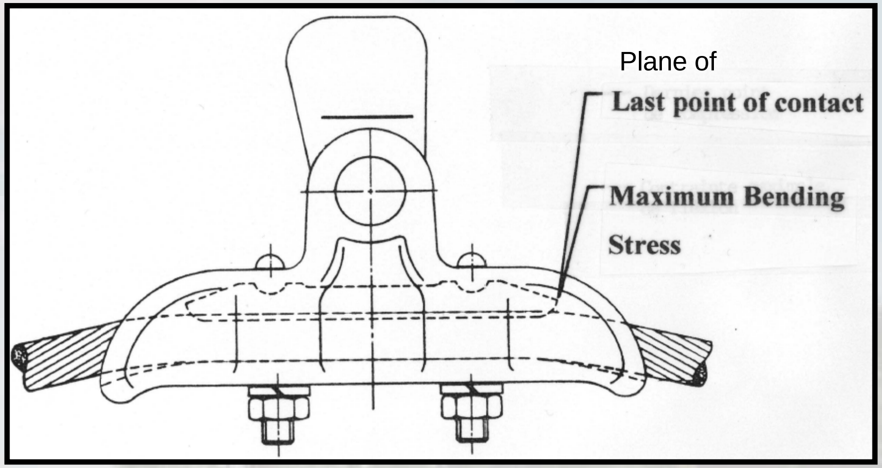
Aeolian vibration amplitudes and fatigue of conductors

OVERHEAD CONDUCTOR SAFE DESIGN TENSION

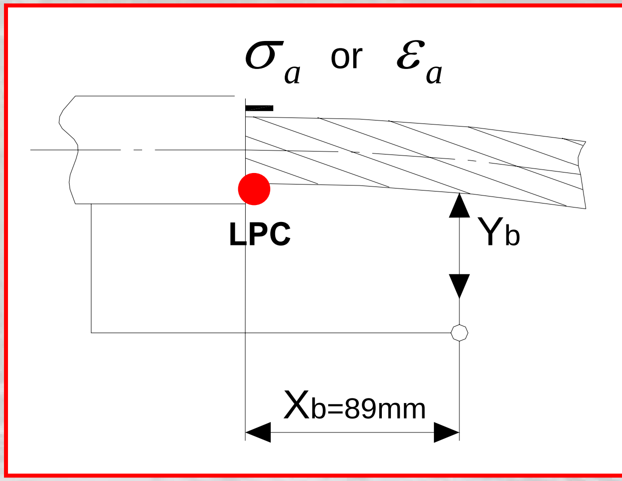
- **The CIGRE guide for conductor safe design tension with respect to aeolian vibrations is based on calculations making use of the EBP**
- **The limitations expressed previously for the use of EPB to evaluate the maximum antinode amplitudes of vibration are thus also inherent in this engineering design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

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)

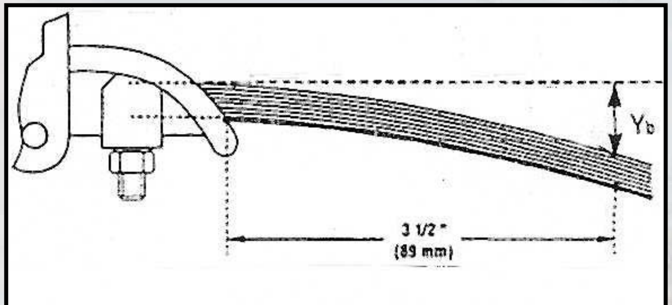


- Cushioned clamps (armored or unarmored) need special treatment.

Technology Watch for Gaps in Knowledge about Conductor Fatigue

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



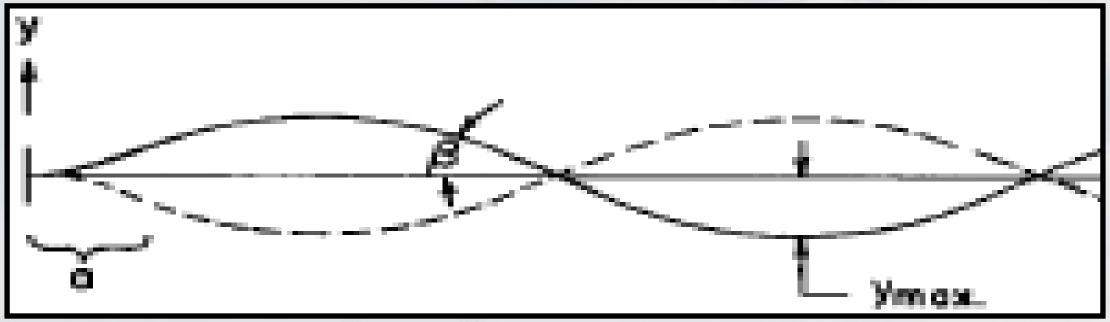
Bending amplitude Y_b

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

***Ea*: modulus of elasticity of outer wire material (N/mm2)**
***d*: diameter of outer- layer wire (mm)**
***p* = (*H*/*EI*)½**
***H*: conductor tension at average temperature during test period (N)**
***EI*: 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**

Technology Watch for Gaps in Knowledge about Conductor Fatigue

Simplified Analytical Representation of the Fatigue Phenomenon (2)



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

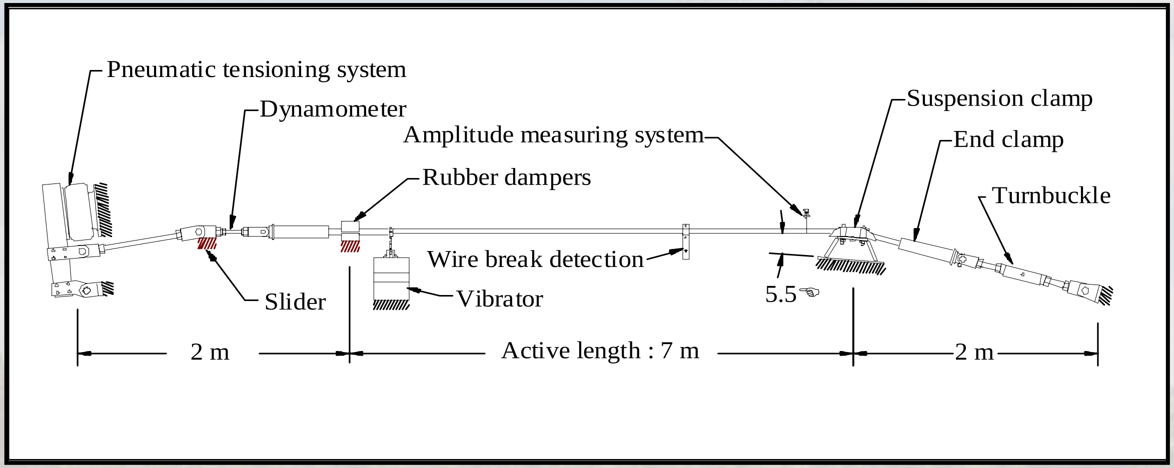
The stress formula becomes:

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

***Ea*: 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)**

LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Laboratory fatigue tests — Resonant type test benches



Courtesy of GREMCA

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 fy_{max}**

Technology Watch for Gaps in Knowledge about Conductor Fatigue

LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

<u>Characterization of the fatigue behaviour of a conductor</u>

- 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 fy_{max},

Endurance limits:

stress as function of Y_b:

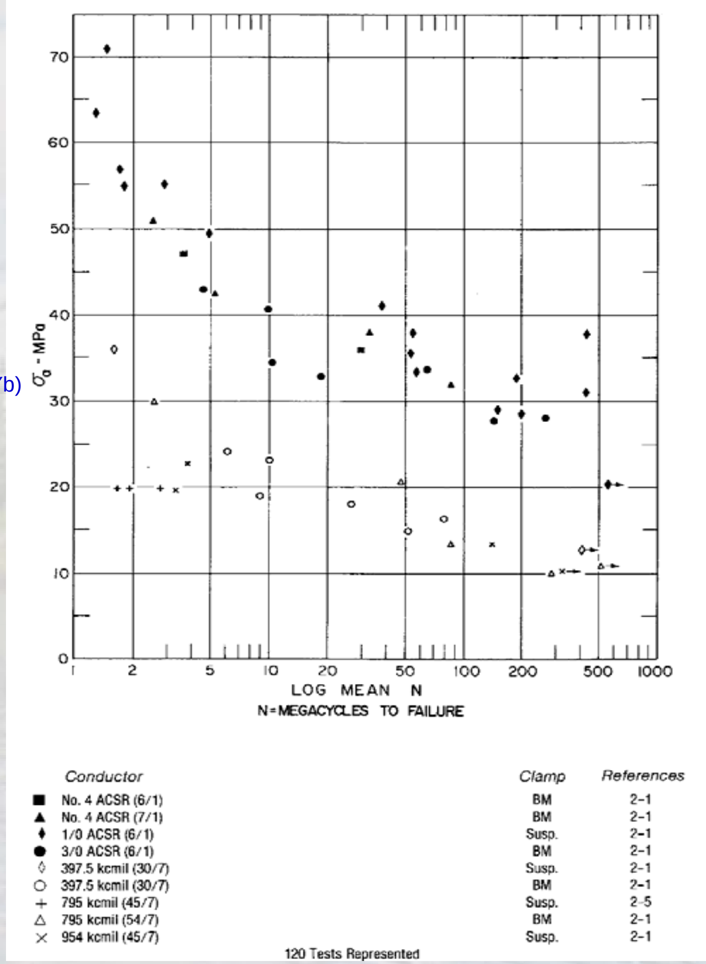
22.5 MPa for single-layer ACSR

8.5 MPa for multi-layer ACSR

stress as function of fy_{max}:

22 MPa for ACSR

f(Yb)



EPRI 1979

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

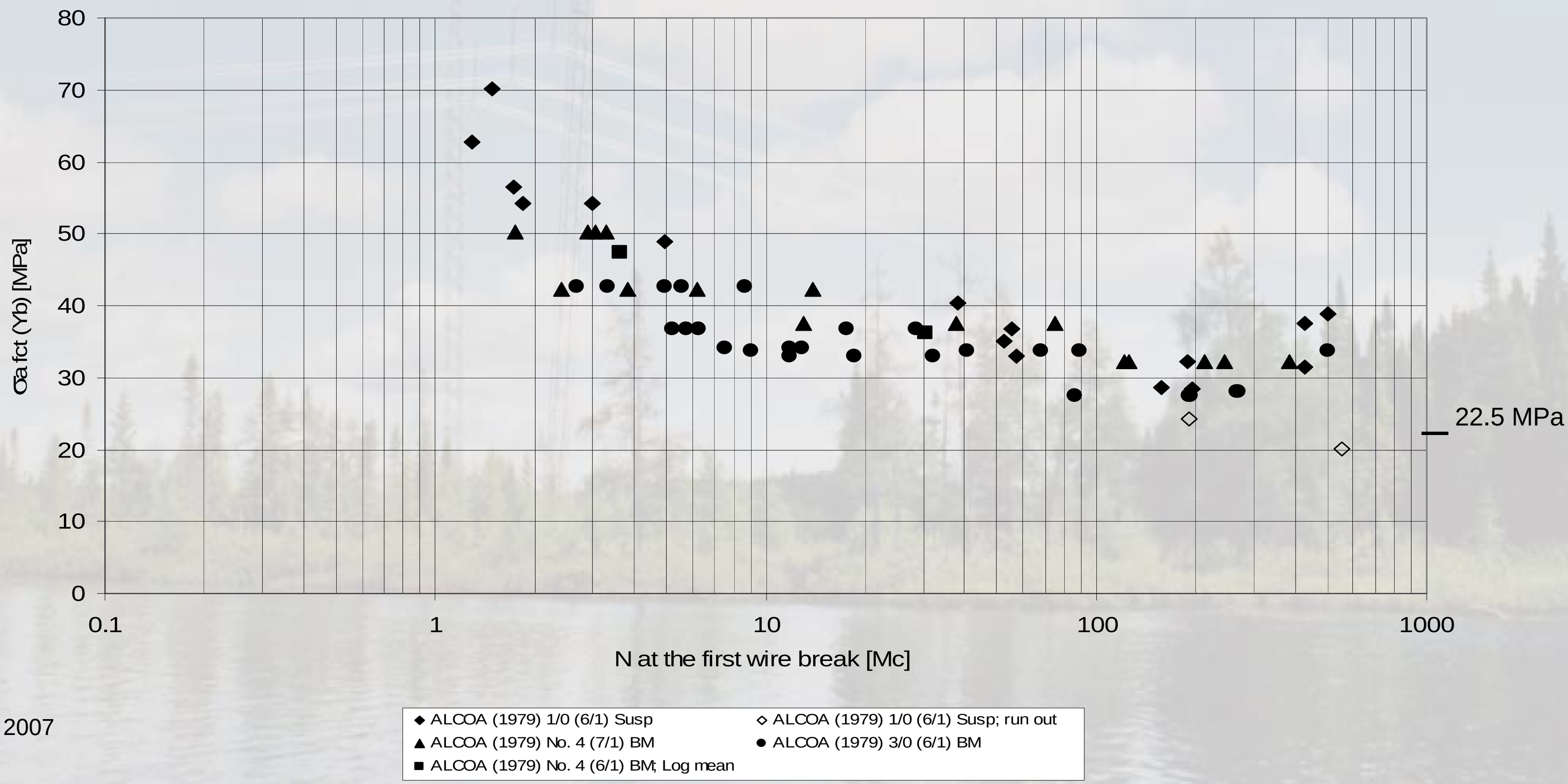

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Figure 3.2-23 Fatigue tests of single-layer ACSR.

Technology Watch for Gaps in Knowledge about Conductor Fatigue

LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

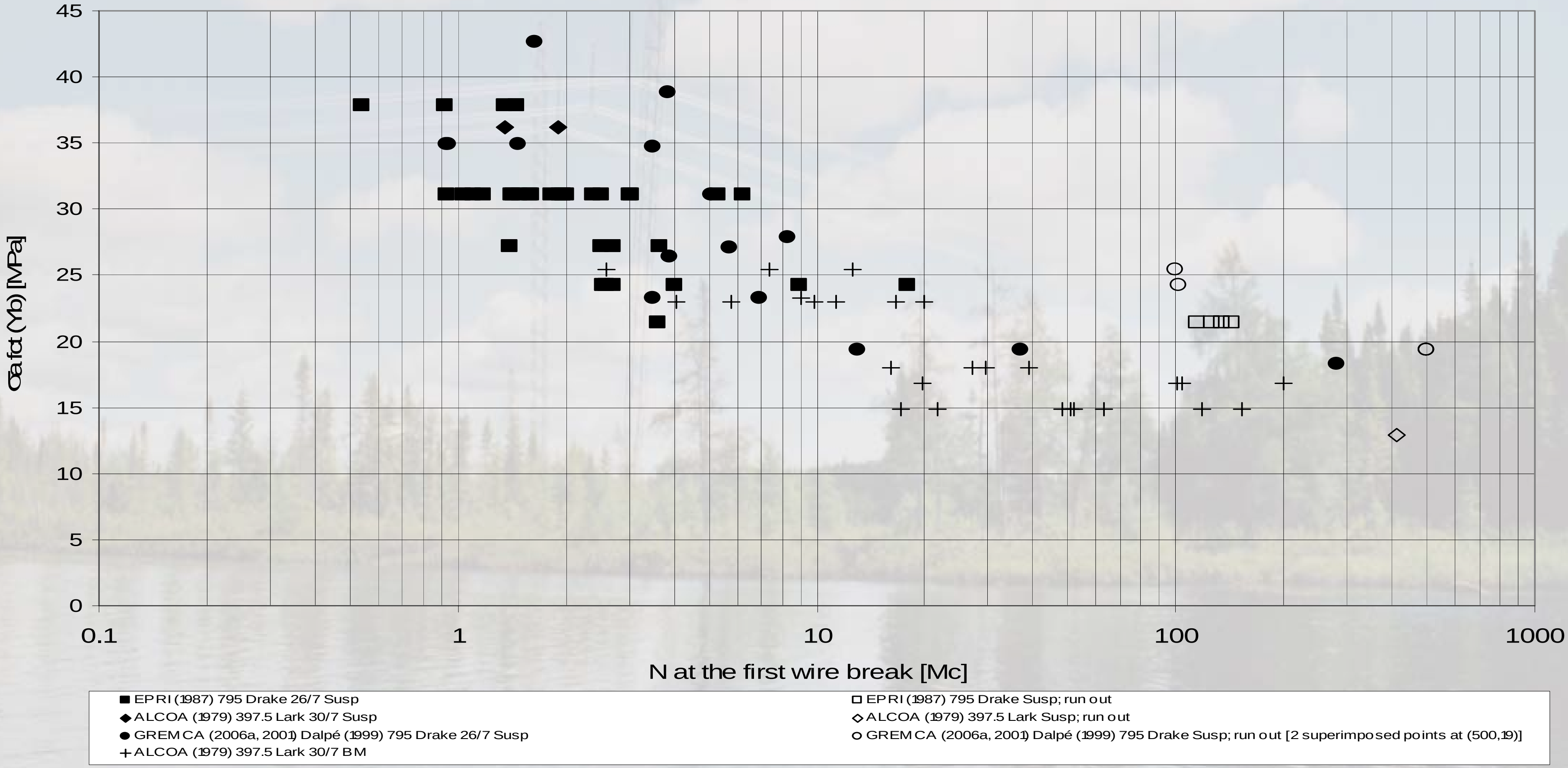

Figure 3.2-24 Fatigue tests of two-layer ACSR

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

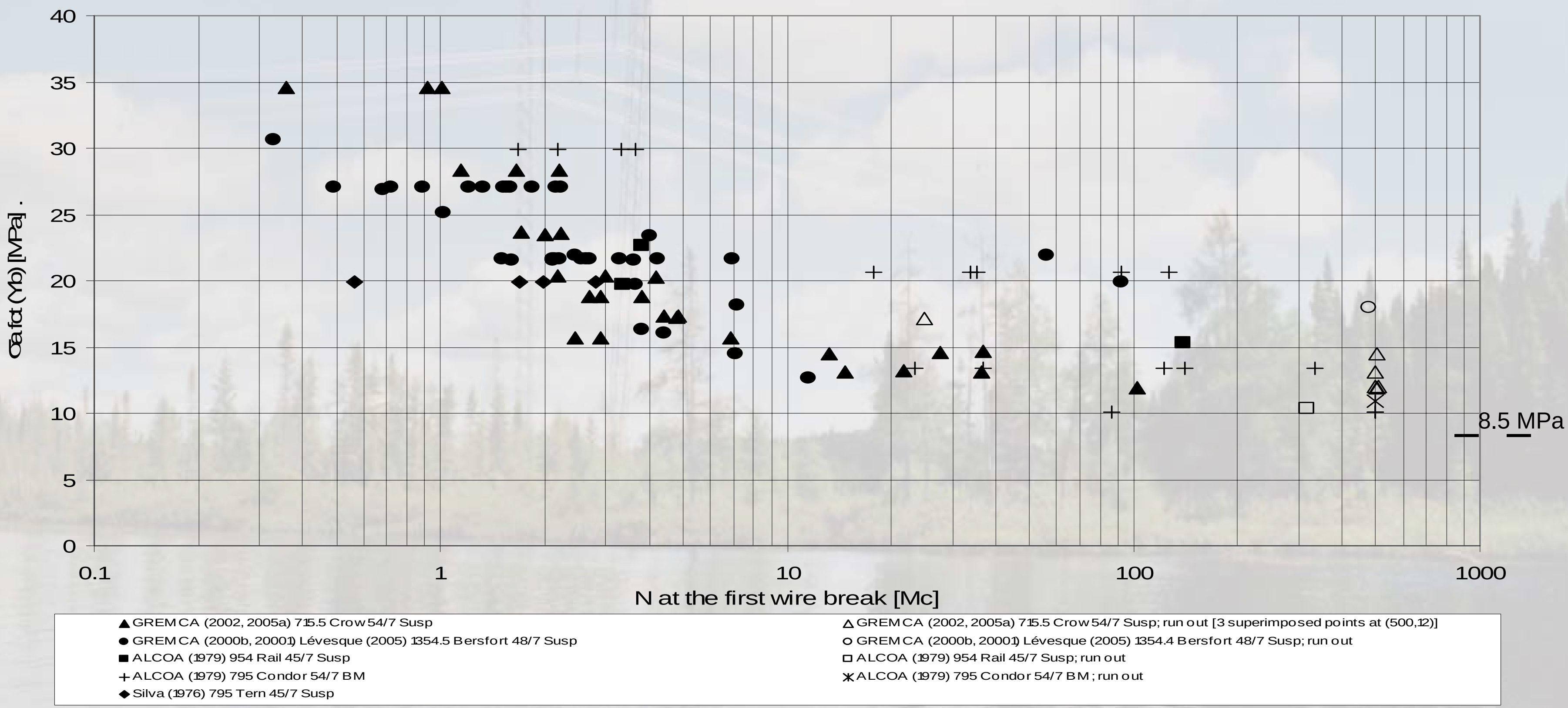

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Figure 3.2-25 Fatigue tests of three-layer ACSR

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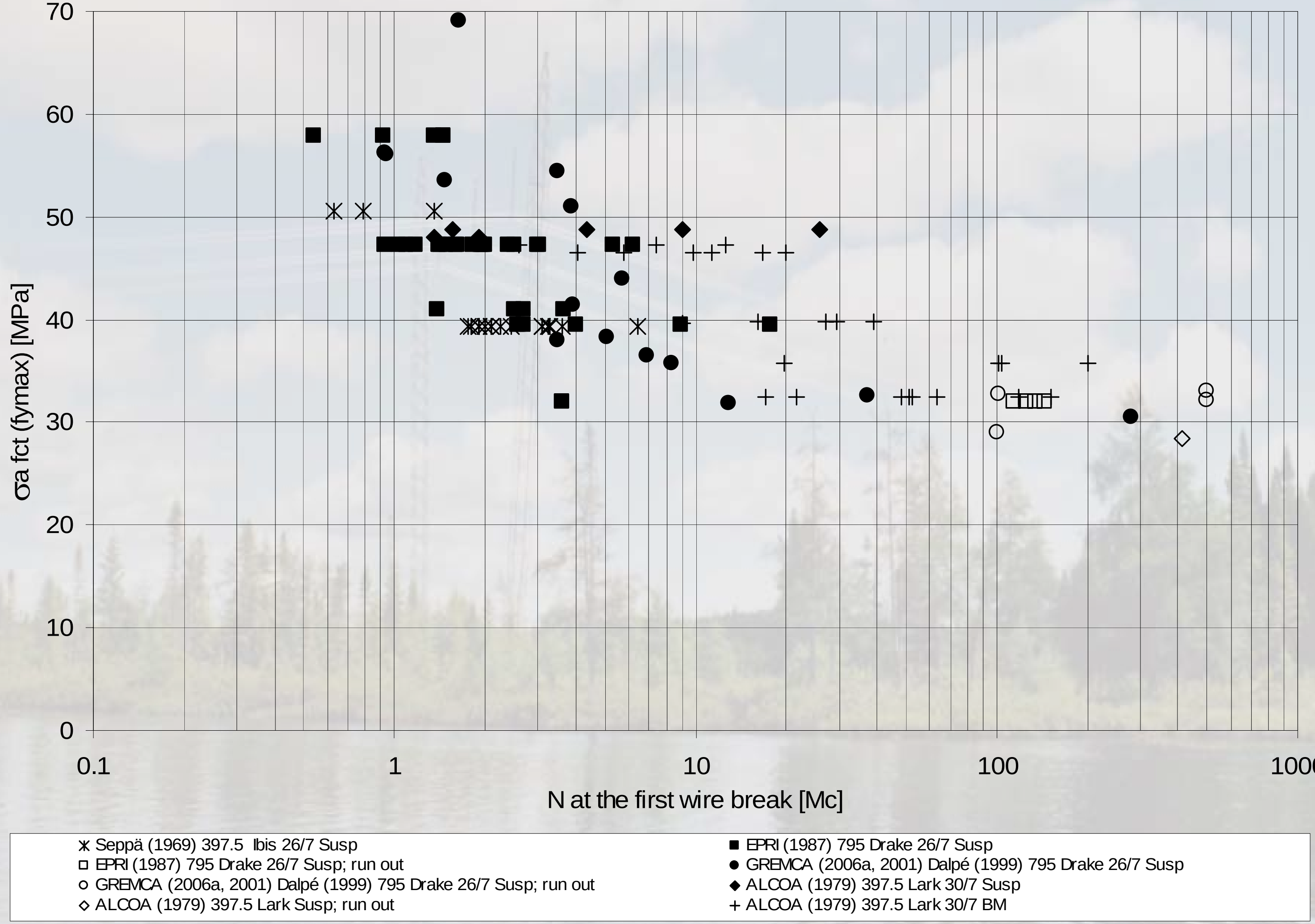

Figure 3.2-13a Fatigue tests of two-layer ACSR

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

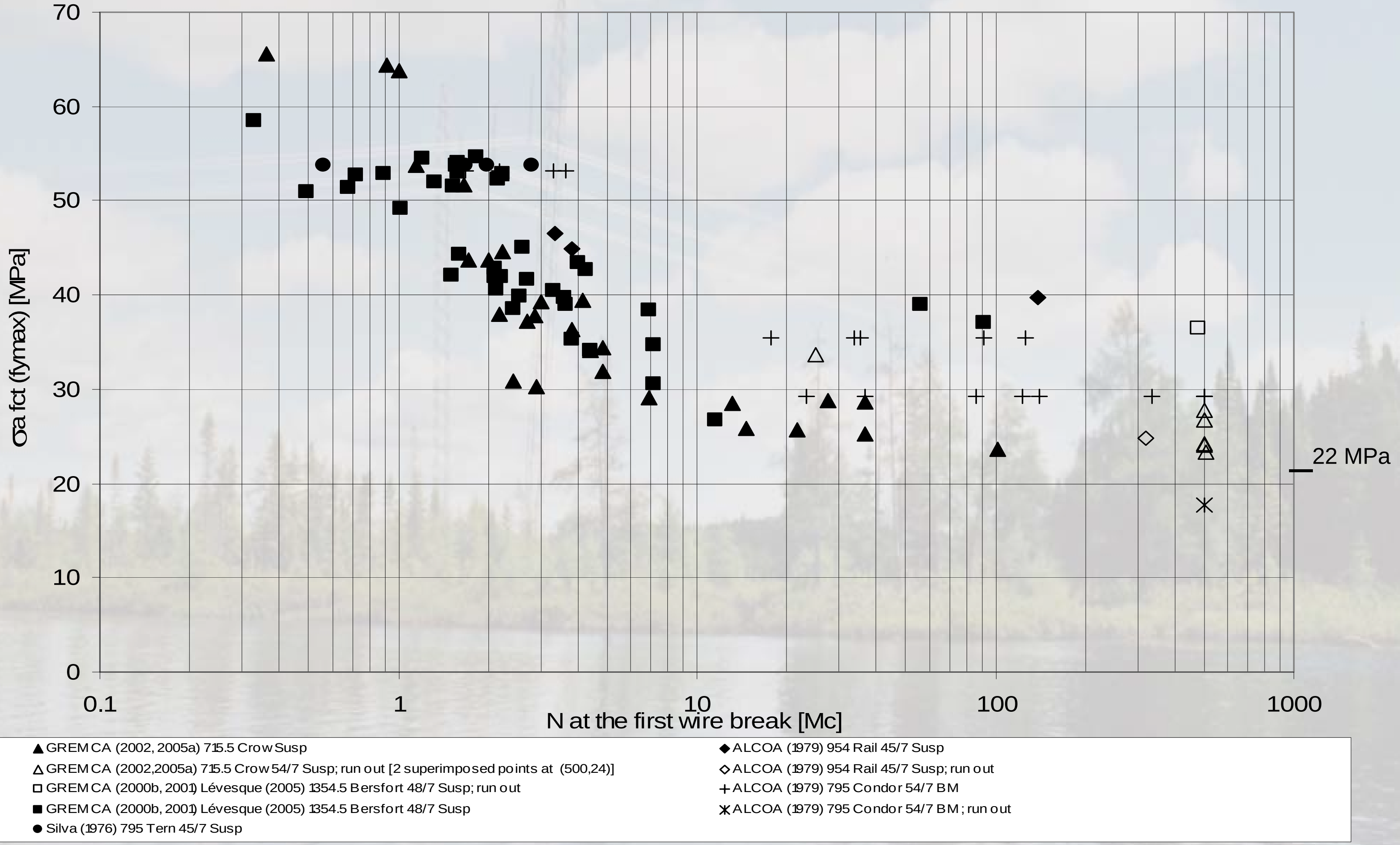

Figure 3.2-13b Fatigue tests of three-layer ACSR

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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Conversion of fy_{max} to Y_b endurance limits

Ratio Y_b/fy_{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.

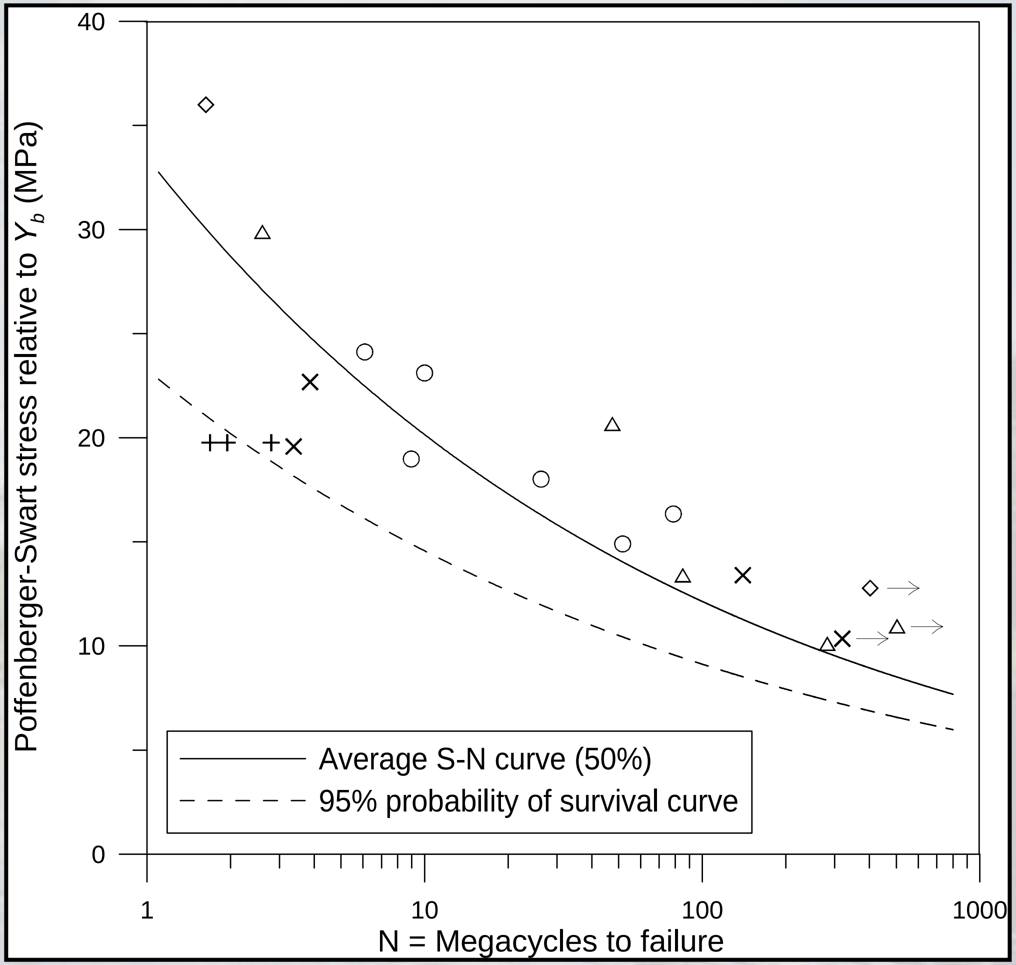
**Endurance limits that have been established in terms of fy_{max} may be converted to Y_b endurance limits by experimental determination in a laboratory span of the value of Y_b that corresponds to the fy_{max} endurance limit.
This should be done at the fy_{max} endurance limit. Y_b does not always vary linearly with fy_{max}.**

Technology Watch for Gaps in Knowledge about Conductor Fatigue

LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Statistical representation of two *S-N curves:*

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



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LABORATORY DETERMINATION OF FATIGUE ENDURANCE CAPABILITY

Estimated bending amplitude endurance limits for ACSR

EPRI 1979

ESTIMATED BENDING AMPLITUDE ENDURANCE LIMITS FOR ACSR (Continued)

Name	Conductor Size (kcmils)	Stranding	15 % Y_b mm	15 % mils	25 % Y_b mm	25 % mils	35 % Y_b mm	35 % mils
			Tension in Percent of Rated Strength*					
Ruddy	900.0	45 / 7	0.30	12	0.26	10	0.23	9
Canary	900.0	54 / 7	0.31	12	0.27	10	0.24	9
Catbird	954.0	36 / 1	0.29	11	0.26	10	0.24	9
Rail	954.0	45 / 7	0.29	12	0.26	10	0.23	9
Cardinal	954.0	54 / 7	0.30	12	0.26	10	0.24	9
Ortolan	1033.5	45 / 7	0.29	11	0.25	10	0.23	9
Curlew	1033.5	54 / 7	0.30	12	0.26	10	0.23	9
Bluejay	1113.0	45 / 7	0.28	11	0.25	10	0.22	9
Finch	1113.0	54 / 19	0.28	11	0.24	9	0.22	9
Bunting	1192.5	45 / 7	0.28	11	0.24	10	0.22	9
Grackle	1192.5	54 / 19	0.27	11	0.24	9	0.21	8
Bittern	1272.0	45 / 7	0.27	11	0.24	9	0.22	9
Pheasant	1272.0	54 / 19	0.27	11	0.24	9	0.21	8
Dipper	1351.5	45 / 7	0.27	11	0.24	9	0.22	9
Martin	1351.5	54 / 19	0.27	11	0.23	9	0.21	8
Bobolink	1431.0	45 / 7	0.26	10	0.23	9	0.21	8
Plover	1431.0	54 / 19	0.26	10	0.23	9	0.21	8
Nuthatch	1510.5	45 / 7	0.26	10	0.23	9	0.21	8
Parrot	1510.5	54 / 19	0.26	10	0.23	9	0.21	8
Lapwing	1590.0	45 / 7	0.26	10	0.23	9	0.21	8
Falcon	1590.0	54 / 19	0.26	10	0.23	9	0.20	8
Chukar	1780.0	84 / 19	0.29	11	0.25	10	0.23	9
Bluebird	2156.0	84 / 19	0.28	11	0.24	10	0.22	9
Kiwi	2167.0	72 / 7	0.27	11	0.24	10	0.22	9
Thrasher	2312.0	76 / 19	0.27	11	0.24	9	0.22	9
Joree	2515.0	76 / 19	0.26	10	0.23	9	0.21	8

- For other tensions, interpolate between values given

Technology Watch for Gaps in Knowledge about Conductor Fatigue

In-situ measurement of conductor vibation

Bending Amplitude Recorders

Vibrec 400

Pavica

Technology Watch for Gaps in Knowledge about Conductor Fatigue

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.

Technology Watch for Gaps in Knowledge about Conductor Fatigue

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:

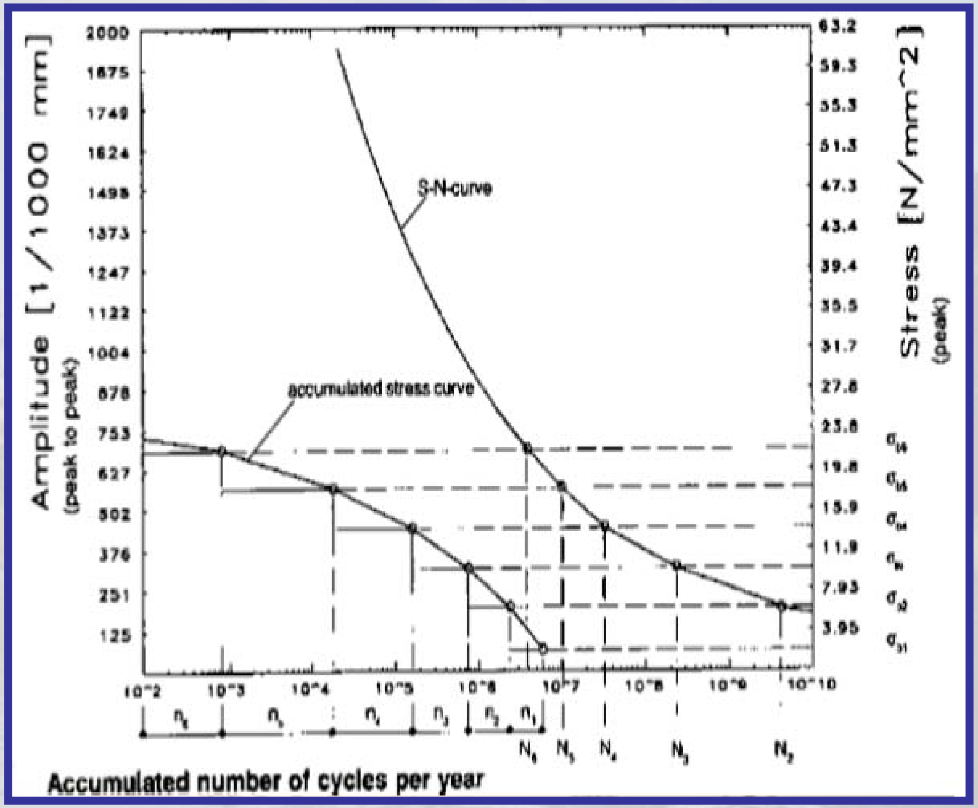
Total damage D at several stress levels σi cumulates linearly:

$$D = \Sigma\, n_i/N_i$$

Failure is predicted when:

$$D = \Sigma\, n_i/N_i = 1$$

Note: the use of D=1 has not been confirmed experimentally for conductors.



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*.**

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 fy_{max} in a fatigue test, the influence of the presence of armour rods could be evaluated.
Armour rods , for a given fy_{max}, will affect the value of Y_b at the clamp. (They could also reduce fy_{max} at given wind conditions)

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.

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)**

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**

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.

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 accomodate 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)

PROPOSAL FOR A RESEARCH PLAN

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**

DISCUSSION