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# ENGINEERING GUIDELINES RELATING TO FATIGUE ENDURANCE CAPABILITY OF CONDUCTOR/CLAMP SYSTEMS

**Working Group**
**B2.30**

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## Working Group B2.30

### Members

Louis Cloutier, **Convenor** (CA), André Leblond, **Secretary** (CA), Umberto Cosmai (IT),
Peter Dulhunty (AU), Magnar Ervik (NO), David G. Havard (CA), David Hearnshaw (GB) (Convenor B2-AG-06), Hans-Jörg Krispin (DE), Marta Landeira (ES), Philippe Mouchard (FR),
Konstantin O. Papailiou (DE), David Sunkle (US), Brian Wareing (GB)

### Corresponding Members

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Giorgio Diana (IT), Kjell Halsan (NO), Charles B. Rawlins (US), Rob Stephen (ZA),
Phil Timbrell (AU)

### Associated Experts

Tom Alderton (US), Jim Duxbury (CA), Anand Goel (CA), Claude Hardy (CA), André Laneville (CA)
Alessandra Manenti Diana (IT), Serge Pichot (FR), Tapani Seppä (US), Pierre Van Dyke (CA)





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Transmission lines are *engineering systems*. Their design and maintenance requires expertise in several aspects of engineering namely: electrical, civil and mechanical. It is common practice though, in engineering, to separate problems into smaller ones and to try to find practical solutions to some particular aspects in order to achieve a safer and more economical product. Aeolian vibration and fatigue of conductors are good examples of such an approach.

The fatigue endurance capability of conductors represents a parameter of paramount importance at the design stage as well as for maintenance programs. However its place does not seem to be always well defined. The common practice often addresses the most frequent phenomenon causing fatigue of conductors, *i.e. the amplitude of aeolian vibration*, to determine appropriate design parameters or accessories and for the assessment of a the projected lifetime of new lines. The assessment of residual service life of a line, needless to say, includes the *evaluation of the occurrence of actual fatigue damage* and it forces one to go deeper in the analysis of the phenomenon itself.

Both aspects are usually the objects of separate studies because one starts when the other finishes. Yet it may lead to misinterpretation (by undue simplification) when establishing the degree of control of the problem, *e.g. what is the parameter one uses in order to estimate that the amplitudes of vibrations (calculated or measured) are kept at an acceptable level?* It is common practice to say that one measures *aeolian vibration* when in fact it is an *index of curvature* at suspension clamps which is sought. The main interest of such an index is that it can be related to laboratory fatigue test results. Too often, one forgets that such results are highly dependant on the *conductor/clamp system* tested. Indeed, most of the stranded conductor fatigue results refer to those obtained when the conductor is *supported in a fixed short metallic clamp*, representing the most stringent conditions. As it is on the conservative side, no strong concerns have yet been expressed for that limitation.

The availability of many different clamp designs, which will be reviewed in this brochure, indicates that the time has come to delve a little more into this aspect and its influence on the evaluation of conductor endurance capability. The subject of conductor fatigue has already been studied extensively and *design tools* have been proposed. It is understood, though, that a lot remains to be done.

The practicing line engineer who tries to draw a line in order to apply the latest technology may face a difficulty in making a choice. In order for the engineer to draw a simplified picture of the state of the art, it could be useful to review the available *design tools* proposed by the experts and to establish as clearly as possible their limitations. It will then be possible for the engineer :

- to identify the *design tools* available to be used and to appreciate the *gaps in their application*;
- to *achieve a better comprehension* of the two phenomena, fatigue of conductors and aeolian vibration, for a more correct interpretation of the results obtained when using these *design tools*.

These *engineering guidelines* present a brief review of the components of the conductor/clamp systems. Too often the transmission line engineer tends to simplify the analysis of the system to be evaluated in order to be in a position to use the limited data base available to establish the fatigue life of a conductor. Conductor designs are not unique and their geometry greatly affects the fatigue performance. Different types of conductor geometry could lead to fatigue endurance results that are very different to those of the most commonly tested, which are the ACSR conductors.

Conductor fatigue most often occurs at suspension clamps, but it may also occur elsewhere on the conductor where a clamp is present (e.g. damper, spacer etc.). To assure a more thorough coverage of this part of the subject, the description of the different types of clamps used on a line is also presented.

Finally, the *design tools presently available* for the prediction of aeolian vibration amplitudes, the measurements of *in situ* conductor vibrations and the determination of the fatigue endurance of a conductor clamp system are presented. Important limitations in the use of the present design tools for the *determination of the fatigue endurance* of a system and *the prediction of aeolian vibration amplitudes* on a line are also discussed.

## 1.2 Conductor/Clamp Systems

The conductor of an overhead power line is considered to be the most important component of the overhead line since its function is to transfer electric power and its contribution towards the total cost of the line is significant. Consequently, much attention has to be given to the selection of a conductor configuration to meet present and predicted future load requirements.

The simplest and most widely used form of conductors is that of layers of round wires stranded first around a so-called core, which can be of the same material or different, and then around each other. In order to keep the integrity of this construction, the stranding takes place in alternating directions from layer to layer. For aluminium conductors, the usual convention is to wrap the outer layer with a right hand lay. For conductors with equal diameter wires, each lay has six wires more than the layer beneath it, which, in most of the cases, gives a good *fit* in every layer.

Apart from the *standard* conductor designs there are also a number of special designs, such as conductors with high steel content for very long spans (river crossings), smooth body conductors and expanded conductors. Another way to improve and tailor conductors to special situations is to shape the aluminium wires. Over the past 30 years, the development of trapezoidal and Z-shaped wires has contributed to the improvement of conductor design. These conductors make better use of the space compared to round-wire conductors and are therefore called *Compact*. The shape of the wires allows for an infinite number of area and strength-to-weight ratios and can be used with almost any alloys.

The fatigue behaviour of stranded conductors is highly complex. It occurs at singular points on the conductor (e.g. suspension clamps) where motion is constrained. Considering the great influence of the type of conductor support on the results of conductor fatigue endurance capability, it is important to have a clear image of the different conductor supports available, despite the fact that a complete study of the impact of their design on the fatigue performance of a conductor *has yet to be completed*.

Practically 99% of vibration failures take place very near to, or at, the clamp location. Clamp design is of great importance for the mechanical integrity of the conductor and thus for the operational safety of a line. Nevertheless the conductor/clamp combination is not susceptible to a quantitative approach and so there are more practical engineering design rules, which have evolved from experience over the years, for a good, practical clamp design (CIGRE 22.11 TF3 1989).

## 1.3 Design Tools: Aeolian Vibration and Conductor Fatigue

### 1.3.1 Background

Relating the measurable vibrations of an overhead span of conductor to the likelihood of fatigue of its strands is a complicated matter. The complications arise primarily from two facts. Firstly, the stresses that cause the failures are complex and not related in a simple way to the gross motions of the conductor involved. Secondly, the failures originate at locations where there is surface contact and fretting between components. Approaches available to guide an assessment of the severity of aeolian vibration can be pragmatic, through design rules based on past experience. Conditions can also be assessed through measurements on existing lines.

### 1.3.2 Energy Balance Principle

Another way is to use an analytical approach to simulate the conditions on the line. This approach can be usefully used to investigate alternatives in the design or redesign process and also, *being aware of its limits,* in the direct design of the damping system for a new line. The most used analytical models are based on the Energy Balance Principle (EBP), which permits the determination of an estimate of an upper limit to the expected vibratory motion. The EBP works in the frequency domain: in its simplest form, one mode of vibrations at a time is considered and steady state conditions computed corresponding to the maximum vibration amplitude which could be excited on that conductor at that frequency. The straightforward EBP is considered acceptable for use for engineering applications. A number of computer programs have been written around it, most of which can be implemented on a personal computer.

### 1.3.3 <u>Conductor Safe Design Tension</u>

It is well known that if the conductor tension, or more precisely the ratio between horizontal tension and conductor unit weight *H/w* exceeds certain limit value (CIGRE SCB2 WG11 TF4 2005), aeolian vibration may cause serious conductor and fitting damage. This limit is often exceeded in transmission lines and it is necessary to protect the conductors with suitable dampers. Thus, while designing a new transmission line it is important to know how much additional damping is needed to control aeolian vibrations within safe levels.

### 1.3.4 <u>*In Situ* Measurement of Conductor Vibration</u>

Several methods to measure *in situ* the vibration intensity of a conductor have been employed. (CIGRE TB # 332). Most of them did not progress to the stage permitting the development of practical instruments for use in a maintenance program. The bending amplitude method finally emerged as the most practical one. It permits a measure of the differential displacement of the conductor, $Y_b$, at 89 mm from the last point of contact (LPC) of the conductor with the clamp. The advantages of the bending amplitude method have been its simplicity and the relative ease with which the measured values could be related to useful parameters for the evaluation of the severity of the phenomenon and also for the possibilities of designing reliable and practical vibration recorders.

### 1.3.5 <u>Laboratory Tests</u>

Either at the design stage or for an evaluation of the residual life of a line, there is a need to relate the potential level of vibrations of an overhead conductor to the likelihood of fatigue of its strands. Fatigue tests are advantageous for an endurance assessment as well as for an improvement of clamp design. The exact modelling of the actual phenomenon is indeed a complicated matter. The failures originate at inter-layer strand contacts or at contacts between the outer strands and the line accessories where conditions for fretting are present. The definition of a more appropriate model than the one presently proposed to represent the actual phenomenon remains to be completed as mentioned above. Thus, it is still opportune to note not only that fatigue characteristics of conductors must be determined by fatigue tests of *conductors themselves* (Rawlins 1979), but also that tests should be conducted *with clamps having similar characteristics* to those of the conductor/clamp system being characterized. A guide for endurance tests of conductors inside clamps was prepared by CIGRE SC22 WG04 in 1985, where it is rightly reminded that *to arrive at comparable results in different laboratories, an agreement on important test parameters and on an uniform method is necessary.* Lately, IEC formed a group of experts to propose a standard for laboratory measurement of fatigue characteristics conductor/clamp systems.

## 1.4 Conclusion

Fatigue endurance capability of conductors is a parameter that the transmission line engineer must control at the design stage as well as for a maintenance program. As explained in this brochure, it is a phenomenon closely related to the presence of aeolian vibration. Both phenomena are highly complex and some of the avenues aimed at the development of more precise and complete solutions are still the object of research studies. CIGRE TB # 332 presented an update of the present knowledge on the subject. Fortunately, engineering solutions were also sought concurrently and design tools are available. This brochure is intended to give the transmission line engineer a review of the design tools that can be used to evaluate the fatigue endurance capability of conductors. It is important for the engineer to recognise and take into account the inherent limitations of those tools.

# 2. Introduction

## 2.1 Aeolian Vibration and Fatigue of Conductors

Transmission lines are *engineering systems*. Their design and maintenance require expertise in several aspects of engineering namely: electrical, civil and mechanical. It is common practice though, in engineering, to separate problems into smaller ones and to try to find practical solutions to some particular aspects in order to achieve a safer and more economical product. Aeolian vibration and fatigue of conductors are good examples of such an approach.

The fatigue endurance capability of conductors represents a parameter of paramount importance at the design stage as well as for maintenance programs. However its place does not seem to be always well defined. The common practice often addresses the most frequent phenomenon causing fatigue of conductors, *i.e. the amplitude of aeolian vibration*, to determine appropriate design parameters or accessories and for the assessment of a the projected lifetime of new lines. The assessment of residual service life of a line, needless to say, includes the *evaluation of the occurrence of actual fatigue damage* and it forces one to go deeper in the analysis of the phenomenon itself.

Both aspects are usually the objects of separate studies because one starts when the other finishes. Yet it may lead to misinterpretation (by undue simplification) when establishing the degree of control of the problem, *e.g. what is the parameter one uses in order to estimate that the amplitudes of vibrations (calculated or measured) are kept at an acceptable level?* It is common practice to say that one measures *aeolian vibration* when in fact it is an *index of curvature* at suspension clamps which is sought. The main interest of such an index is that it can be related to laboratory fatigue test results. Too often, one forgets that such results are highly dependant on the *conductor/clamp system* tested. Indeed, most of the stranded conductor fatigue results refer to those obtained when the conductor is *supported in a fixed short metallic clamp*, representing the most stringent conditions. As it is on the conservative side, no strong concerns have yet been expressed for that limitation. The availability of many different clamp designs, which will be reviewed in this brochure, indicates that the time has come to delve a little more into this aspect and its influence on the evaluation of conductor endurance capability. The subject of conductor fatigue has already been studied extensively and *design tools* have been proposed. It is understood, though, that a lot remains to be done.

A recent CIGRE Technical Brochure # 332, *Fatigue Endurance Capability of Conductor/Clamp Systems – Update of Present Knowledge* reviews the whole subject. The reader is also referred to Chapter 3, *Fatigue of Overhead Conductors,* of the recent EPRI Transmission Line Reference Book-Wind-induced Conductor Motion, Second Edition, for detailed information on the phenomenon and on recent findings aimed at a better understanding of the problem.

## 2.2 Making the Choice

The practicing line engineer who tries to draw a line in order to apply the latest technology may face a difficulty in making a choice. In order for the engineer to draw a simplified picture of the state of the art, it could be useful to review the available *design tools* proposed by the experts and to establish as clearly as possible their limitations. It will then be possible for the engineer:

- to identify the *design tools* available to be used and to appreciate the *gaps in their application*;
- to *achieve a better comprehension* of the two phenomena, fatigue of conductors and aeolian vibration, for a more correct interpretation of the results obtained when using these *design tools*.

These *engineering guidelines* will first present a brief review of the components of the conductor/clamp systems. Too often the transmission line engineer tends to simplify the analysis of the system to be evaluated in order to be in a position to use the limited data base available to establish the fatigue life of a conductor. Conductor designs are not unique and their geometry greatly affects the fatigue performance. The reader will realise that several types of conductor geometry could lead to fatigue endurance results that are very different to those of the most commonly tested, which are the ACSR conductors.

The fatigue behaviour of stranded conductors is highly complex. It occurs at singular points on the conductor (e.g. suspension clamps) where motion is constrained. Considering the great influence of the type of conductor support on the results of conductor fatigue endurance capability, it is important to have a clear image of the different conductor supports available, despite the fact that a complete study of the impact of their design on the fatigue performance of a conductor *has yet to be completed*. Conductor fatigue most often occurs at suspension clamps, but it may also occur elsewhere on the conductor where a clamp is present (e.g. damper, spacer etc.). To assure a more thorough coverage of this part of the subject, the description of the different types of clamps used on a line is also presented.

Finally, the *design tools presently available* for the prediction of aeolian vibration amplitudes, the measurements of *in situ* conductor vibrations and the determination of the fatigue endurance of a conductor clamp system are presented. Important limitations in the use of the present design tools for the *determination of the fatigue endurance* of a system and *the prediction of aeolian vibration amplitudes* on a line are also discussed.

# 3. Conductor/Clamp Systems

## 3.1 Conductors

### 3.1.1 Introduction

The conductor of an overhead power line is considered to be the most important component of the overhead line since its function is to transfer electric power and its contribution towards the total cost of the line is significant. Conductor cost (material and installation costs) associated with the capital investment of a new overhead power line can contribute to up to 40% of total capital costs of the line. Consequently, much attention has to be given to the selection of a conductor configuration to meet present and predicted future load requirements.

Continuous changes in the cost of suitable conductive materials for bare conductors, changes in mechanical requirements, changes in electrical requirements and improvements in manufacturing technology have led to dynamic development resulting in a variety of possible options and applications. The move has been from simple copper wire or copper based bare conductors in the early days to more cost-effective solutions, such as aluminium and variations of aluminium alloy conductors.

As mentioned above, the geometric and mechanical properties of conductors play an important role in vibration assessment.

### 3.1.2 Types and basic properties of conductors

Overhead transmission lines transmit electric power using stranded cables called conductors. In fact, conductors are the only active component of a transmission line. Conductors have to sustain a range of electrical, mechanical and environmental loads over the projected life expectancy of a line, which can be well over 50 years of service. Therefore special attention is given to the selection of their constituent materials, their layout and design. It is relevant to briefly summarize here the common types and basic properties of conductors employed today in transmission lines (Aluminium Association 1982, Southwire Company 1994).

The simplest and most widely used form of conductors is that of layers of round wires stranded first around a so-called core, which can be of the same material or different, and then around each other. In order to keep the integrity of this construction, the stranding takes place in alternating directions from layer to layer. For aluminium conductors, the usual convention is to wrap the outer layer with a right hand lay. For conductors with equal diameter wires, each lay has six wires more than the layer beneath it, which, in most of the cases, gives a good ***fit*** in every layer, Figure 1. However, in order to tailor the conductor for various strength-to-weight ratios, unequal diameter wires are often used with success.

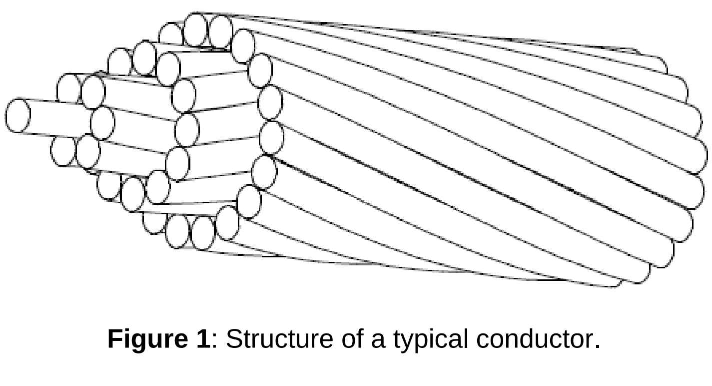


**Figure 1**: Structure of a typical conductor.

Most of the requirements for conductor design come from mechanical constraints. The electrical aspects of conductors are usually limited to current density and voltage gradient and are usually easily solved by adding area and adjusting the outside diameter or using multi-conductor bundles on the line. The most common types of bare overhead conductors are constructed from commercially pure aluminium, known as AA1350 and referred to as All Aluminium Conductor (AAC) or Aluminium Stranded conductor (ASC). Because of its relative low strength-to-weight ratio (which is the most important mechanical criterion) these types of conductors are suitable for short spans in distribution networks and for areas where ice and wind loads are limited, Figure 2, as well as in transmission lines for slack spans at line extremities.

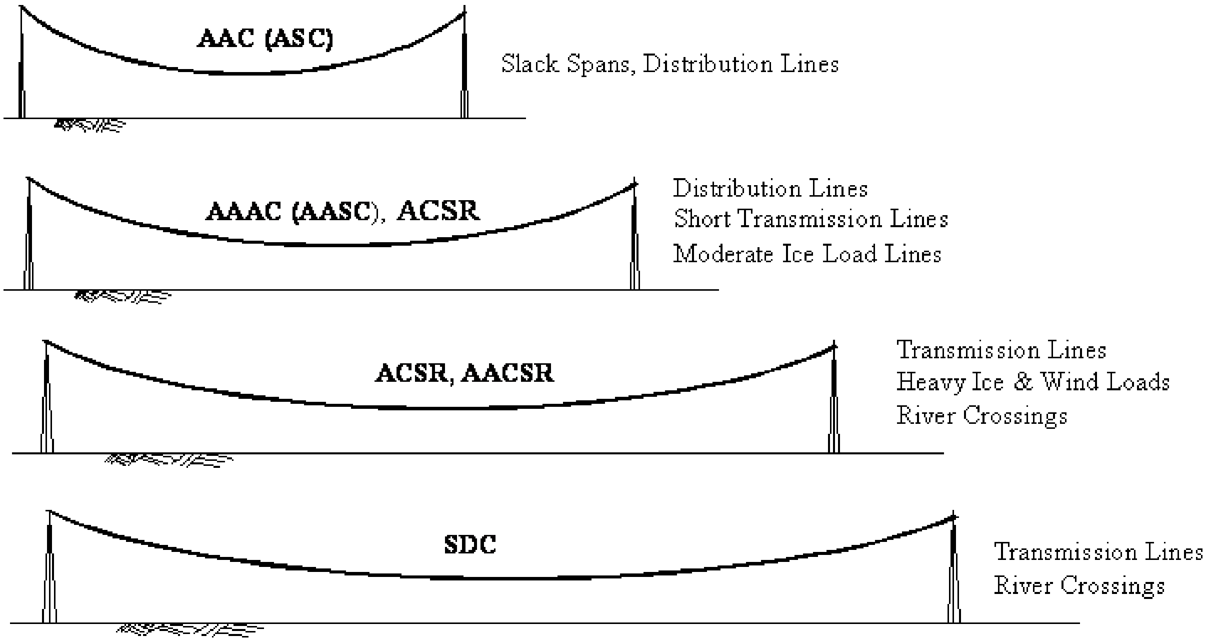



**Figure 2**: Bare conductors typical use.

For added strength, various aluminium alloys have been developed, and these conductors are referred to as All Aluminium Alloy Conductor (AAAC) or Aluminium Alloy Stranded Conductor (AASC). Early versions of these alloys used magnesium as the main alloying element, which had strain-hardening properties. This produced mechanical characteristics that vary with wire diameters, which is not desirable. For this reason, most alloys used today are of the AA6000 series, which are heat-treatable and more consistent.  It should be noted that any improvement in strength is usually to the detriment of conductivity, Figure 3.

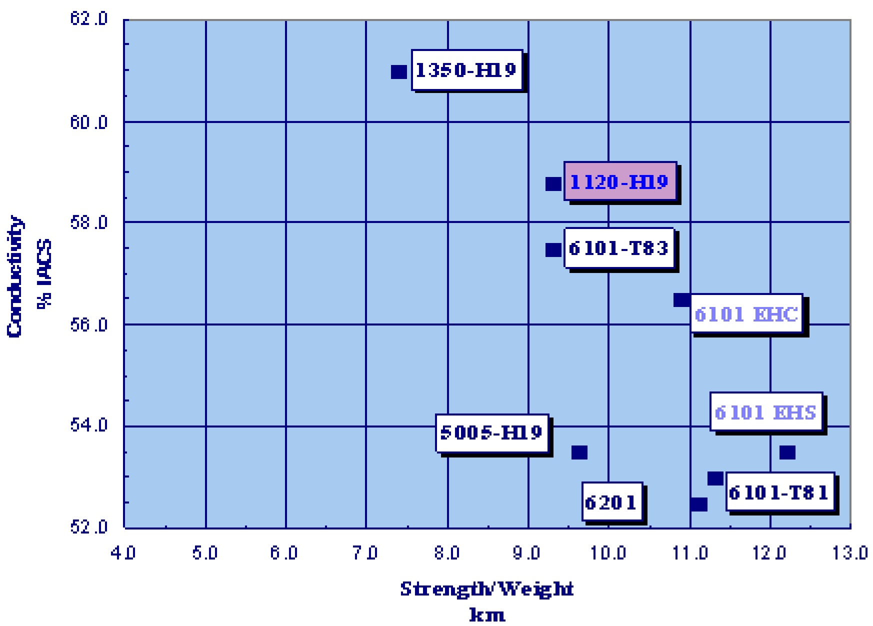



**Figure 3**: Properties of aluminium alloys.

Aluminium Conductor Steel Reinforced (ACSR), Aluminium Conductor Alloy Reinforced (ACAR) and Aluminium Alloy Conductor Steel Reinforced (AACSR) are variations of the above conductors. When a better strength-to-weight ratio is required, a strength member has to be added to the conductor. This is usually achieved with steel wires offering much higher strength-to-weight ratios than aluminium alloys, Figure 4.

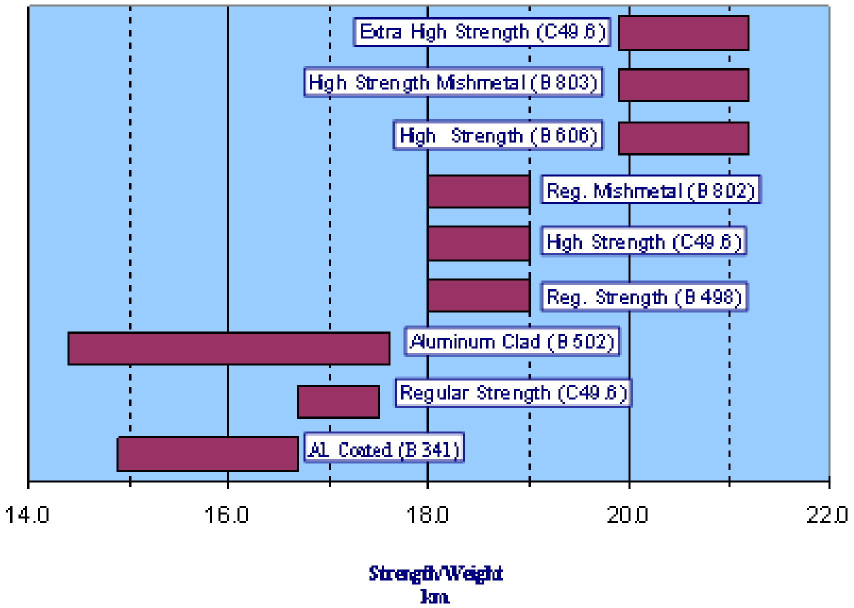



**Figure 4**: Properties of steel.

In a few special cases, for example in an extremely corrosive (marine) environment, the use of ACAR eliminates the possible galvanic reaction that can occur between the steel and the aluminium. Copper conductors have been used on few occasions in extremely polluted areas but copper is too expensive and too heavy compared to aluminium. Steel conductors and steel based conductors (more steel than aluminium) can be used for long spans at crossings.

Apart from the *standard* conductor designs there are also a number of special designs, such as conductors with high steel content for very long spans (river crossings), smooth body conductors and expanded conductors. Another way to improve and tailor conductors to special situations is to shape the aluminium wires. Over the past 30 years, the development of trapezoidal and Z-shaped wires has contributed to the improvement of conductor design. These conductors make better use of the space compared to round-wire conductors and are therefore called *Compact*. The shape of the wires allows for an infinite number of area and strength-to-weight ratios and can be used with almost any alloys. Noteworthy is the Self-Damping Conductor (SDC), which allows much higher conductor tensions without the harmful effect of aeolian vibration, Figure 5.

A number of national and international standards exist for these conductors – ASTM in the US, CSA in Canada, CENELEC and IEC, all of which regulate the various constructions and properties of these conductors. It should be noted that these standards set the properties of the conductors but not their geometry. This is why the same conductor geometry will yield slightly different properties, depending on which standard is used to manufacture the conductors.

In the last few years, due to the ever increasing need to transport more power, there has been an increased use of so called high temperature conductors with special designs and materials, which are used for increasing the transmission capacity of a line, the so-called up-rating (CIGRE SCB2 WG12 2004). New ways have been devised to limit the harmful effect of high temperature on aluminium and its alloys by either adding zirconium to the aluminium or by fully annealing the wires before use. New core materials have been designed to limit the sag of the conductors at high temperature. Still relatively new, these new products will no doubt find their way into common usage in line design. Appendix 1 presents some more details concerning high temperature conductors. Their fatigue endurance limits remain to be evaluated though, considering the particular mechanical properties of their aluminium wires.

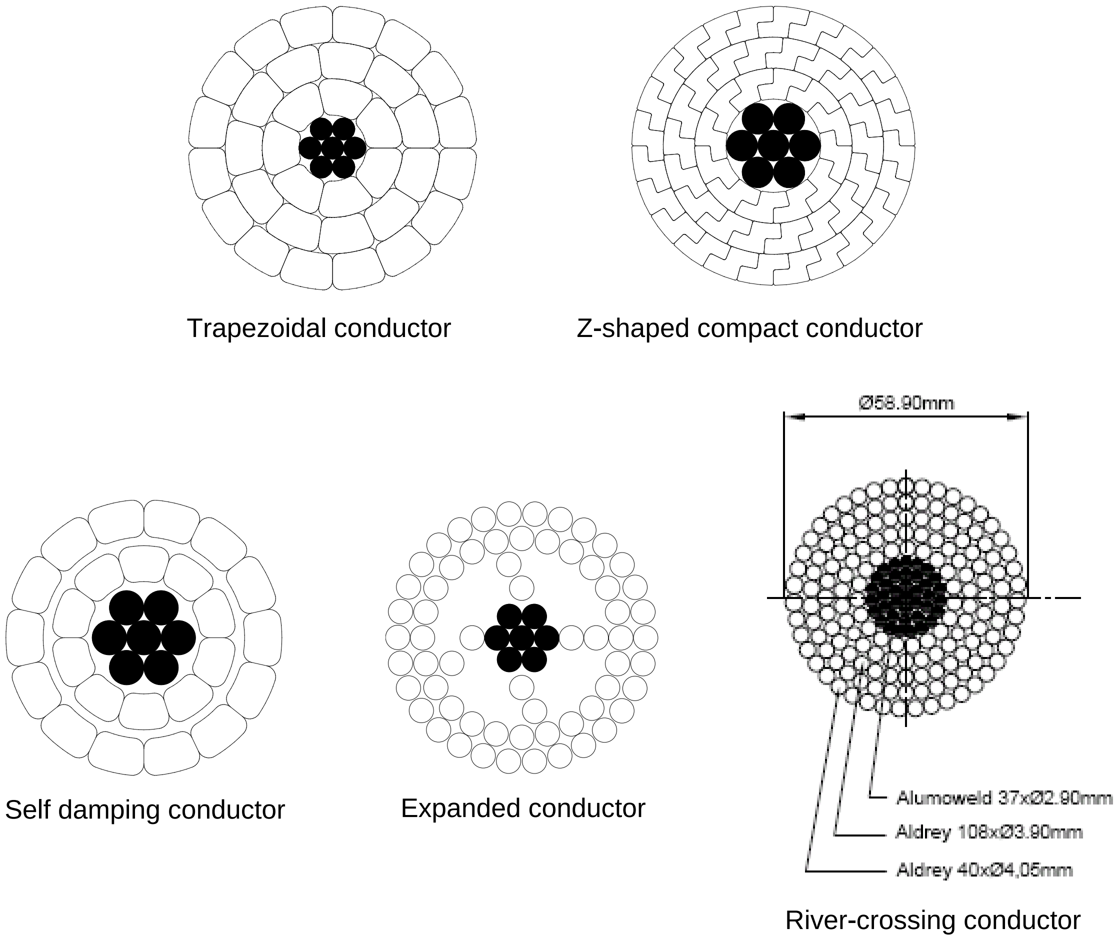



**Figure 5**: Cross sections of special conductors.

## 3.2 Clamping Systems

### 3.2.1 The Suspension

Suspension clamps are used to suspend the conductors from a suspension tower and have to fulfil a number of duties such as to:

- Withstand the mechanical loads imposed by the conductor;
- Avoid damage to the conductor in the clamp area
- Prevent/reduce strand failures because of vibrations as much as possible
- Assure good resistance to corrosion
- Assure sufficient corona inception voltage for the respective voltage level of the line
- Withstand short circuits, have low contact resistance and low electrical losses
- Assure simple and safe erection

As practically 99% of vibration failures take place very near to, or at, the clamp location, clamp design is of great importance for the mechanical integrity of the conductor and thus for the operational safety of a line. Nevertheless the conductor/clamp combination is not susceptible to a quantitative approach and so there are more practical engineering design rules, which have evolved from experience over the years, for a good, practical clamp design (CIGRE SC22 WG11 TF3 1989). These will be summarized in the following, with particular emphasis on the conductor clamps and their interactions with conductors.

Figure 6 shows some examples of suspension clamps while Figure 7 shows a special clamp for a long river crossing.

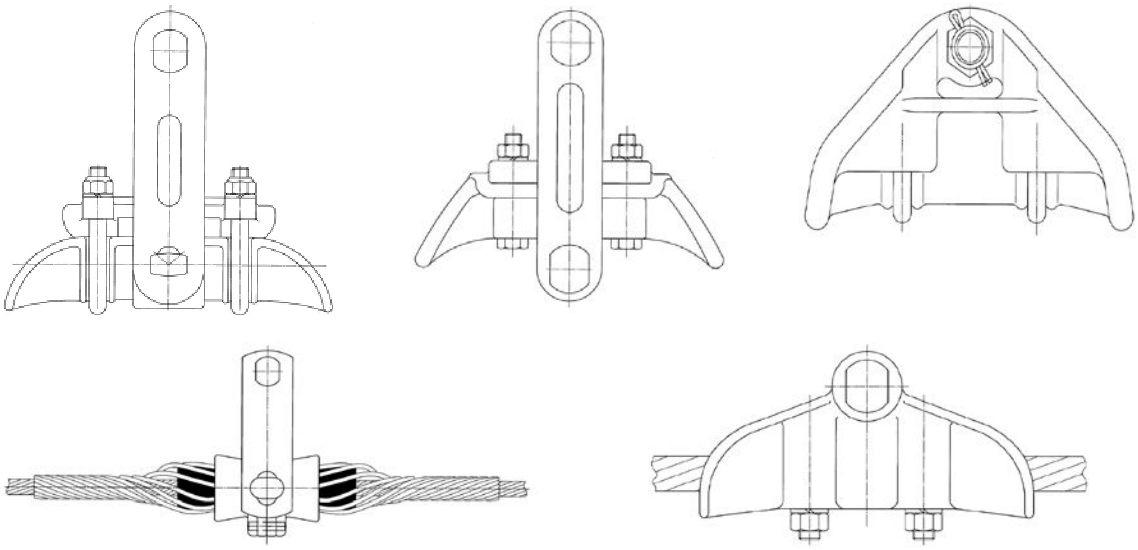


**Figure 6**: Various types of suspension clamps.

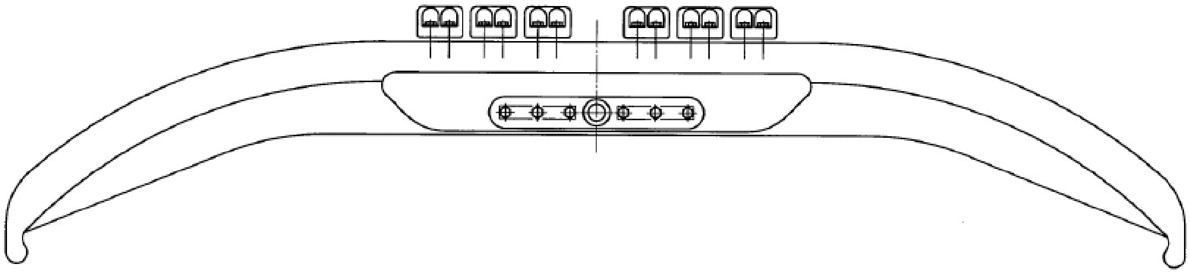


**Figure 7**: Special River crossing clamp made from hard drawn aluminum alloy material.

### 3.2.2 Body and Keeper Profile

Theoretically, the profile of the body should follow the natural curvature of the conductor and should not reduce the breaking strength of the conductor. However, as there are different load assumptions, it is not possible to satisfy this theoretical requirement under maximum, minimum or average turning angles.

An optimum profile design of the body and keeper must be found for the different load assumptions and the contact length of the suspension clamp. The profile of the body must also cope with asymmetrical adjacent spans, *i.e.* with different sag angles on each side of the clamp. The manufacturer should explain which criteria have been take into account for the optimisation of the shape, for instance which tests or what type of calculations have been carried out.

The main profile of the body must be rounded and curved into a bell mouth at the ends in order to avoid damage to the conductor in the case of exceptional overloads. This consideration should also be applied to the keeper design when conductor uplift is assumed.

As armour rods increase the stiffness of the conductor, they will also decrease its bending in the clamp.

### 3.2.3 Mobility

A suspension clamp should be able to rotate in a longitudinal vertical plane in order to accommodate asymmetrical loads and different spans on each side of the clamp. The amount of rotation required at the pivot point is generally much greater for earth wires than for phase conductors because of the short link in the support assembly of the former.

It is generally believed that the axis of rotation should not be more than a few conductor diameters from the conductor axis. In the case of a slip clamp, the rotational axis of the clamp should correspond as nearly as possible to the longitudinal axis of the conductor, i.e. the moment of inertia related to the rotational axis is minimised in order to reduce dynamic stresses. Whilst keeping the clamp mass low is an advantage, the contact area and contact pressure between conductor and clamp must withstand high current flows during flashovers, i.e. in these cases, the suspension clamp has to act as a current carrying clamp. This requirement may contradict the requirements for good vibration behaviour of the clamp. As is usual in these cases, the design will ultimately be a compromise.

The reader will find a more thorough coverage of clamp design in Appendix 2. It includes practical comments on different design of suspension, spacer, damper, termination and compression clamps.

# 4. Design Tools: Aeolian Vibration and Conductor Fatigue

## 4.1 Design Tools for the Prediction of Aeolian Vibration Amplitudes and for *in situ* Conductor Vibration Measurements

### 4.1.1 Background

Aeolian vibrations are caused by the regular shedding of vortices from bare conductors. It takes the form of vibration waves traveling back and forth in a span. Waves traveling in opposite directions superimpose on each other, tending to form standing waves. Wave reflection can cause localized bending at singular points on the conductor, which sometimes leads to fretting fatigue of the conductor strands and in some instances, to complete conductor failure.

Conductor fatigue became a major problem in the 1920's when ACSR conductors came into wide usage. Close observation of the conductors soon associated the failures with vibration waves somehow excited by the wind. In a short time, studies revealed the shedding of vortices as the cause of the vibrations. Theodore von Karman's previous theoretical investigations of the vortex street led to their identification as *Karman vortices.* The formula relating the frequency of these vortices to wind velocity and cylinder diameter had been determined by Strouhal's formula.

During the 1930's, there were several laboratories at work on the aeolian vibration problem because of its adverse impact on utilities that had made significant installations of ACSR. It quickly became apparent that the amount of energy being supplied by the wind to excite the vibrations was small and thus, that some modest form of damping might be found that would remove energy from a span faster than the wind could supply it. The motion causing conductor fatigue could then be suppressed. The first damping device to find commercial application was invented by George F. Stockbridge of the Southern California Edison Co. Damper development and application were essentially empirical. It was accompanied by numerous efforts to develop analytical methods for designing and applying dampers.

In addition, the adoption of certain constraints on conductor bare-wire tensions effected major improvements during that period. These did not assure safety from conductor fatigue but for most spans, rather limited the severity of the vibration problem to bring it within the reach of damping practices available at the time. These bare-wire limits, though, were not sufficient in that regard for long river crossing spans and some of these spans suffered chronically from vibration damage and required frequent repairs.

Relating the measurable vibrations of an overhead span of conductor to the likelihood of fatigue of its strands is a complicated matter. The complications arise primarily from two facts. Firstly, the stresses that cause the failures are complex and not related in a simple way to the gross motions of the conductor involved. Secondly, the failures originate at locations where there is surface contact and fretting between components.

Inspection and failure analysis of a large number of fatigue breaks from field and laboratory spans indicate that fatigue cracks always originate at places where the strand that broke was in contact with another strand, with an armor rod or with the clamping device (Fricke and Rawlins 1968; Moecks 1970; Cardou et al. 1994). The stresses at these locations are combinations of static stresses due to conductor tension, bending, the compressive force between the members and of dynamic stresses due to bending, fluctuation of tension, and traction between the contacting members.

Theoretical and numerical models are available to evaluate a conductor global bending behaviour at a fixing point such as a suspension clamp, a spacer clamp or a dead end clamp (Papailiou 1997, Rawlins 2005). The interested reader will find a summary of such bending behaviour analysis in the CIGRE TB # 332 (CIGRE SCB2 WG11 TF7 2007). However, a realistic analysis relating all these stresses, including contact stresses and microslip for a specific conductor-clamp system to the vibrations of the conductor *has yet to be developed*.

The endurance of metals to combined stresses has received considerable attention in recent decades, and several criteria for rating such stresses relative to fatigue have been developed and are in use. A similar effort has been made to obtain criteria for fretting damage to the contacting surfaces (Nowell and Hills 1987). Application of these criteria is generally restricted to specific materials, contact conditions and loadings.

#### 4.1.2 Fatigue Characteristics

No satisfactory criterion is available yet to analytically evaluate the fatigue behaviour of conductors from the fatigue properties of the materials used in their construction and the stresses that occur in them. *Thus, fatigue characteristics of conductors must be determined by fatigue tests of conductors themselves.* These tests should be performed on conductor-clamp systems reproducing as closely as possible the field loading conditions. In such tests, the fatigue life of the conductor must be determined as a function of some measure of vibration intensity, rather than of *the stress or stress combination that causes the failure,* since that stress is not accessible to measurement.

After nearly 90 years of active work on aeolian vibration and its serious consequence, the fatigue of conductors, the complexity of both phenomena did not permit the proposal of complete solutions supported by thorough analysis, taking into account the numerous parameters varying both in space and time. However (and fortunately), *engineering solutions* were sought concurrently. Through the years they have become reliable *design tools* when correctly applied within the limits inherent to their definition. They assure an acceptable control of the situation pending the completion of more complete analytical tools.

#### 4.1.3 Energy Balance Principle

Approaches available to guide an assessment of the severity of aeolian vibration can be pragmatic, through design rules based on past experience. Conditions can also be assessed through measurements on existing lines.

Another way is to use an analytical approach to simulate the conditions on the line. This approach can be usefully used to investigate alternatives in the design or redesign process and also, *being aware of its limits,* in the direct design of the damping system for a new line. The most used analytical models are based on the Energy Balance Principle (EBP), which permits the determination of an estimate of an upper limit to the expected vibratory motion. The EBP works in the frequency domain: in its simplest form, one mode of vibrations at a time is considered and steady state conditions computed corresponding to the maximum vibration amplitude which could be excited on that conductor at that frequency. Transient effects, like those due to wind turbulence, cannot be taken into account. The straightforward EBP is considered acceptable for use for engineering applications. A number of computer programs have been written around it, most of which can be implemented on a personal computer. For the conditions applied in the simulation of the cases evaluated, it indicates the maximum amplitude of vibrations to be expected. In addition, most computer programs calculate the maximum conductor strain at the support for that maximum amplitude of vibrations.

The reliability of results of these analytical computations is no better than the background data used in them, particularly data on power supplied by wind during aeolian vibration and data on self-damping in stranded conductors. A report by CIGRE TF22.11.1 (CIGRE SC22 WG11 TF1 1998) gives a complete assessment of the EBP applied to the vibrations of single conductors. The report provides:

- a critical analysis of the available data pertaining to wind power input;
- an analysis of data on conductor self-damping;
- a comparison of analytical to experimentally determined vibration behaviour;
- a study of how uncertainties regarding wind power input and conductor self-damping are reflected in analytical predictions of vibration behaviour.

It is well known that stranded conductors get more vulnerable to aeolian vibrations as tension is increased causing serious conductor and fitting damage. Safe design tension with respect to aeolian vibrations was provided by CIGRE SCB2 WG11 TF4 in 2005 specifying an upper limit to conductor unloaded tension that prevails for significant periods of time. Thus, while designing a new transmission line it is important to know how much additional damping is needed to control aeolian vibration within safe levels. Computation methods based on EBP to predict the vibration behaviour of a single conductor have been extended to the case of a conductor plus damper in order to allow for the selection of the damping suitable for different cases. The study extended to the case of a conductor plus damper was presented in a subsequent report (CIGRE SCB2 WG11 TF1 2005).These methods are based on the knowledge of the damper dynamic characteristics as measured on a shaker. The aim of the report was to compare the results of different computer programs to the results obtained on an experimental span, in order to show the uncertainty of the methodology. It is noteworthy to cite the *conclusion* of the report:

*"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"*.

#### 4.1.4 *In Situ* Measurements of Conductor Vibrations

Several methods to measure *in situ* the vibration intensity of a conductor have been employed (CIGRE SCB2 WG11 TF7 2007). Most of them did not progress to the stage permitting the development of practical instruments for use in a maintenance program.

The bending amplitude method finally emerged as the most practical one. It permits a measure of the differential displacement of the conductor, $Y_b$, at 89 mm from the last point of contact (LPC) of the conductor with the clamp. Figure 8 shows a conductor at the mouth of a metallic commercial clamp.

The advantages of the bending amplitude method have been its simplicity and the relative ease with which the measured values could be related to useful parameters for the evaluation of the severity of the phenomenon and also for the possibilities of designing reliable and practical vibration recorders. It possesses a long history; it was first introduced by Tebo in 1941, pursued by Edwards and Boyd in 1963. It has been recommended in 1966 by the IEEE Task Force on the Standardization of Conductor Vibration Measurements (IEEE 1966) and retained in the revision of that guide (IEEE 1368-2006). CIGRE SC22 WG04 also supported its use in 1979. It has been also the principal recommendation for aeolian vibration measurements of the CIGRE SC22 WG11 TF2 in 1995.

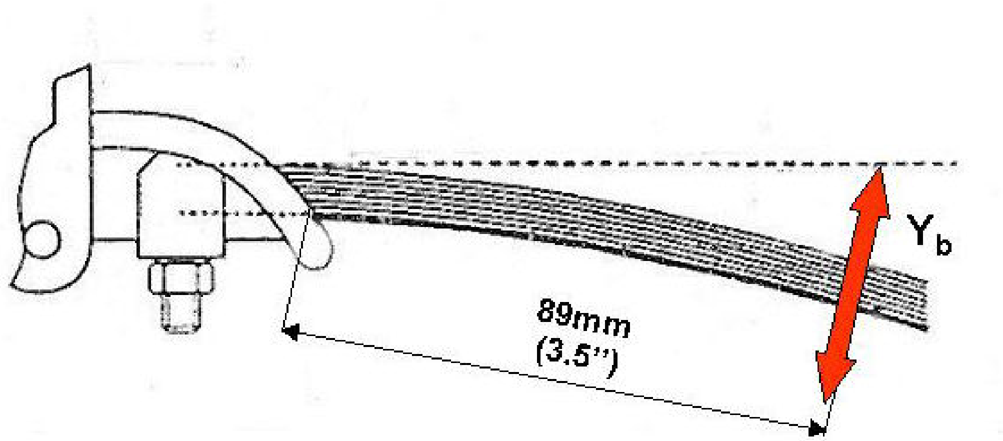



**Figure 8**: Bending amplitude measurement of conductor vibrations.

The reverse bending amplitude (Hardy et al. 1981) was presented as an alternative to permit the installation of the vibration recorder directly onto the conductor, Figure 9.

As mentioned above, the application of the bending amplitude method evolved through the years with its adaptation to new technologies. Although the present practice has focused on a limited number of the instruments made available, Figure 10 gives a review of the most common bending amplitude recorders that were proposed (CIGRE SCB2 WG11 TF7 2007).

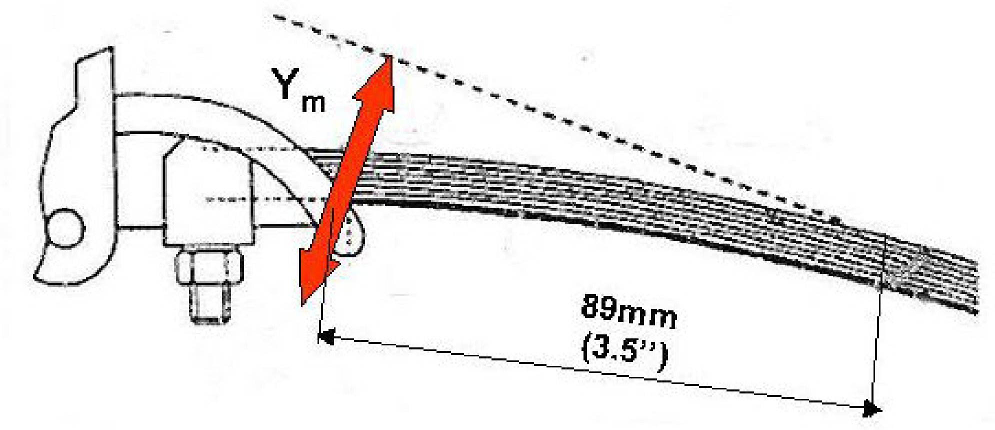



**Figure 9**: Reverse bending amplitude measurement of conductor vibrations.

Ontario Hydro Recorder

HILDA

TVM 90

Vibrec 400

Ribe LVR

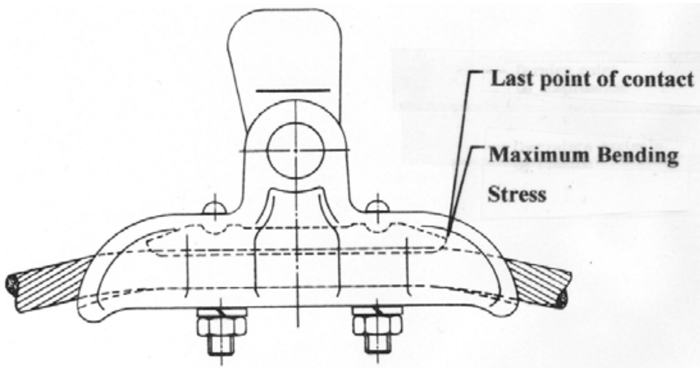
Pavica

Scolar III

**Figure 10**: Vibration recorders for *in situ* measurements of conductor motions.

### 4.1.5 <u>Simple Analytical Representation of Fatigue Phenomenon</u>

The conductor/clamp system may be simply represented as a cantilever beam under tension, Figure 11. Although this model is not exact, the conductor fatigue is caused by inter wire fretting and not by flexion of the wire only, it gave the engineer some useful tools to correctly monitor different aspects of the fatigue endurance capability of conductor clamp/systems. Figure 11 also illustrates clearly why the bending amplitude method may be valid for conductors fitted with solid metallic clamps, but invalid for conductors in cushioned clamps. In the latter case, it is not possible to locate a precise position for an equivalent last point of contact (LPC).



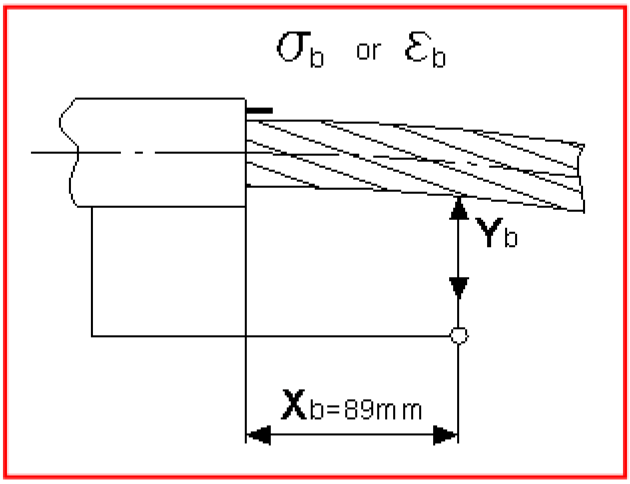




**Figure 11**: Flexion model of a conductor supported in a metallic clamp.

### 4.1.6 <u>Idealized Bending Stress</u>

From the model shown in Figure 11, the calculation of an idealized bending stress $\sigma_a$ in the top-most outer-layer strand of the conductor, in the plane of the last point of contact was proposed (Poffenberger and Swart 1965), where $\sigma_a$ is <u>zero to peak</u> bending stress:

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

where:

$E_a$: Young's modulus of elasticity of outer-layer wire material (N/mm$^2$)

$d$: 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 mm$^2$)

$x$: distance from the point of measurement to the last point of contact between the clamp and the conductor.

In Equation (1) the bending stress is expressed as a function of the bending amplitude $Y_b$.

However in certain circumstances, the free loop amplitude of vibrations, $y_{max}$ could be a more practical parameter. Figure 12 shows the case of a standing wave vibration with rigidly fixed supporting clamp at left end of section (a) and a free-span vibration angle $\beta$.

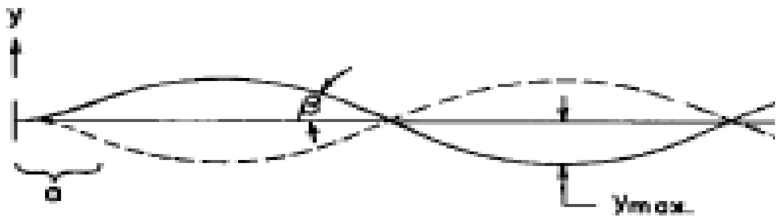



**Figure 12**: Free loop amplitude $y_{max}$.

In that case, the idealized bending stress can be expressed by the following equation:

$$\sigma_a = \pi d \, E_a \sqrt{\frac{m}{EI}} \, f y_{max} \qquad (2)$$

where:

$E_a$: Young's modulus of elasticity of outer-layer wire material (N/mm$^2$)

$d$: 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 mm$^2$).

The correlation of calculated with measured values of $\sigma_a$ may appear to be somewhat academic, since the stresses that initiate fatigue failures are located at metal-to-metal contacts and $\sigma_a$ is a free-surface stress. The comparisons do, however, provide some measure of the sensitivity of the analysis to the degree of idealization involved in the assumptions employed. There is a strong temptation to attribute a meaning different to $\sigma_a$ than that of a *useful index* for a rational interpretation of the bending amplitude of conductors measured at the mouth of a rigid metallic clamp. *The reader is urged not to yield to this temptation*. It is common practice to report fatigue performance of conductors relative to either $Y_b$ or $fy_{max}$ (Cloutier et al. 2006).

## 4.2 Design Tools for the Determination of Fatigue Endurance of a Conductor/Clamp System

### 4.2.1 <u>Laboratory Tests</u>

Either at the design stage or for an evaluation of the residual life of a line, there is a need to relate the potential level of vibrations of an overhead conductor to the likelihood of fatigue of its strands. Fatigue tests are advantageous for an endurance assessment as well as for an improvement of clamp design. The exact modelling of the actual phenomenon is indeed a complicated matter. The failures originate at inter-layer strand contacts or at contacts between the outer strands and the line accessories where conditions for fretting are present. The definition of a more appropriate model than the one presently proposed to represent the actual phenomenon remains to be completed as mentioned above. Thus it is still opportune to note not only that fatigue characteristics of conductors must be determined by fatigue tests of *conductors themselves* (Rawlins 1979), but also that tests should be conducted *with clamps having similar characteristics* to those of the conductor/clamp system being characterized. A guide for endurance tests of conductors inside clamps was prepared by CIGRE SC22 WG 04 in 1985, where it is rightly reminded that *to arrive at comparable results in different laboratories, an agreement on important test parameters and on an uniform method is necessary.* Lately, IEC formed a group of experts to propose a standard for laboratory measurement of fatigue characteristics conductor/clamp systems.

### 4.2.2 <u>Configuration of a Typical Laboratory Test Span</u>

Different systems have been developed to simulate conductor motion in a laboratory (Elton et al. 1959, Goudreau et al. 2003, Cardou et al. 1994, Philipps et al. 1972), each presenting specific advantages. However, a test bench of the resonance type imposing a conductor motion in a vertical plane is to be preferred, where the conductor is excited at a single natural frequency. It is indeed important to reproduce the actual situation in the field as closely as possible and to be able to control the parameters evaluated in the tests. This approach is recommended and it is applied to the case of a conductor supported in a standard metallic clamp, normally a short clamp. The limitations of this approach relate to the ability to reproduce the actual conditions experienced by the conductor, the clamp supports and the range of bending amplitudes associated with the phenomenon reproduced.

Figure 13 shows a typical installation of a resonance type test bench. The active length of the conductor specimen must be long enough, at least 5 m between the clamp and the point of excitation, to ensure a good distribution of the load within the strands at the test end where the clamp is held. Of course, longer laboratory spans are less susceptible to non-homogeneous distribution of loads (CIGRE SC22 WG04 1985) without the need to control the stresses in the wires with strain gages. Also, longer spans have many resonant frequencies (higher nodal density) with more options for testing.

The clamp is placed in a position to reproduce the static bending angle of the conductor. Typically, this angle is 5° to 10° for suspension clamps, and 0° for spacer clamps. The length of the conductor specimen is chosen to ensure that the length of the clamp is still small relative to the wavelength induced. The minimum distance between the clamp under test and the back dead end of the conductor should be at least 2 m, again to ensure an adequately uniform load distribution in the conductor strands. That section of the conductor experiences no motion. A complete description of laboratory installation can be found in CIGRE TB # 332 (CIGRE SCB2 WG 11 TF7 2007).

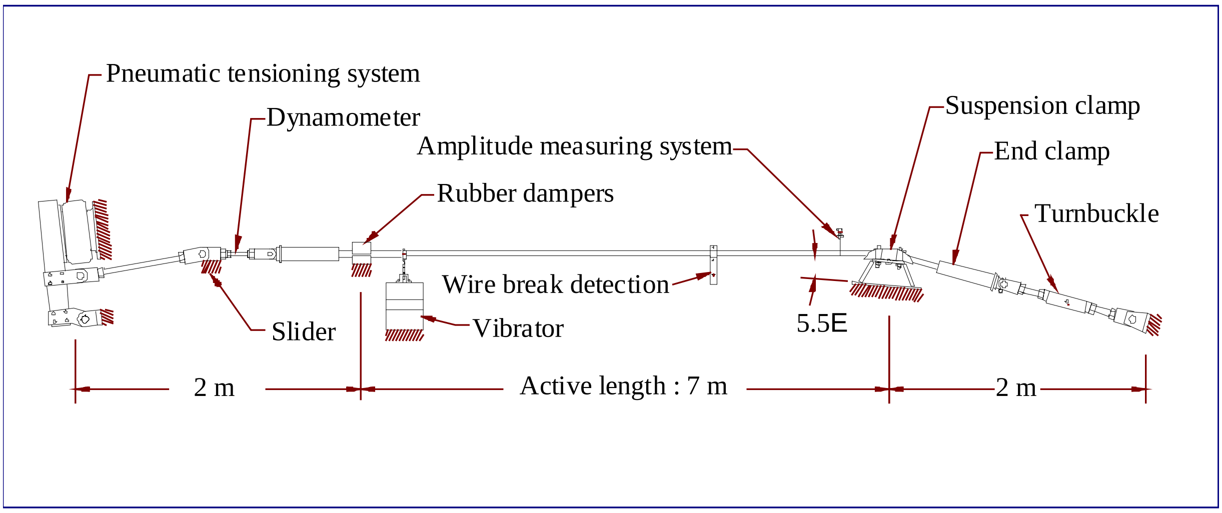



**Figure 13**: Schema of a typical installation of a resonance type test bench.

### 4.2.3 Test Parameters and Analysis of Results

In such tests, the fatigue life of the conductor must be determined as a function of some measure of vibration intensity. The stresses or stress combinations that would characterize the conditions favouring strand failures are not easily accessible to direct measurement.

Several measures of vibrations have been employed: vibration bending angle $\beta$, dynamic strain in an outer-layer strand in the vicinity of the clamp, free-loop amplitude of vibrations $y_{max,}$ and bending amplitude $Y_b$ (amplitude of conductor motion relative to clamp at 89 mm from the last point of conductor/clamp contact).

Bending amplitude, $Y_{b,}$ is the most widely used parameter for measurement of vibrations in the field and its use is recommended in laboratory tests to avoid the necessity of converting this bending amplitude into any of the other parameters. That conversion is heavily dependant on the proper choice of the bending stiffness of the actual conductor (Rawlins, 1979). It is also advisable to measure the free loop amplitude, $y_{max,}$ to facilitate the correlation of the test results of conductors supported with clamps of different configuration and also to permit their use in establishing an endurance limit for a range of conductor sizes. However, results from tests on one conductor size are not necessarily applicable to all the others of the same size. Two conductors of similar size but of different geometry e.g., i.e. two layers of coarse strands as compared to three layers of finer strands, could lead to different fatigue curves.

*The concept that there is some idealized stress that can be calculated from vibration amplitude and that correlates well enough with conductor fatigue life has given the engineer a useful tool to overcome the complexity of the problem and find results that are reliable enough to be usefully applied.*

The number of cycles to failure, N, generally refers to failure of the first strand (Rawlins 1979). However, in (CIGRE SC22 WG04 1985), one reads that *three broken wires or 10% of the aluminium wires – whichever is smaller – should be used as the damage criterion in respect of the relationship between the stress amplitude and the number of cycles.* In practice, to the failure criterion used should be stated when reporting test results. This should also be taken into account when comparing results from different laboratories.

Detection of failures by periodic visual inspection of the conductor outer surface was made in some early tests. It is well established that failures often occur at inner-layer strands, so that this practice is certainly not preferred. The strand failure detector is a solution to this problem. A simple method developed at Alcoa Laboratories (Rawlins 1979) has been extensively used at GREMCA's Laboratories (Cloutier et al. 1999). It consists of a small arm attached to the conductor in order to amplify its relaxation in torsion when a strand failure occurs. The rotational motion of the arm is detected by any suitable sensor (LVDT, proximity sensor, optical sensor), and it results in a step signal that may be associated with N, the number of cycles applied. Tests conducted until three and more strand failures have occurred are providing much more useful information, taking into account the inherent scatter of such test results.

Tests should be carried out with different values of the vibration parameters to obtain fatigue endurance curves (similar to the so-called S/N curves or Wöhler curves for a material). Those curves also provide a value for the endurance limit, which is the amplitude of bending below which a particular clamp-conductor combination will endure almost indefinitely. The endurance limit is defined, as currently accepted for aluminium, as the highest amplitude with no break at 500 Mc. In practice, a test is interrupted when n failures are observed or alternatively, when 500 Mc are reached but this is a choice left to the laboratory conducting the tests, as stated above. Because of the scatter of fatigue data, three tests per level of vibration amplitude should be considered as a minimum, and four amplitude levels are the absolute minimum required to define the fatigue diagram with sufficient accuracy.

After completion of a test, the conductor in the region of the clamp should be submitted to a dissection process that will permit the strand failures observed to be correlated with those indicated by the strand failure detector and to produce a map of the failures in the transverse plane as well as in the longitudinal plane (the position of the failure relative to the clamp support). This information is very helpful to improve our understanding of the complex mechanism responsible for conductor fatigue. In several instances, laboratories conducting such tests will extend their analysis by a closer examination of the interlayer strand contact area where fretting occurred. This is particularly useful when tests are performed to compare or improve the design of clamps and to evaluate the use of lining materials.

The most common format in which to present conductor fatigue test results is the semi logarithmic fatigue endurance curve, mentioned previously as the S/N curve. It is possible to superimpose on the same graph, points indicating the first, second, third, and $k^{th}$ strand failures for a series of tests. The dispersion of the results is then shown as well as certain particular anomalies when, for instance, an early first failure occurs but is not followed by a second one within the 500-Mc duration of the test.

To assist in the interpretation of available data on the fatigue endurance of certain conductor/clamp systems, a statistical analysis (Hardy and Leblond 2001) was presented that led to the determination of various S/N curves on a sound probabilistic basis.

### 4.2.4 Typical Results from Laboratory Fatigue Tests

Figures 14 to 18 give a representation of typical results obtained from fatigue tests conducted on resonance type test bench. It shows the difference one could encounter when testing conductors of different geometry such as one, two or three-layer ACSR. Figures 16 and 18 give the results of the stresses calculated as a function of $fy_{max}$.

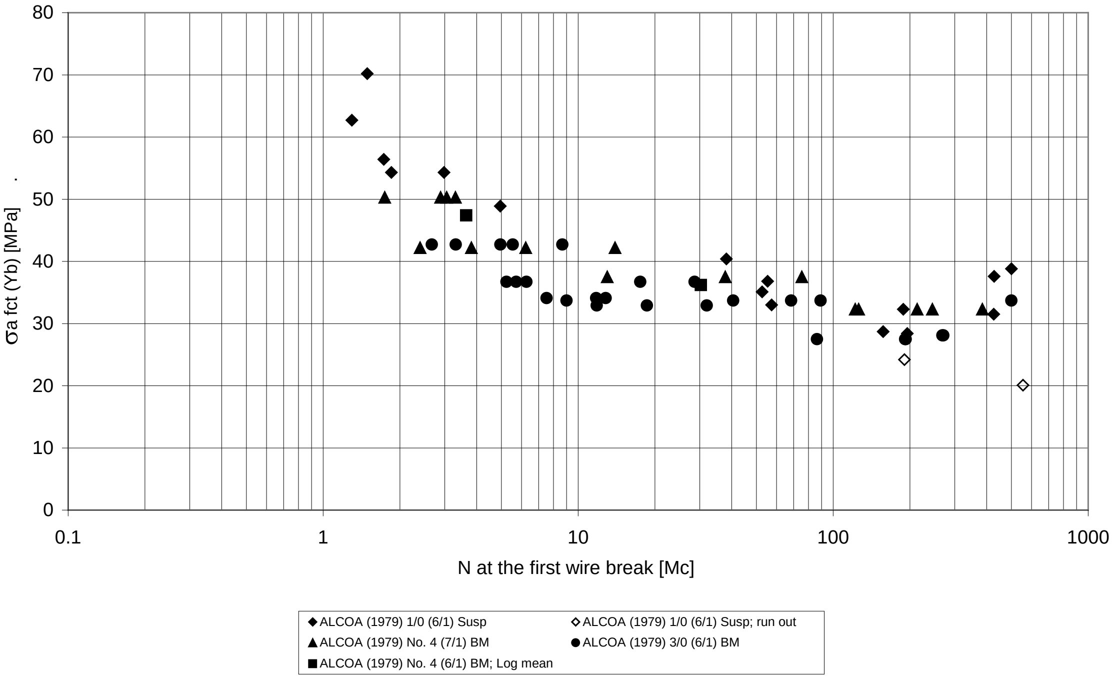



**Figure 14**: Typical results from fatigue tests on single layer ACSR as a function of $Y_b$.

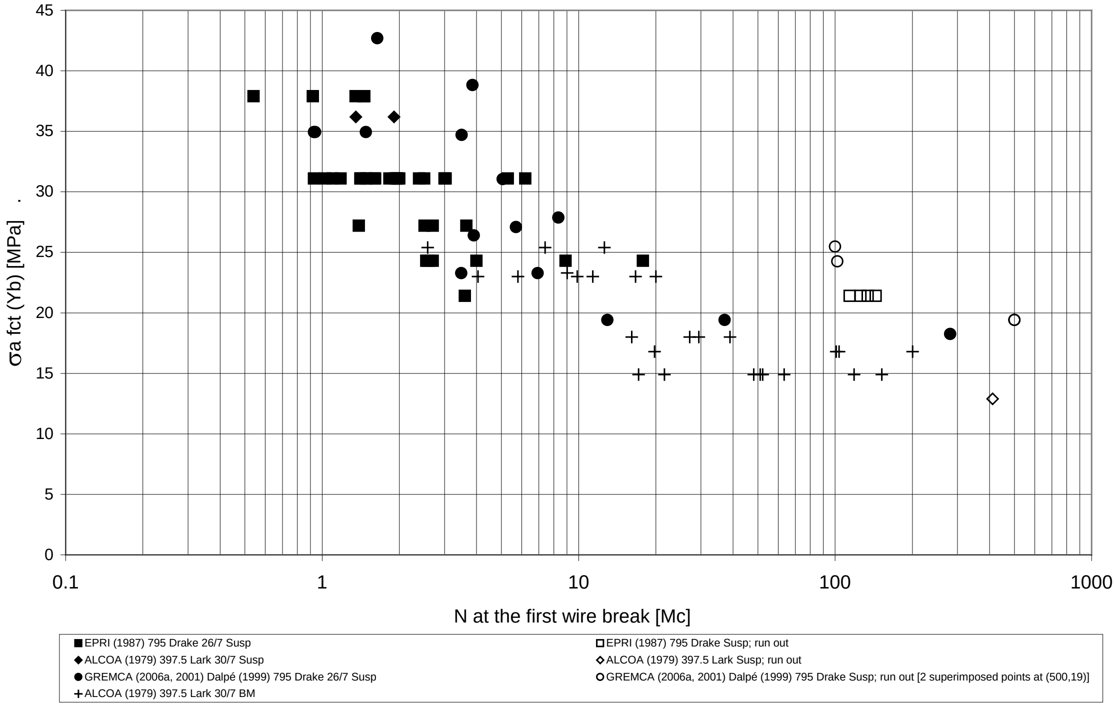



**Figure 15**: Typical results from fatigue tests on double layer ACSR as a function of $Y_b$.

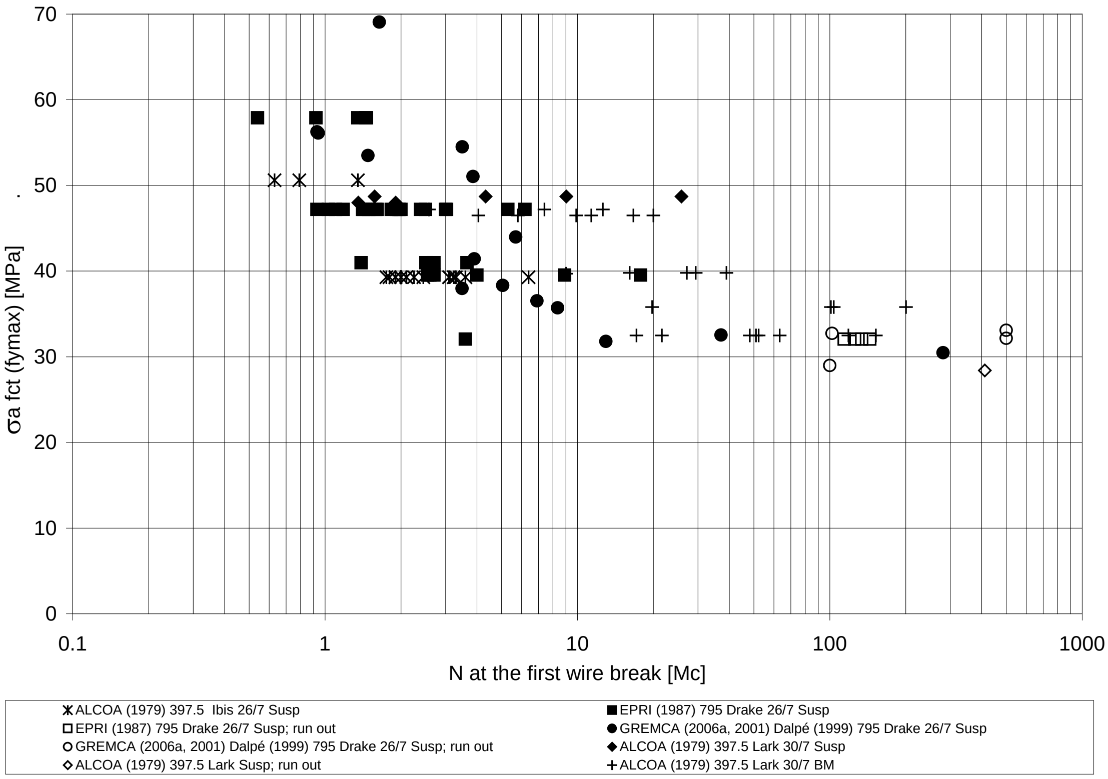



**Figure 16**: Typical results from fatigue tests on double layer ACSR as a function of $fy_{max}$.

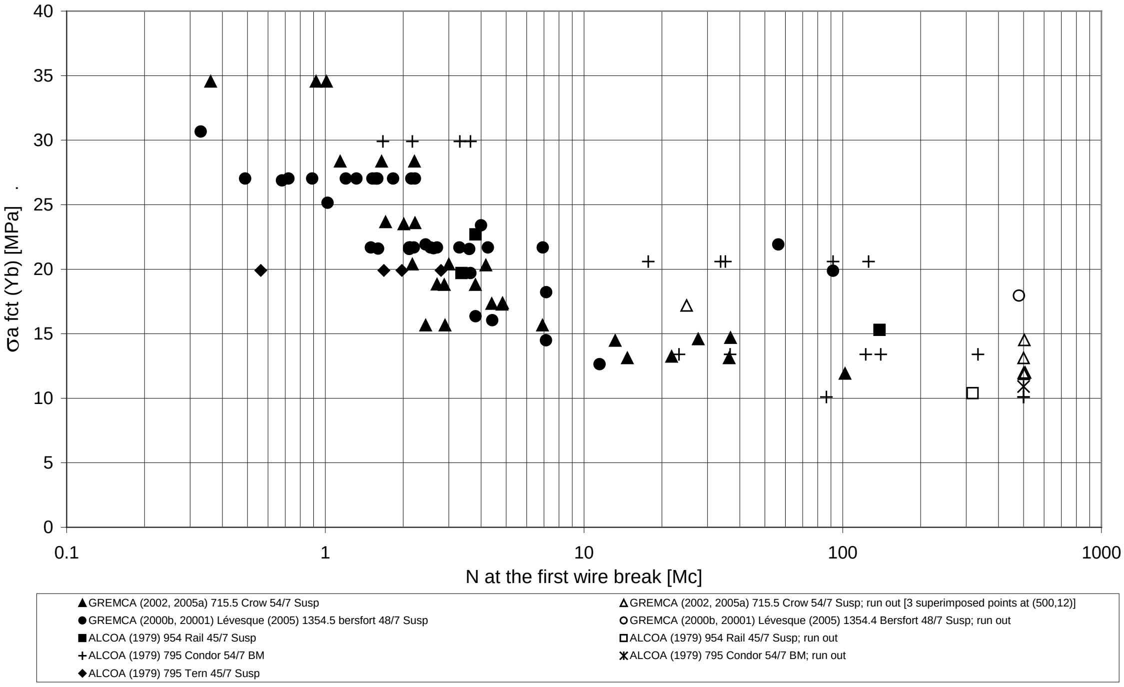



**Figure 17**: Typical results from fatigue tests on three-layer ACSR as a function of $Y_b$.

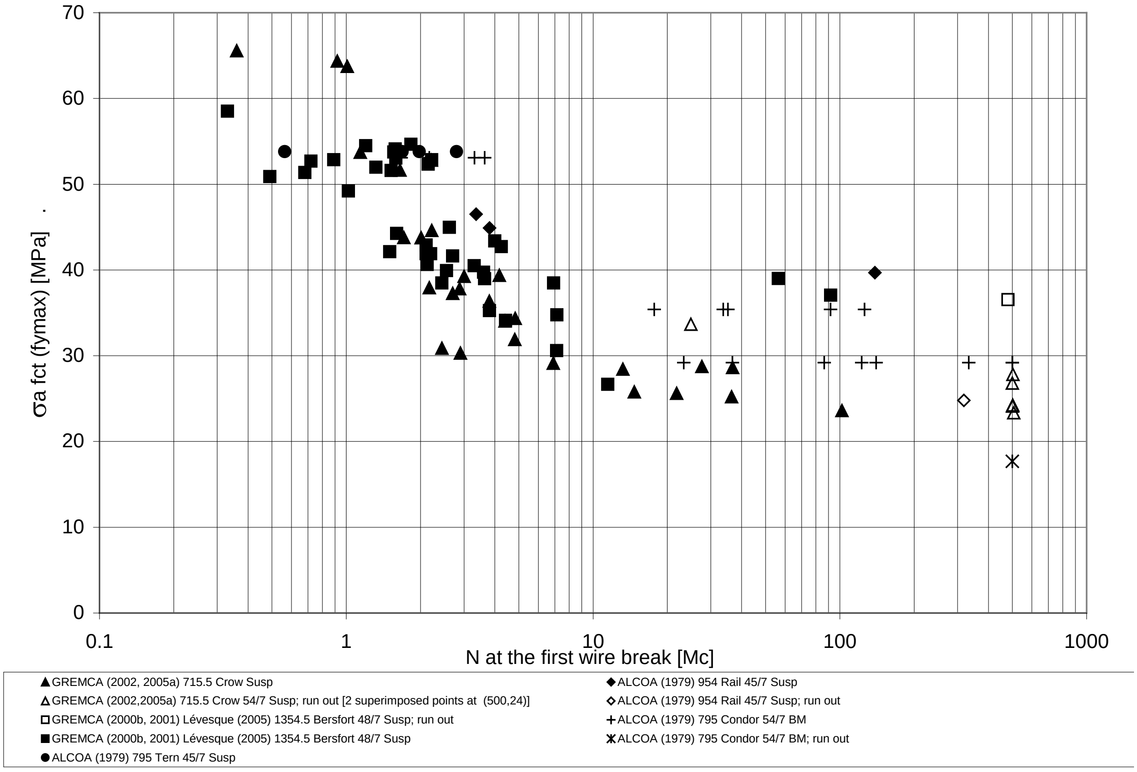



**Figure 18**: Typical results from fatigue tests on three-layer ACSR as a function of $fy_{max}$.

# 5. Conclusion

Fatigue endurance capability of conductors is a parameter that the transmission line engineer must control at the design stage as well as for a maintenance program. As explained in this report, it is a phenomenon closely related to the presence of aeolian vibration. Both phenomena are highly complex and some of the avenues aimed at the development of more precise and complete solutions are still the object of research studies. CIGRE TB # 332 (CIGRE SC B2 WG11 TF7 2007) presented an update of the present knowledge on the subject.

Fortunately, engineering solutions were also sought concurrently and design tools are available. This report is intended to give the transmission line engineer a review of the design tools that can be used to evaluate the fatigue endurance capability of conductors. It is important for the engineer to recognise and take into account the inherent limitations of those tools.

For that purpose, this report started by a description of the conductor/clamp systems and emphasis was given to the diversity of the components of the system, conductors and clamps. When design tools were described, care was taken to clearly establish the limits of their direct application. The *art of engineering* has to be employed to evaluate the acceptability of any extrapolation of their application.

The review presented will enable the transmission line engineer to apply correctly the tools available for cases normally encountered. If appropriate, the reader is referred to more advanced reports and studies to better understand the importance of many other parameters or conditions of applications not covered in this report. For additional information to the reader, the next section, References, includes also the references that were considered as pertinent to complete the *sister brochure* TB # 332 (CIGRE SC B2 WG11 TF7 2007).

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# 7. Appendix 1 – High Temperature Conductors

The need to transport an ever-increasing amount of electrical power coupled with the difficulties to gain approval for new transmission corridors has forced Utilities to find creative ways of increasing the capacity of their lines. One of the solutions found is to increase the operating temperature of the conductors. However, the use of conductors at high temperature usually leads to relatively important loss of strength in its aluminium portion. Whereas in some areas of the world this difficulty was avoided by use of special heat resistant aluminium alloys, in North America the solutions was found to be the use of an ACSS (Asselin 2002).

ACSS (Aluminium Conductor, Steel Supported), formerly known as SSAC (Steel Supported Aluminium Conductor) and patented in 1974, is a composite concentric lay-stranded conductor consisting of a stranded steel core with one or more layers of 1350-0 aluminium wires. This high temperature conductor constitutes approximately 15% of all the American line installed. At a glance, there is almost no difference in appearance between an ACSR and an ACSS. They have the same geometry, including the possibility of being compacted. There are however, important differences in the properties and performance of the two constructions.

ACSS can carry a significant increase in current compared with ACSR. ACSS can operate continuously at 200°C, and up to 250°C with an aluminised or mishmetal steel core. Since the aluminium wires have been annealed in the factory, there is no concern about the conductor losing strength at high temperature. The annealing process also increases the conductivity of the aluminium, from 61% IACS to typically over 63% IACS.

When the ACSS is heated up, the aluminium wires elongate and quickly shift their load onto the steel core. At this point, the conductor essentially behaves as a steel conductor, i.e. the thermal elongation and the modulus of elasticity are those of the steel core. When the temperature is reduced, the aluminium wires are in a plastic condition and will not return to their original length. Therefore they will carry a lower load. The low stress in the aluminium wires decreases the effects of aeolian vibration and increases the self-damping of the conductor since their relative looseness simulates the mechanism of an impact damper. This is why it is generally recommended to pre-stress this conductor.

In an ACSS, the minimum elongation of the annealed aluminium wires is approximately 20%. Contrary to an ACSR, where the steel core is limited to its strength at 1% elongation, this property allows the conductor to utilise the steel core at its full strength. This fact makes the use of extra-high strength steel more attractive. The conductor may have a rated strength almost as high as its equivalent ACSR. Moreover, the high elongation of the aluminium means that the creep properties of the conductor are ruled by the steel core, which usually exhibits very low creep. As for most other conductors, ACSS constructions can be compacted. This and other factors allow an ACSS compact to carry approximately 20% more current, due to its increase in area.

There are a certain number of other high-temperature conductors that are beginning to emerge over the world. A list of high-temperature conductor types has recently been published by CIGRE TB # 331 (CIGRE SCB2 WG03, WG11 and WG12 2007). As in Japan, most of those new constructions rely on aluminium-zirconium alloys to circumvent the harmful effects of high-temperature on aluminium wires.

A small addition of zirconium in aluminium tends to increase its re-crystallisation temperature, thus retaining its original strength after an excursion at higher temperature. The maximum attainable temperature depends on the amount of zirconium alloyed in the aluminium. The conductivity of these alloys varies from 55% to 60% IACS, with a strength from 170 MPa up to 250 MPa. Elongation is similar to 1350-H19 wires. The continuous maximum temperature can be in excess of 250°C.

These conductors usually replace the traditional steel core of the ACSR with a core made of composite material. One of these products consists of alumina fibres in an aluminium matrix. The strength of this core is comparable to a steel core and has a lot of other interesting properties. The alumina fibres have a lower thermal expansion than aluminium or steel, the core has great resistance to corrosion, exhibits no creep, no undesirable magnetic properties and can operate at high temperature. The ampacity gains are estimated at 1.5 to 3.0 times the equivalent ACSR.

# 8. Appendix 2 – Clamping Systems

## 8.1 General principles

Experience has shown that although successful clamp designs for overhead transmission conductors and other overhead cables are wide ranging in concept and form, they tend to conform to some or all of the following general design principles:

- The clamp should be capable of easy, reliable installation, preferably verifiable by ground based inspection and should provide a safe, reliable, non-damaging, long-term grip on the conductor.
- High, localised clamping stresses should be avoided and the clamp conductor groove should be smooth and free from irregularities.
- Particular attention should be paid to the edges of the clamp where the conductor has its last point of contact. These should be smooth and rounded to avoid creating any stress concentrations or mechanical damage to the outer conductor strands.
- Component parts should be captivated and an energy storing mechanism is required to prevent clamp loosening due to the effect of vibrations, thermal cycling and conductor creep.
- All materials should be compatible with the conductor and avoid corrosion.
- In the case of conductors of unusual constructions and shapes, such as GAP high temperature conductor and T2 conductor, particular care needs to be taken regarding the mechanism of exerting the clamp's grip to avoid both short term and long-term damage.
- In the case of overhead optical fibre cables, clamp designs should reflect the need to ensure that the integrity of the fibre optics is fully protected under all anticipated operating conditions. There were some early instances of damage to these cables because conventional clamps were used.

In the following sections, the word "clamp" is used to mean the type of clamp to which the section refers.

## 8.2 Suspension Clamps

### 8.2.1 <u>Function</u>

A wide range of suspension clamps is used on overhead lines. These clamps have to perform the important function of safely carrying the conductor in the context of combinations of the normal static loads and dynamic loads caused by vibrations, galloping, wind and ice drop.

At one end of the scale is the *conventional* metal clamp where the conductor is carried in a contoured metal body and secured by a keeper using U bolts or bolts locating in captivated nuts or threaded holes in the clamp body. The clamp is attached to the suspension hardware via trunnions and straps. At the other end of the scale is the clamp in which the conductor is completely enclosed by elastomeric housings carried in metal shells and secured to the conductor by helically formed rods. Variations exist between these two types, including the fitting of helically formed rods on the conductor under the clamp and the use of *long bodied* curved clamps where loads are high, such as river crossings.

Some clamps are designed to meet a *slip load* window arising from unbalanced longitudinal loads.

### 8.2.2 <u>Basic Types of Suspension Clamps</u>

Suspension clamps have an effect on the fatigue life of the conductor based on how the suspension clamp accommodates the cable motion.

There are three basic types of suspensions that are used in transmission construction:

1. Bolted suspension clamps on bare conductor;

2. Bolted suspension clamp over armor rods;
3. Armor Grip type suspension.

Each of these types of suspension offers varying degrees of protection against fatigue.

### 8.2.3 Bolted Suspension Clamps on Bare Conductor

The bolted suspension clamp on bare conductor (Figure 19) offers the least amount of protection against vibration fatigue. The reason for increased fatigue is two fold. Firstly, the high compressive loads of the range-taking bolted suspension clamp, which can cause damage to, or indentations in, the soft aluminum conductor. These indentations are effectively stress raisers. Secondly, the bending amplitude due to cable motion (either aeolian vibration or galloping) is high since the cable is not armored. The curvatures are much larger, interstrand microslip amplitude increases, small cracks are generated and some propagate to cause complete strand failures.

This type of suspension is normally used in areas where aeolian vibration levels are low and galloping is not expected. Often, these suspensions are used in conjunction with dampers, which reduce cable vibrations. This type of suspension clamp is used in probably over 50% of the suspension application.

**Figure 19**: Typical bolted suspension clamp on bare conductor.

### 8.2.4 Bolted Suspension Clamps over Armor Rods

The bolted clamp over armor rods (Figure 20) offers moderate protection against vibration fatigue. Armor rods are typically made of aluminum alloy wire, which has a higher tensile strength and endurance limit than most conductors. These helically formed wires are wrapped around the conductor, effectively stiffening the conductor at the suspension clamp location. A larger size suspension clamp body is then placed over the armor rods. The addition of armor rods improves the fatigue endurance of the conductor in two ways. Firstly, the extra layer of high strength rods spreads the high compressive load of the suspension clamp over a larger area. This in effect reduces the damage (indentations) on the conductor. Secondly, the increased stiffness of the rods reduces the bending angle at the suspension clamp during cable motion. This reduction in bending angle reduces curvature on the conductor and thus improves its fatigue performance. This type of suspension clamp is commonly used in areas where moderate levels of cable motion are expected and is probably used in at least 25% of suspension clamp applications overall.

**Figure 20**: Typical bolted suspension clamp over armor rods.

### 8.2.5 Armor Grip Type Suspension

The Armor Grip Suspension (AGS) clamp type (Figure 21) offers the highest protection against vibration fatigue. It is a special stress reducing suspension clamp that utilizes and elastomeric insert and helical attachment rods. This device was initially designed in the 1950's and is still regarded today as the best suspension from a fatigue endurance standpoint. The increased fatigue life performance in both aeolian vibration and galloping can be attributed to a reduction in not only dynamic stresses but also static stresses. The helical rods gently but securely attach the suspension clamp to the conductor, which almost completely eliminates any notching to the conductor, thereby eliminating the high stress riser associated with notching. The elastomeric insert reduces the dynamic stress since the vibrating conductor bends over a larger cushioned area. This suspension clamp is heavily used in areas where galloping occurs due to its fatigue endurance characteristics. The overall performance history of this type of suspension clamp has been excellent and is probably used in less than 10% of the suspension applications for conductor. It is, however, the suspension clamp that is used predominantly on OPGW and ADSS.

**Figure 21**: Example of Armor Grip Suspension clamp type.

### 8.2.6 Newer Types of Suspensions

There are newer suspension clamps that utilize the benefits of an elastomeric liner without armor rods (Figure 22). The elastomeric liner improves the fatigue performance compared to a bare suspension clamp. In testing, this type of elastomer-lined clamp has similar fatigue performance characteristics to those of a bolted suspension clamp over armor rods. This type of suspension clamp is starting to become accepted although its usage to date has been small.

**Figure 22**: Example of a newer suspension clamp having an elastomeric liner without armor rods.

## 8.3 Spacer and Spacer-Damper Clamps

### 8.3.1 Design Characteristics

The clamp must be capable of easy installation on the conductor and provide a safe, reliable long-term grip.

The design of such clamps should aim to:

- Avoid high, localised clamping stresses – this is a function of clamp length, clamping force (bolt torque) and clamp geometry;
- Avoid damage to the conductor due to clamping surface irregularities – the conductor contact surfaces must be smooth;
- Minimise the possibility of incorrect installation;
- Ensure that, if feasible, all components are captive – bolts may be peened or, if in a blind tapped hole, secured by an O-ring to the clamp keeper which itself may be secured to the body of the clamp by a tie or captive hinge;
- Incorporate a stored-energy mechanism to prevent clamp loosening due to temperature cycling and conductor creep;
- Exert an adequate, non-damaging long-term grip on the conductor - axial and torsional grip are often specified by the end user;
- Be manufactured from a material that is compatible with the conductor and generally avoids corrosion;
- Be profiled to minimise the possibility of corona and RI discharge at specified line voltages;
- Be capable of ground level inspection to verify correct installation;
- Preferably, be capable of being installed with hot line/helicopter techniques.

Elastomer-lined clamps generally have some range-taking capability whereas metal-to-metal clamps should ideally be matched to the conductor diameter in question, although a very limited degree of ranging is possible.

Metal-to-metal clamps may be installed over helical, factory-formed rods to provide an enhanced degree of conductor protection.

There are a number of clamp types with widely differing characteristics including :

### 8.3.2 Cantilever Clamp

The cantilever clamp (Figures 23 to 25) is a metal-to-metal clamp secured by a captive, galvanised steel bolt bearing on a plain and split washer and secured by a captive, galvanised steel nut.

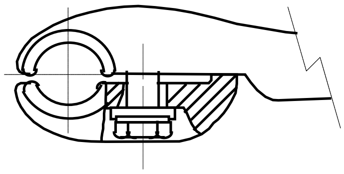

**Figure 23**: Cantilever bolted clamp.

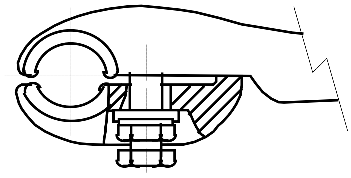

**Figure 24**: Break-away head.

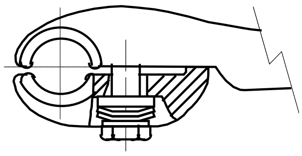

**Figure 25**: Belleville washers.

The geometry of the cantilever clamp is such that it is less sensitive to changes in the conductor and errors in tightening.

### 8.3.3 Opposed Hinge Clamp

The opposed hinge clamp (Figure 26) is a heavy-duty metal-to-metal clamp that, because of its hinge/conductor/bolt geometry, imposes a significantly higher grip on the conductor than the cantilever clamp (Figure 23) that has conductor/bolt/hinge geometry. The opposed hinge clamp almost completely encloses the conductor. The clamp keeper pivots on a detachable or captive hinge and is secured by a galvanised steel bolt bearing on a plain and split washer and secured by a captive, galvanised steel nut.

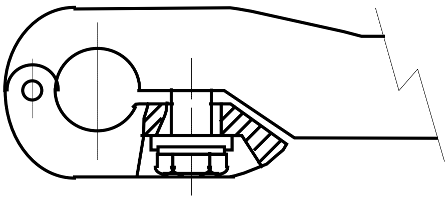

**Figure 26**: Hinged bolt.

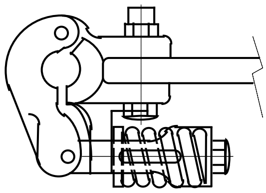

**Figure 27**: Coil spring loaded.

Because of the high mechanical advantage offered by the clamp geometry, the bolt installation torque for the opposed hinge clamp is generally about 50 to 75% of that of the equivalent cantilever clamp to avoid excessive localised clamping stresses in the conductor.

For both Cantilever and Opposed Hinge clamps, Belleville washers may be used instead of the split washer to enhance energy storage and the nut may incorporate a locking mechanism, such as a nylon patch or ring. The Belleville washers must be protected by a suitable anti-corrosion finish because galvanising is not feasible.

As an alternative to the bolt, a loaded coil spring may be used to exert a constant clamping force on the conductor (Figure 27).

### 8.3.4 Elastomer-lined Cantilever or Hinged Clamp

Clamp types described above can also be used with an elastomer lining.

A widely used version of the elastomer-lined clamp utilises a boltless construction with an opposed captive hinge and fastener.  The clamp is lined with elastomeric inserts that cushion and grip the conductor (Figures 28 and 29).  The clamp is closed using a special tool and locked by a quarter-turn fastener or a latch.  The clamp is not reliant on a bolt being correctly tightened; therefore there is no danger of conductor damage or clamp loosening arising from this source.  The design is such that the elastomer remains under a predetermined degree of compression under all service conditions.  A bolt may be used in place of the quarter-turn fastener.

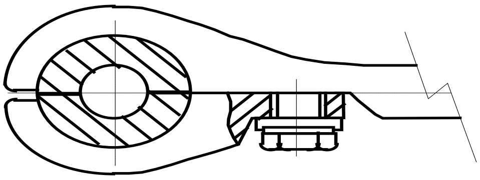

**Figure 28**: Cantilever bolted.

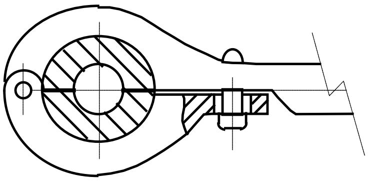

**Figure 29**: Hinged latching.

The formulation of the elastomer is c#ritical to the satisfactory long-term performance of the clamp.  Essential properties include good resistance to ageing, pollution, environmental effects, ozone and grease.  Compression set must be at a minimum to ensure that a positive grip is always exerted on the conductor.  Electrical semi-conductivity must also be controlled within defined limits and there must be no corrosive interaction between the constituents of the elastomer, such as carbon, and the conductor strand material.

The slip load achieved by elastomer-lined clamps is significantly less than with metal-to-metal clamps.  This is acceptable because, if an exceptional event causes the elastomer-lined clamp to move, there will be no consequential damage to the conductor.

### 8.3.5 Helically Attached Clamp

The helically attached clamp is a boltless construction in which the conductor is cushioned in a U-shaped elastomer-lined clamp and securely held by helical, factory-formed rods (Figures 30 and 31). The clamp is generally elastomer-lined to protect the conductor, although some unlined clamps are in use. Correct installation may easily be verified from ground level.  The rods must be manufactured from material that is compatible with the conductor strands. Essential properties of the elastomer include good resistance to ageing, pollution, environmental effects, ozone and grease.  Compression set must be at a minimum to ensure that a positive grip is always exerted on the conductor.  Electrical semi-conductivity must also be controlled within defined limits and there must be no corrosive interaction between the constituents of the elastomer, such as carbon and the conductor strand material.

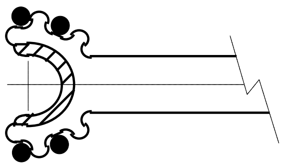

**Figure 30**: Elastomer-lined.

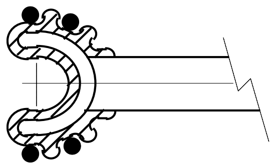

**Figure 31**: Elastomer-covered.

The elastomer may be fully bonded to the clamp to prevent any ingress of pollutants and moisture whilst in service.  The characteristics of the helical rods should be such that their ends are facing towards the centre of the sub-conductor bundle to minimise corona and RI discharge at specified line voltages.

The slip load achieved by helically-attached clamps is significantly less than metal-to-metal clamps. This is acceptable because, if an exceptional event causes the helically-attached clamp to move, there will be no con-sequential damage to the conductor.

#### 8.3.6 Vibration Damper Clamp

Vibration dampers tend to use metal to metal bolted cantilever type clamps but the geometry is somewhat different to that used for spacers. The body of the clamp, which includes the mechanism for attaching the messenger cable, is *hooked* so that it will hang on the conductor whilst the clamp keeper is fastened into place.

Experience has shown that vibration damper clamps can have wider range taking capabilities than spacer clamps because the service conditions are less severe.

Versions of the helically attached clamp are also used and have the same *hook* feature.

The plastic helically formed impact vibration damper is a one piece construction and has a helical gripping section with an internal diameter less than that of the conductor.

#### 8.3.7 Helically Attached Damper Clamp

The helically attached damper clamp is a boltless construction in which the conductor is cushioned in a U-shaped elastomer-lined clamp and securely held in place by helical factory-formed rods as shown in Figure 32. Sets of four or six helical rods are generally used to that purpose. The rods must be manufactured from material that is compatible with the conductor strands. It is possible to do live line work with the helical rod attachment but it is more tedious than with a bolted clamp. Correct installation may easily be verified from ground level.

Helical rod attachment introduces a small additional amount of damping in the system but its main advantage is that it reduces the conductor bending severity at the damper clamp. It does so because the rods provide a local increase of the conductor bending stiffness and the elastomer allows the conductor bending to be more distributed along the clamp whilst maintaining the vertical and longitudinal grip on the conductor. The discontinuity of the conductor slope is thus reduced considerably in comparison to a metal-to-metal clamp. Since there are many cases where the severity of bending amplitude is more severe at the damper clamp than at the suspension clamp, this clamp increases the efficiency of the damping system.

Aeolian vibration dampers with helically attached damper clamps are mainly used on small conductors and ground wires.

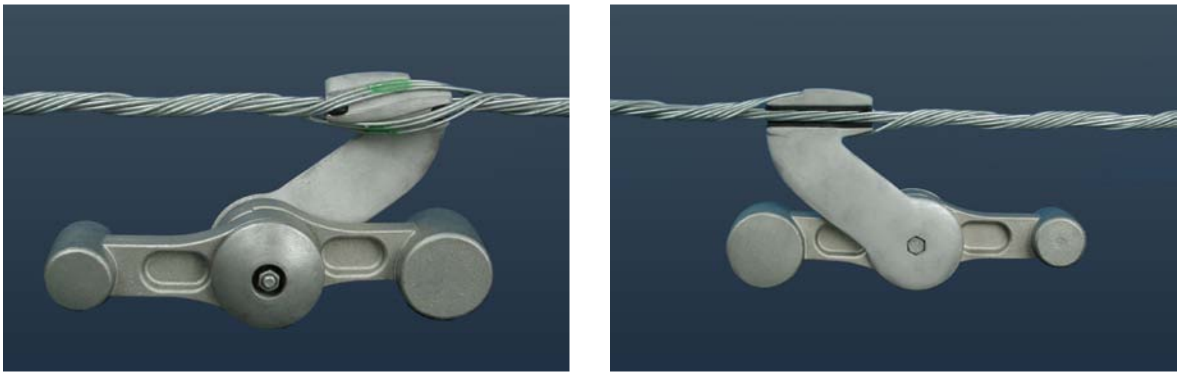

**Figure 32**: Aeolian vibration damper with helically-attached clamp.

## 8.4 Termination Clamps

In this section, some types of termination clamps are presented, such as compression, wedge, helical formed wire and bolted types. This is not an exhaustive list but it gives the reader an overview of the different designs and types that are commonly used. Compression clamps are unique in that the continuity of the conductor is broken so it is necessary to ensure good electrical conductivity. They will be discussed in Section 8.5.

### 8.4.1 Helical Terminations for Conductors

Helical dead-ends are used to terminate conductors. The typical device is designed to hold the mechanical load of the conductor and is not designed to transfer electrical loads. A secondary tap is required to transfer the electrical current. Most helical terminations for smaller ACSR conductors and conductors of homogeneous construction (such as AAAC) are single layer, as shown in Figure 33.


**Figure 33**: Single layer helical termination.

Helical terminations for ADSS, OPGW and high temperature conductor can consist of two layers (Figure 34). The structural reinforcing rod layer is similar to an armor rod layer and increases the contact length of the dead-end. The second layer is a helical termination that is wrapped over the structural reinforcing layer. Helical terminations for conductors have been used successfully for the past 40 years. The helical termination is designed such that the bore of the helical wrap is smaller than the diameter of the conductor. This results in compressive force being applied to the conductor along the contact length of the product. Typical single layer helical terminations will develop a minimum of 90% RTS on homogeneous AAAC and single layer ACSR. The helical termination only contacts the outside layer of the conductor so it must pass the compressive load into the inner layer of the conductor. In case with multi-layer ACSR conductor, where the high strength steel is in the inner most layers of the conductor, the helical dead-end cannot pass enough holding strength into the core to develop 90% RTS of the conductor. In these cases, specially designed two-layer helical terminations may increase the holding strength above the 95% RTS level.

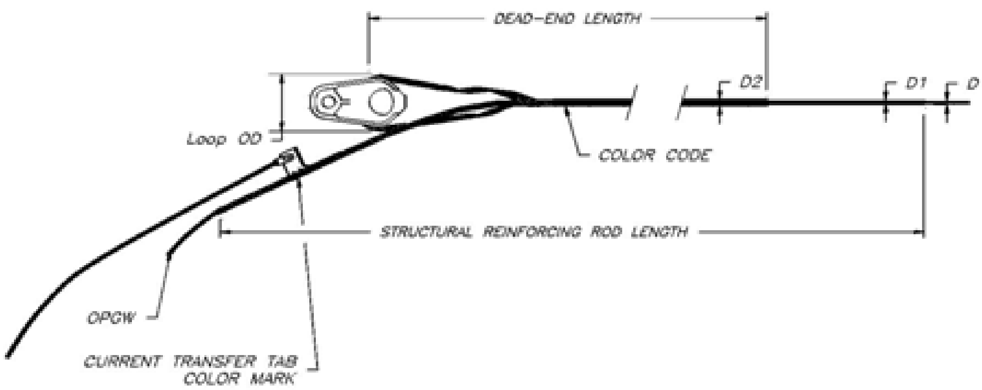


**Figure 34**: Two-layer helical termination.

Conductor construction may also affect the holding strength of helical terminations. Trapezoidal wire construction can also affect holding strength of the helical termination if bridging of the wire occurs and does not allow the compressive load to pass into the core wires.

There is low stress concentration since the compressive load is applied over a long contact length. In addition, the relatively low weight concentration does not result in forcing nodal points at the ends of the termination. This reduces the bending strain during cable motion such as aeolian vibration.

**Typical Installation**

Most applications of helical terminations include a reinforcing thimble for attachment to the insulator. The helical dead-end is simply wrapped around the conductor. No special tools are required. The conductor can be permitted to extend through the termination loop of the dead-end for the purpose of electrically tapping the conductor.

### 8.4.2 Wedge Type Dead-End Clamps

Wedge type dead-end clamps are used for terminating overhead conductors. Such typical devices used on both transmission and distribution lines are typically shown in Figure 35.

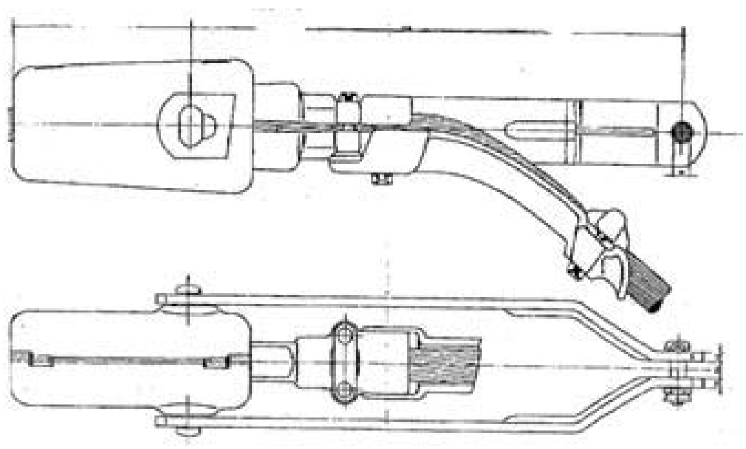

**Figure 35**: Wedge type dead-end clamp.

### 8.4.3 Bolted Type Dead-End Clamps

Bolted dead-ends are commonly used to terminate conductors. In such fittings, the conductor passes through this clamp and not being cut. The bolt torque and the length of the clamp are calibrated to prevent the slipping of the conductor and avoid any damage on the outmost layer.

Typical devices for lower voltage transmission and distribution lines are called bolted quadrant type dead-end clamps as shown in Figure 36.

Devices that are mainly used on distribution lines, such as bolted straight type dead-end clamps, are shown in Figure 37.

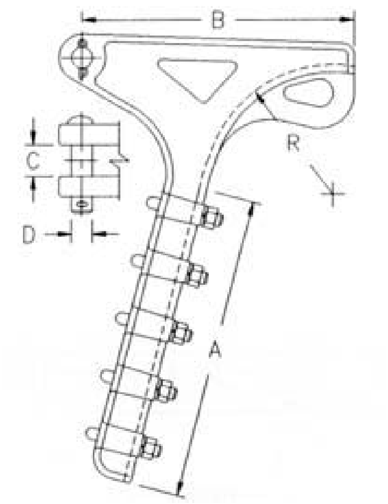


Figure 36: Bolted quadrant type dead-end clamp.

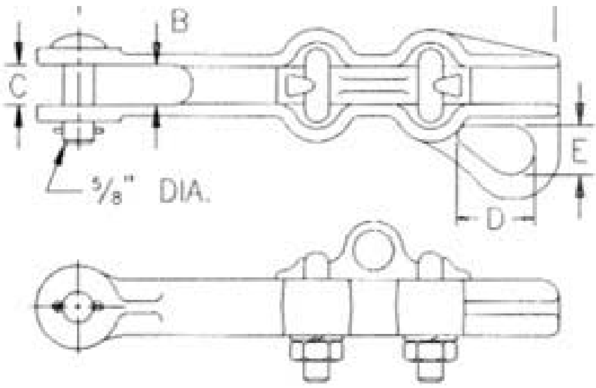


**Figure 37**: Bolted straight type dead-end clamp.

#### 8.4.4 Testing

Testing is normally focussed on holding strength. Typical testing includes loading to destruction to determine ultimate holding strength (up to 95% RTS). Typical tests such as BS 3288 may be conducted. In addition, long-term sustained loads testing at appropriate operating tensions (35% RTS) have been conducted to verify creep and long-term holding performance. Vibration testing should also be conducted to verify that the design does not force nodes and high bending stress.

### 8.5 Compression Clamps

#### 8.5.1 Function

To hold the conductor in towers where the line is to be supported, and therefore, the full mechanical tension of the line is to be applied.

These clamps are specified to be able to withstand at least 95% of the rated breaking load of the conductor without any slippage or breakage of the conductor-clamp system.

#### 8.5.2 Description and Design

Compression clamps are composed of two main parts :

- An aluminium or aluminium alloy tube into which the conductor is inserted. Once the conductor is inside, the tube is compressed so that tube and conductor "become one". When the clamp is not installed in line-ends, it has an aluminium connection pad to which a jumper lug can be joined, usually by bolts (2 or 4 bolts, depending on the clamp's size), as can be seen in Figure 38.

**Figure 38**: Aluminium tube of a compression clamp.

- A steel terminal to join the clamp to the insulator string (Figure 39). This is also inserted into the aluminium tube and joined to it by compression. In ACSR conductors the cable's steel core is inserted into this terminal and compressed.

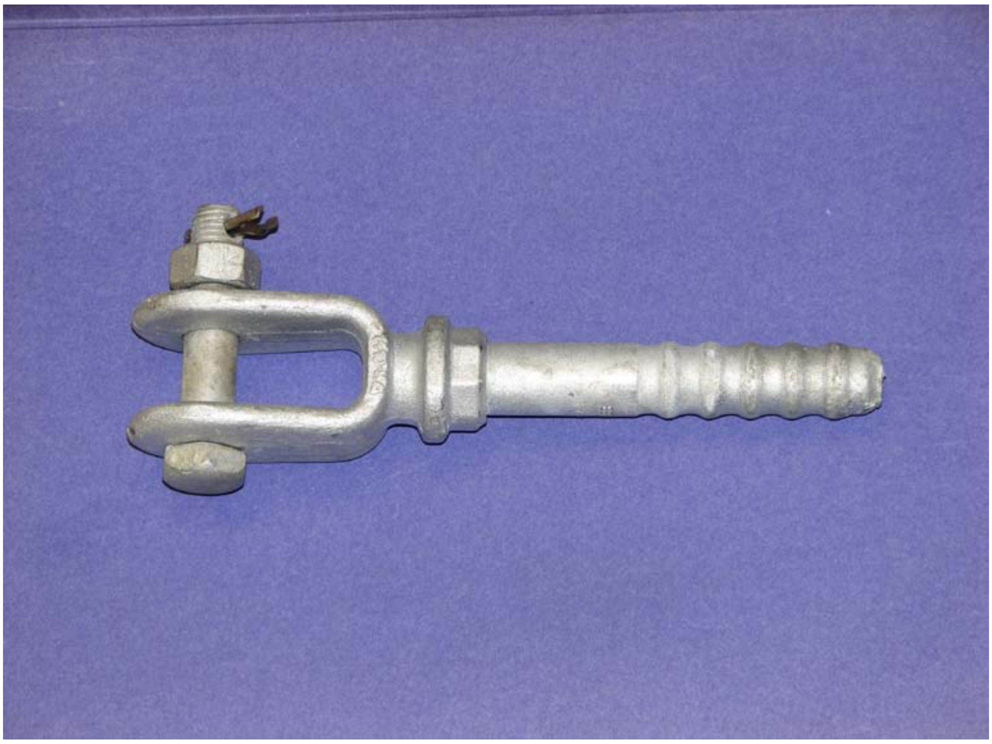

**Figure 39**: Steel terminal of a compression clamp.

They can be classified in two types according to the compression method :

1. Implosive clamps: They are compressed by means of an explosive charge and a fuse that goes with each clamp (Figure 40).

**Figure 40**: Implosive clamp.

2. Hexagonal die compression clamps: They are compressed using hexagonal die compression machines. Different dies are used for conductors of different sizes (Figure 41).

**Figure 41**: Hexagonal die compression clamp.

Both types must fulfill the following electrical and mechanical characteristics :

1. They must assure a good conductivity of the electrical circuit, avoiding the appearance of hot spots in conductor-clamp junctions.
2. The compression clamp must be designed in such a way that it does not harm the conductor during the compression process.
3. The conductor-clamp system must be able to withstand at least 95% of the conductor breaking load without slippage or breakage.
4. The onset of corrosion must be avoided for as long as possible by applying some kind of grease or by any other means which prevent water and pollution from entering the clamp.

### 8.5.3 Typical Applications and Factors to be Taken Into Account During Installation

#### 8.5.3.1 Implosive Compression Clamps

They are mainly used in cold weather countries, such as Canada or Norway, but also in USA.

Advantages:

- The distribution of compression forces on the conductor will be more regular because of its round shape;
- Bad conductor preparation before installation will have less harmful consequences than in the case of hydraulic compression clamps.

Disadvantages:

- They make a loud, intrusive noise, which means people will be more disturbed by their installation;
- The workers who are going to install them need special qualifications;
- Special permits are needed for their transportation.

#### 8.5.3.2 Hexagonal Die Compression Clamps

They are the most commonly used compression clamps. Main aspects to be taken into account when installing this type of clamp:

1. Distance between flats: the distance between the flats of the compressed tube must be the one stated in the manufacturer's specifications. The die used for the compression must be the one that is specified in the clamp's marking.
2. Compression length: the clamp's markings have also to be taken into account to achieve the proper compression length.
3. Regularity of the hexagon: it is important that the shape of the hexagon be as regular as possible to get an even distribution of tensions in the compressed conductor.
4. Conductor preparation: the grease on the conductor must be wiped off before compression and the grease supplied by the manufacturer must be applied where the conductor is going to be installed in order to avoid early corrosion.