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Fatigue performance of overhead conductors tested under the same value of H/w parameter

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Abstract

The objective of this work is to conduct an experimental campaign to evaluate the effects of the catenary parameter (*H/w*) on the fatigue life of overhead conductors, being *H* the horizontal tensile load of the power line and *w* the weight per unit length of the conductor. A battery of twenty seven (27) fatigue tests was carried out on three types of conductors, an AAAC 900 MCM, an AAC Orchid and an ACSR Tern. For this study, all tests were conducted using the value of *H/w* = 2144 m. Fatigue damage, one of the major problems affecting power line conductors around the world, is caused by Aeolian vibration, characterised by high frequency and low amplitude movements. Based on field observations, the *H/w* parameter has recently been proposed as a fatigue design criterion for different families of cables. However, there is little experimental data available in the literature to assess the impacts of this hypothesis. Comparison between the generated S-N curves proved that an ACSR Tern conductor could sustain a significantly higher number of cycles before fatigue failure than the AAAC 900 MCM for this level of *H/w*. Meanwhile, the AAC Orchid presents a fatigue life situated between the AAAC 900 MCM and the ACSR Tern conductors. Failure analysis of the broken samples revealed not only that cracks initiated in the fretted areas of the aluminium wires but also that their morphology presented clear evidence of fatigue failure, such as observable beach marks and secondary cracks. Additionally, a failure map has been raised to determine the precise layer and the position from the clamp mouth where the wires broke. Furthermore, the provided information could be helpful for planning the maintenance of power lines.

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Keywords: fatigue; fretting fatigue; H/w parameter; conductor; transmission line

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1. Introduction

The overhead conductor is the only part carrying electricity, so its contribution has been estimated as carrying up to 40% of all power line transmission costs. However, this transmission line is susceptible to wind, snow, earthquakes and other weather conditions [1]. Aeolian vibration is the main cause of conductor fatigue failure, especially at devices which restrain its movements [2-4]. Frequently, the observed fatigue failure on overhead conductors occurs near or inside the suspension clamp, or devices attached to the conductor. That fatigue is characterized as the fretting fatigue of conductor strand during its aeolian vibration due to the fixation torque of the device on the conductor and also due to the microslip motion between wires and between the conductor and the device. A suspension clamp is one of the critical devices in term of fretting fatigue of conductor strand as there are many loads acting on the assembly conductor/clamp [5,6]. Among the loads, there are the tensile load of the conductor, the bending displacement due to the Aeolian vibration and the clamping torque.

The control of the stretching tension of conductors at the design stage has been a concern for many years [1]. One of the reasons is that the tension of conductors during the most severe climate period does not exceed the allowable tension of the conductor. On the other hand, the stretching tension must be controlled in order to restrict the violation of the line clearance and also to protect the conductor against the harmful Aeolian vibration. It is well-known that a conductor becomes more vulnerable to Aeolian vibration when its tensile tension increases. Therefore, the *Conseil International des Grands Réseaux Électriques* (International Council on Large Electric Systems), abbreviated CIGRÉ, has found necessary to establish an upper limit for conductor tension that can prevail for a significant period of time. The Every Day Stress (EDS) panel was created by CIGRÉ to investigate the safe parameter design of power line conductors [7,8]. One of the problems in the use of the EDS (percentage of conductor rated tensile strength) parameter is that the CIGRÉ group made its study when most of the transmission lines around the world were made of the ACSR (Aluminium Conductor Steel Reinforced) conductors with a specify amount of ratio steel/aluminum wires. In addition, the EDS dos not take in account the conductor diameter nor the terrain condition where the power line transmission will operate. The EDS is the maximum tension load to which the conductor can be subjected, at the temperature which will occur for the longest period of time in one year, without any risk of damage from Aeolian vibrations. It is expressed in percentage of the rated tensile strength of the conductor, and CIGRÉ has fixed its values according to the type of the conductor. However, failure on overhead conductors due to Aeolian vibration has been observed in situ even when the transmission line has been designed with the recommended EDS value, for instance 78% of power line failure by fatigue before 20 years after their launching. Thus, to explain the damages found, there is importantly a need of another parameter [8].

The *H/w* parameter has recently been suggested by CIGRÉ to better explain and describe the fatigue damage occurring on power line conductors due to the Aeolian vibration. The proponents of this parameter suggest that all overhead conductors stretched with the same value of *H/w* will have the same fatigue life [9]. Although, no experimental laboratory on overhead conductors was conducted to corroborate this idea. After a thorough literature investigation, some publications have been identified regarding fatigue of power lines related to the EDS parameter [1,5,6]; however, there are few publications related to the *H/w* parameter. This present work, then, has the objective of conducting an experimental campaign to evaluate the effects of the catenary parameter (*H/w*) on the fatigue life of power line conductors. Twenty seven (27) fatigue tests were carried out on three types of conductors, namely an Aluminium Conductor Steel Reinforced (ACSR Tern), an All Aluminium Alloy Conductor (AAAC 900 MCM) and an All Aluminium Conductor (AAC Orchid). Additionally, the failure analysis in terms of distance where the failure occurs from the suspension clamp mouth was considered. Moreover, failure analysis on the broken wires was also conducted as part of this work and fatigue marks identified.

2. Bending stress and H/w parameter

2.1. Bending stress

The main cause of fatigue failure of strands in overhead conductors is Aeolian vibration, a fatigue which generally occurs at points where conductor motion is constrained against transverse vibration, such as at suspension clamps. During Aeolian vibration, the conductor undergoes cyclic movement which induces bending stress in power line conductor wires.

Most fatigue failures in strands of conductors occurs in the suspension clamp at the contact points of wires-to-wires and wires-to-suspension clamp [10,11]. Because of the difficulty on accurate measurement of mechanical strain or stress at these points, the adoption of some assumptions is vital. A mathematical model was developed by Poffenberger and Swart [12] to calculate the bending strain or stress in the outer layer of the conductor's aluminium wire. This mathematical model considers the cable, near the suspension clamp, as an Euler beam (Fig.1).

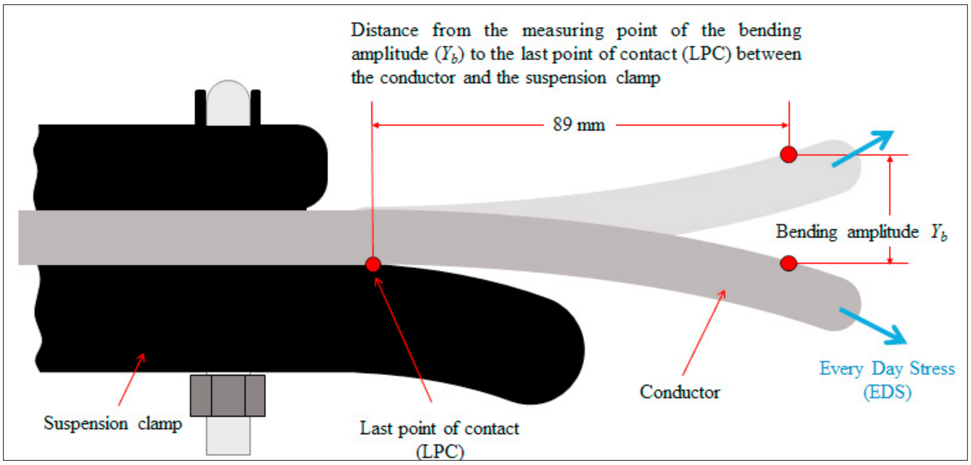

Fig. 1. Schematic montage of the conductor and the suspension clamp showing the standard position to measure the bending amplitude.

Thus, the vertical amplitude, measured peak-to-peak at 89 mm (3.5 in) from the last point of contact (LPC) between cable and suspension clamp, can be converted to the bending strain or stress in the outer layer of the aluminium wire conductor using Eq. 1. The Poffenberger-Swart Equation has been developed as follows:

$$\sigma_a = KY_b \tag{1}$$

where σ_a is the dynamic bending stress amplitude (0-to-peak); Y_b is the conductor's vertical amplitude range (peak-to-peak) measured at 89 mm from LPC; and:

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

where E_a (MPa) is the aluminium Young's modulus; d (mm) is the diameter of wire in the outer layer; x is the distance on the conductor from the LPC (between the conductor and the suspension clamp) and the vertical displacement measuring point, (usually $x = 89$ mm), as one can see on Fig 1; and

$$p = \sqrt{\frac{T}{EI}} \tag{3}$$

where T (N) is the static conductor tension at average ambient temperature during test period; and EI (N.mm^2) is the flexural stiffness of the conductor, whose minimum value is as follows:

$$EI_{\min} = n_a E_a \frac{\pi d_a^4}{64} + n_s E_s \frac{\pi d_s^4}{64} \tag{4}$$

where n_a, E_a, d_a are the number, individual diameter and Young's modulus of the aluminium wires; and n_s, E_s, d_s are the respective values for the steel wires. In this approach, the conductor is considered as a bundle of individual wires free to move relative to each other; the flexural stiffness takes its minimum value, EI_{min}. For smaller bending amplitudes, the individual wires would stick together; thus the conductor would behave as a solid rod, increasing the flexural stiffness to its maximum. Formulae that consider the stick-slip theory to compute EI and hence the dynamic bending stress were proposed by Papailiou [13,14].

2.2. H/w parameter

The design of overhead power lines has been guided by the control of the conductor tension. Many reasons have justified this option: among them is the objective of ensuring that the maximum tension of the conductor corresponding to the assumed most severe climatic loading does not exceed a predefined load. Another reason is related to the maximum temperature operation of the conductor which could allow the conductor to work in respect to the conduct clearance. It is well-known that the conductor becomes increasingly vulnerable to Aeolian vibration when its static tension increases. Therefore, some organizations related to power line conductors have found necessary to establish an upper limit for conductor tension that can prevail for a significant period of time. Consequently, the Every Day Stress (EDS) panel was created by CIGRÉ to investigate the safe parameter design of power line conductors. Many parameters have been proposed for the safe design of overhead conductors, but two – Every Day Stress and the catenary parameter *H/w* – are the most prevalent in the literature.

Every Day Stress (EDS) is the parameter of overhead conductors, with respect to Aeolian vibration, initially proposed by CIGRÉ in 1960 [9]. The EDS, expressed as a percentage of the conductor rated tensile strength (RTS), is defined as the maximum tensile load to which the conductor can be subjected, at the temperature which will occur for the longest period of the time without any risk of damage due to Aeolian vibrations. CIGRÉ recommends different values of EDS for overhead conductors and for conductors with dampers only, armor rods only, as well as for conductors with both dampers and armor rods. However, observations from the field have reported fatigue of power lines after the application of the recommended EDS values by CIGRÉ [1,7,9]. Consequently, the EDS parameter appears to be insufficient for explaining the recent damage found on power lines. It has been observed by the CIGRÉ's EDS panel that lines are damaged, even when they were designed with the recommended EDS value less than 18% of the conductor RTS. Clearly, the requirement for a new parameter is evident.

Another parameter adopted by CIGRÉ, is defined as the ratio between the initial horizontal tensile load (*H*) and the conductor weight (*w*) per unit length*, H/w*; this parameter is also called the catenary parameter. The tensile load (*H*) is the initial horizontal tension before any significant wind and ice loading and before creep at the average temperature of the coldest month at the site of the power line [1,11]. Compared to the EDS, the *H/w* presents several advantages, as it affects a number of parameters involved in the fatigue characteristic of conductors. One of them is that the *H/w* parameter takes into account the diameter of the power line conductor, which influences the energy induced by the wind and the frequency of vortex formation [7,9].

3. Materials and experimental procedure

Three types of conductor – Aluminium Conductor Steel Reinforced ACSR, All Aluminium Alloy Conductor AAAC and All Aluminium Conductor AAC, named respectively ACSR Tern, AAAC 900 MCM and AAC Orchid conductors – were tested. The first conductor, AAC Orchid, is made of pure Aluminium AA 1350-H19 and the second conductor, AAAC 900 MCM, is made of aluminium alloy AA 6201-T81 which contains alloys elements and undergo heat treatment to add mechanical strength to the pure aluminium. The last conductor, ACSR Tern, is the most commonly used conductor around the world. This conductor consists of the core and the first layer in steel and the other layers are in commercial pure aluminium AA 1350-H19. The mechanical properties of the three different conductors used for the publication are presented in Table 1. The schemes as well as the cross section, where the outer and inner layers are identified, of the three conductors are shown on Fig. 2.

Table 1. Mechanical properties of conductors

Conductor Type	Conductor diameter (mm)	Rate Tensile Strength (kgf)	Material, Number and Diameter of wire (mm)		Linear mass (kg/m)
			Steel	Aluminium	
ACSR Tern	27.03	10010	7x2.25	45x3.38	1.339
AAAC 900 MCM	27.74	13485	-	37 x 3.962	1.252
AAC Orchid	23.30	5143	-	37x3.33	0.889

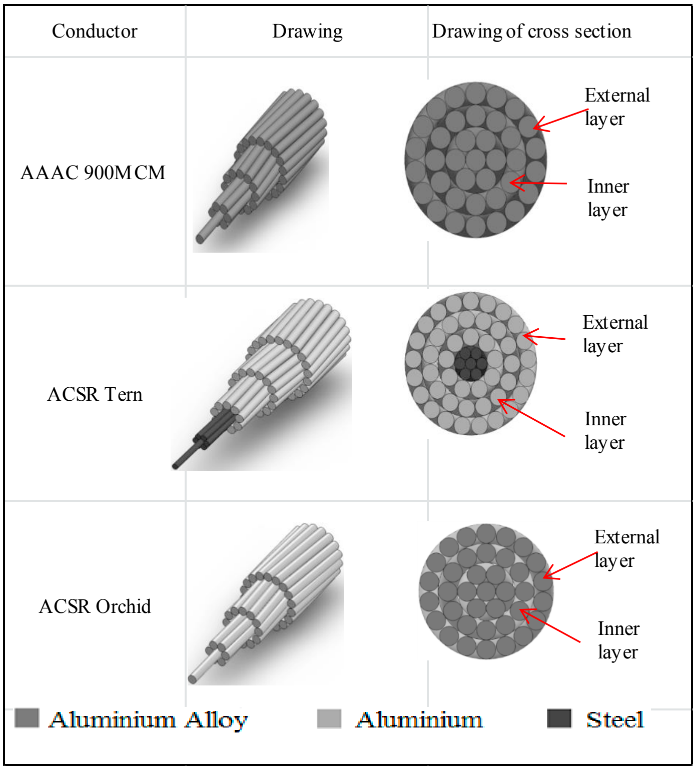

Fig. 2. Scheme of different conductors used and their cross section with the external and inner layer

At the GFFM (Fatigue, Fracture and Materials Research Group) laboratory (University of Brasília), three similar resonance fatigue test benches of conductors were used. A brief description of the bench is provided below as it was previously described in other publications [2,5,15]. Each bench has a length of 46 m divided in two spans – the active and the passive span – which have, respectively, 40 and 6.8 m. The scheme of the three benches is shown in Fig. 3(a), while Fig. 3(b) represents the benches side view. The test starts by anchoring the conductor on the two fixed blocks (fixed blocks 1 and 3) and thereafter mounting the suspension clamp on the support which is rigidly fixed on the adjustable block 3. The conductor is stretched at the recommended value of *H/w* through the strain clamp by using the hand traction winch and weight. To simulate the vibration, an electrodynamic shaker is connected to the conductor via a device which allows a good alignment between the shaker and the conductor axes. A wire break detector is attached to the conductor at the first node of the conductor from the suspension clamp toward the shaker.

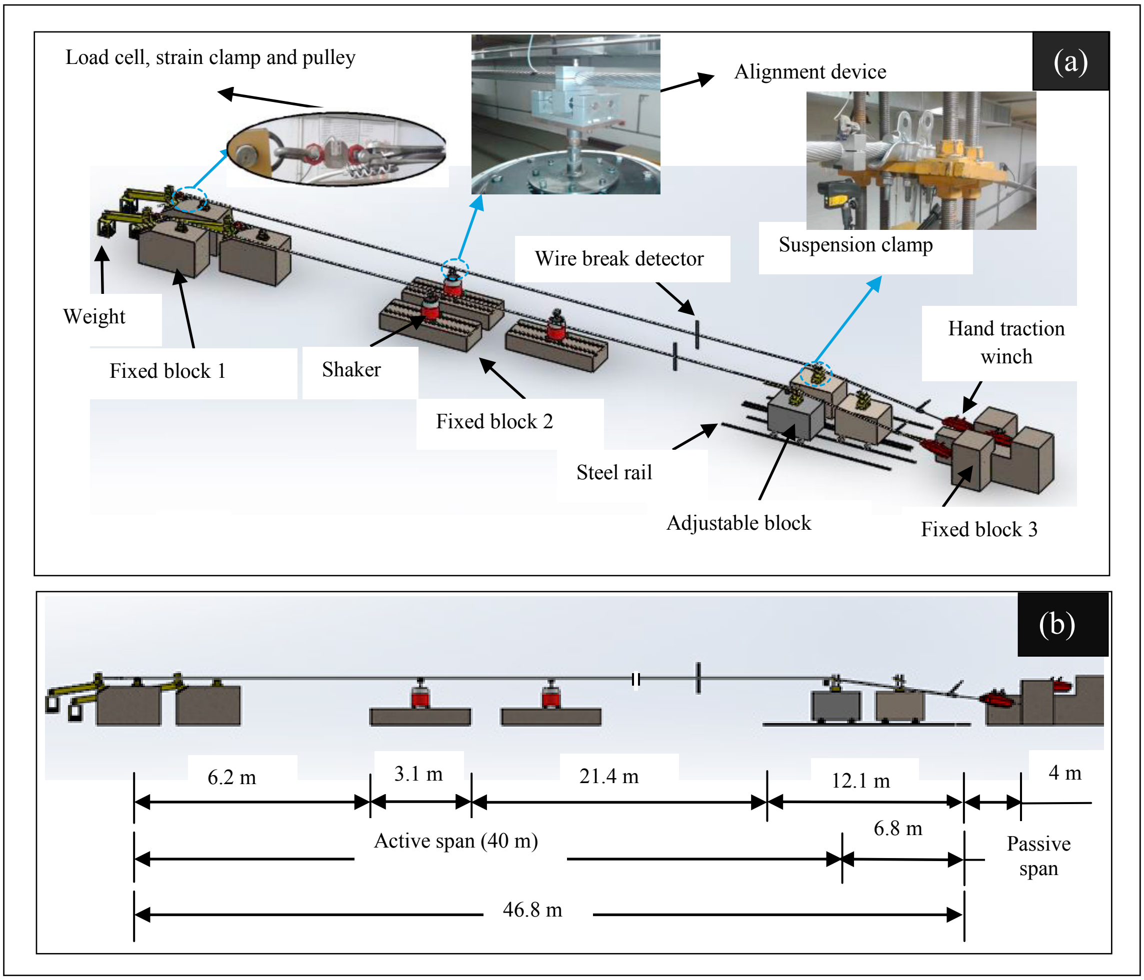

Fig. 3. Three fatigue test benches for overhead conductors at the University of Brasilia: (a) overall three dimensional view and (b) side view.

A series of fatigue tests were carried out on the three conductors cited above, which were stretched with the same level of *H/w* parameter (2144 m). All fatigue tests were performed according to IEEE (Institute of Electrical and Electronics Engineers) and CIGRÉ standards which establish the criterion to stop the conductor´s fatigue test when the number of strands broken is 10% of the total number of conductor aluminium wires [16,17]. To measure the bending stress of the conductor, three strain gauges were glued on the most upper conductor’s wires (being one strain gauge by wire) diametrically opposed to the LPC between the suspension clamp and the conductor (Fig. 4). The bending displacement peak-to-peak (Yb) measured at 89 mm from the LPC between the conductor and the suspension clamp was controlled, along with the vibration frequency, during all fatigue tests. For each conductor, the S-N graph was generated by performing nine fatigue tests (three different bending stress were used and three tests were performed per each bending stress). The three levels of bending stress considered during the experimental program and the corresponding bending displacement peak-to-peak generated by applying the Poffenberger-Swart constant (K) are presented in Table 2 for the same H/w value of 2144 m.

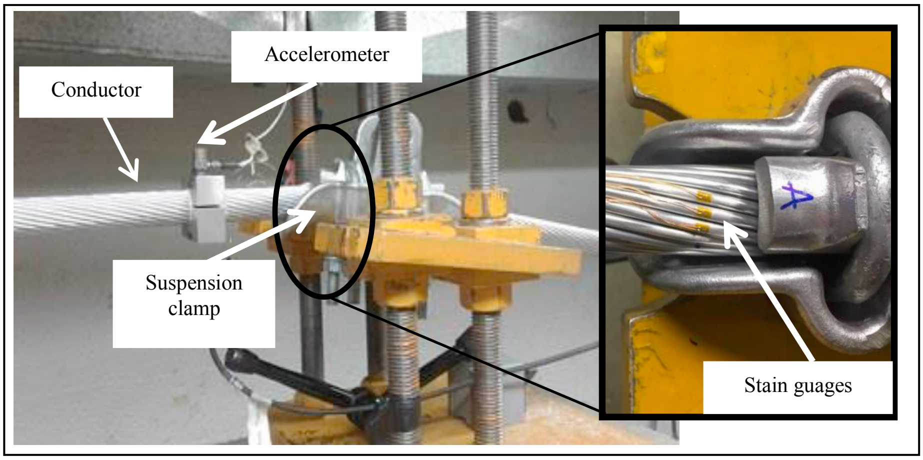

Fig. 4. The system conductor/suspension clamp with strain guages glued on the most upper conductor's wires to measure the bending stress

Table 2. The bending amplitude (Y_b) at 89 mm from the LPC between the suspension clamp and the conductor and the Poffenberger-Swart constant (K) calculated using Eq. 1 and Eq. 2 for different conductors.

	K (MPa/mm)	H (kgf)	Stress (MPa)		
ACSR Tern	33.66	2873	26.8	28.22	31.35
			Bending amplitude (mm)		
			0.8	0.84	0.93
AAAC 900 MCM	34.83	2684	23.7	28.22	31.35
			Bending amplitude (mm)		
			0.68	0.81	0.9
AAC Orchid	32.49	1903	26.8	28.22	31.35
			Bending amplitude (mm)		
			0.84	0.87	0.96

4. Results, analysis and discussions

4.1. Results of fatigue tests

Twenty seven fatigue tests were conducted on three types of conductors, nine for each conductor at H/w = 2144m. The S-N graphs generated are presented in Fig. 5 using the bending stress (bending displacement, Y_b) as shown in Table 2. Comparison between these generated S-N curves proved that the ACSR Tern conductor could sustain a significantly higher number of cycles before fatigue failure than the AAAC 900 MCM for this level of H/w. Meanwhile, the AAC Orchid presents a fatigue life situated between the AAAC 900 MCM and the ACSR Tern conductors. Comparisons between fatigue life ratios of the three conductors showed that, on average, the cables ACSR Tern and AAC Orchid presented a durability four and two times greater than the AAAC 900 MCM conductor respectively. Nevertheless, these ratios tend to increase at the low bending displacement and decrease at high bending amplitude, measured at 89 mm from the LPC. As the aluminium alloy (6201-T81) from the AAAC 900 MCM has higher ultimate and yield strengths than the pure aluminium AA 1350-H19 (ASCR Tern and AAC Orchid) [1, 18], one could in principle expect that the AAAC 900 MCM would also have a higher fatigue life than the other two conductors under the same stress amplitude. However, because of the complexity of the phenomena occurring within the cable/clamp mechanical assembly and in the wire to wire contact in the cable, care must been taken in the analysis. One possible explanation to this behaviour is the fact the stress concentration and the superficial fretting damage caused by the contact among the wires and the contact of the wires with the suspension clamp may have seriously interfered in the crack initiation stage. In this case, our hypothesis is that the more resistant 6201-T81 alloy had its crack initiation resistance a lot reduced by these effects, while the pure aluminium was less sensitive to them.

Worthy of note is the fact that the ACSR Tern conductor presented a higher fatigue life than the AAC Orchid for all stress amplitudes considered in the tests despite the fact that both conductors have their two outer layers made of the same pure aluminium (1350-H19). This could be explained by the fact that the steel wires in the ACSR Tern sustain a higher static stress than the aluminium ones. Therefore, the aluminium wires of the ACSR Tern could experience a lower mean tensile stress than the ones in the AAC Orchid. Due to the obvious difficulties in measuring strains in the internal wires the use of numerical simulation would be quite interesting to assess the difference between tensile stresses in these wires for different cables.

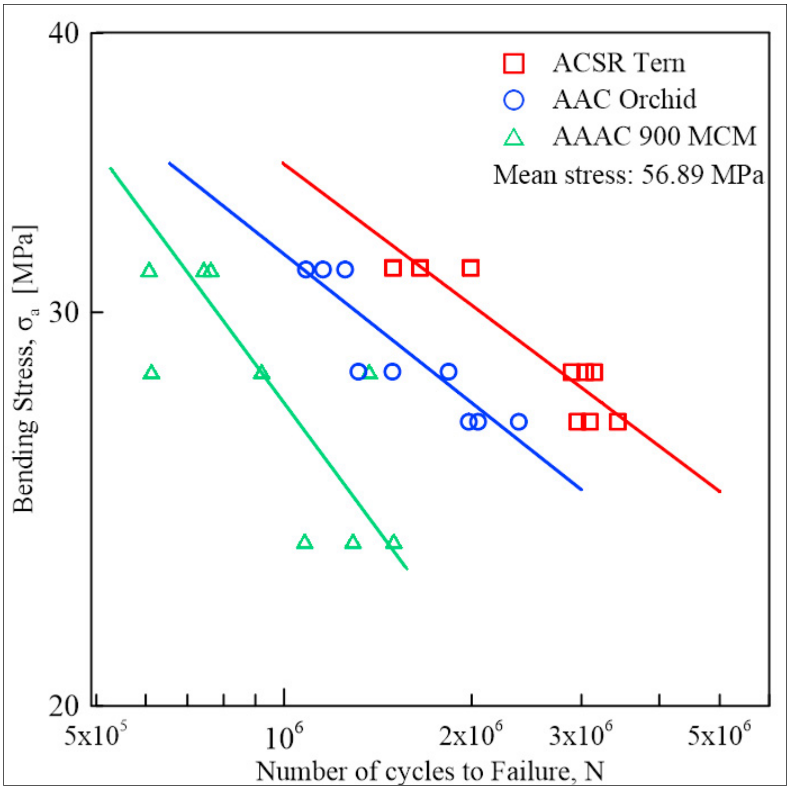

Fig. 5. S-N graphs of the different conductors at the same value of H/w (2144 m).

Figure 6 shows a graph of constant life (10^6 cycles) for the three conductors tested. It can be observed that for a same fatigue life, the ACSR Tern and the AAC Orchid can hold a stress amplitude 35% and 17% higher than the AAAC 900 MCM conductor, respectively. Based on the results presented in Figs. 5 and 6, it seems clear that the use of the same value of *H/w* to design different types of overhead conductors against fatigue is not an appropriate choice. Indeed, to have the same fatigue life, the ACSR Tern could be stretched using a higher value of *H/w* than the

AAAC 900 MCM and still the power line would be safe against Aeolian vibration, assuming similar type of terrain and weather condition and that the level of vibration in these cables would be similar due to an efficient protection/dumping system. Notice that, by using a higher value of *H/w*, not only the towers of the transmission lines could be smaller but also less cable would be necessary in the line.

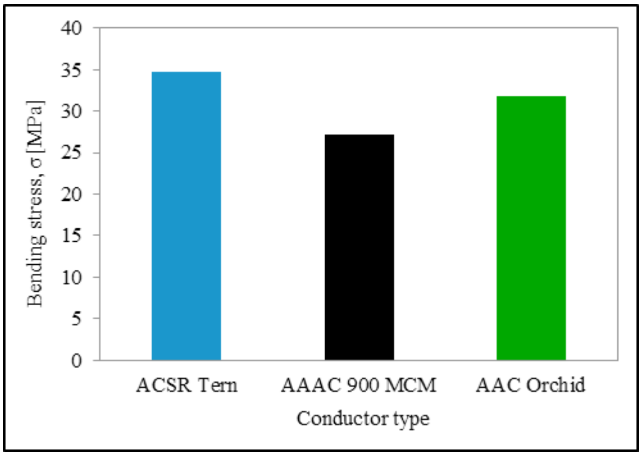

Fig. 6. Constant fatigue life diagram of the conductors tested considering a life of 10^6 cycles.

4.2. Failures analysis

Three types of failure analyses were considered in this work. First, we investigated the distance of the broken wires from the suspension clamp mouth after each test. Then, we identified the layer where such breaks occurred, and at last we conducted a microscopic failure analysis. These types of analysis can be quite useful to line men involved in the mechanical maintenance of the power lines, as they provide essential information to localize the wire breaks in field [18]. Also the microscopic failure analysis can provide us information on the dominant type of stress (shear/normal) that seems to control the process of crack initiation for these types of fretting contacts.

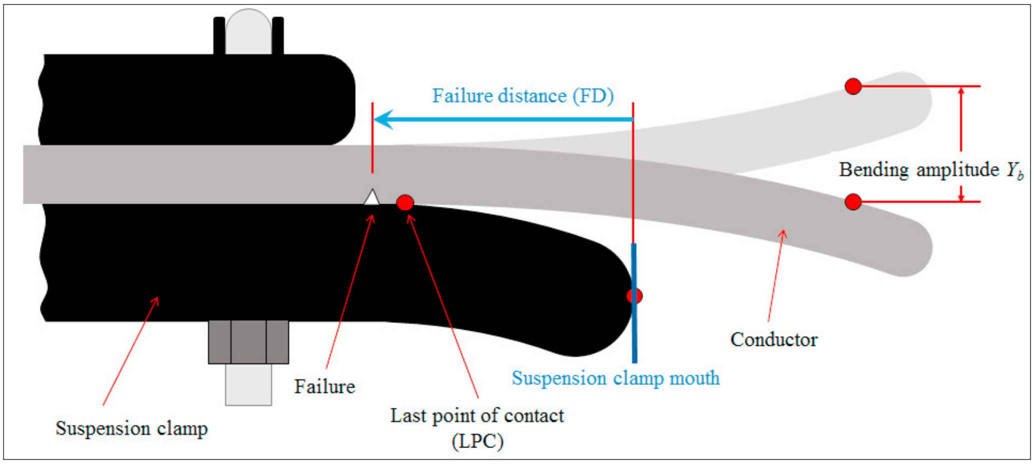

Fig. 7. Scheme of the system conductor/suspension clamp showing the failure distance.

Figure 7 presents the system conductor/suspension clamp with the wire failure distance (FD), measured from the suspension clamp mouth for the three conductors tested at the same value of the H/w. All wires break occurred inside the suspension clamp therefore the FD was measured from the mouth toward the suspension clamp (Fig.7). On average, the failure distance was 35 mm for ACSR Tern and AAC Orchid, while it was 40 mm for the AAAC 900 MCM conductor for the bending displacements/stresses considered in this publication (Fig. 8). These distances seem to depend on the material, as it was observed that different conductors (ACSR Tern and AAC Orchid) but with outer wire layers made of the same pure aluminium (1350-H19) broke almost at the same mean value, while the FD for the aluminium alloy was a different one. Concerning the layer of the conductor where the wire break occurred, it was noticed that most of these were observed in the outer layer (Fig. 9). This situation, underlined by other researchers, may be associated with the presence of an aggressive superficial damage condition between the suspension clamp and the conductor during vibration. The aggressive condition is presented by the formation of the debris, SiO3 and Al2O3, between the conductor and the suspension during the fatigue test. These debris have an higher hardness, respectively 1050 and 2000 HV, than the aluminium of conductor strand [2,19,20].

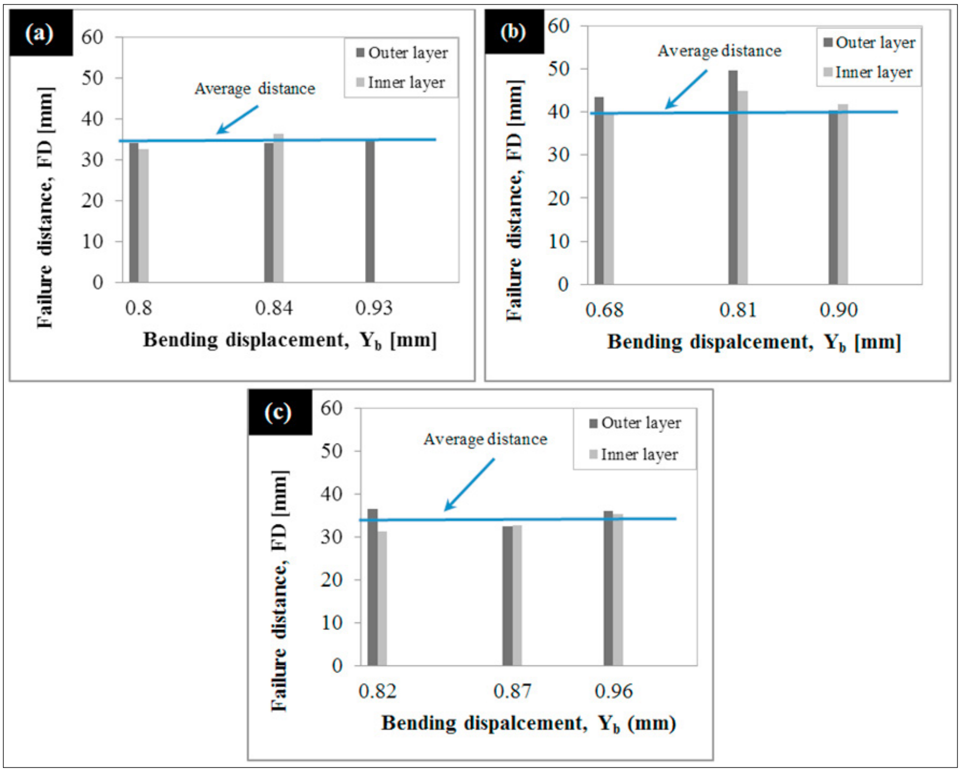

Fig. 8. Failure distance measured from the mouth of the suspension clamp as a function of bending displacement for different conductors: (a) ACSR Tern, (b) AAAC 900 MCM and (c) AAC Orchid conductor.

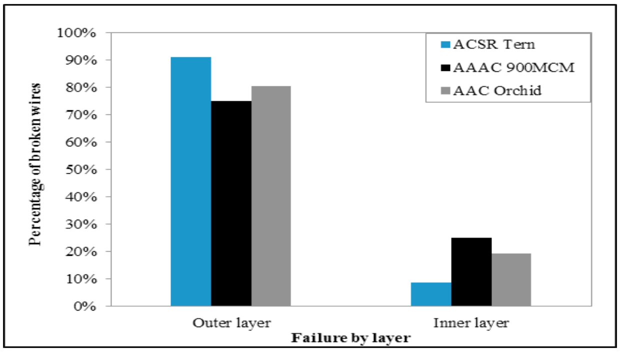

Fig. 9. Percentage of wire breaks by layer for different conductors tested.

The microscopic failure analysis was carried out on the broken strands of the conductors tested by fatigue. It was observed that for the wires of the three different conductors the cracks always initiated in the fretting marks caused by the small relative movement between the suspension clamp and the conductor, and between conductor layers during its vibration movement. The fretting marks were elliptic with two zones, a stick and a slip zone, as shown in Fig. 10.

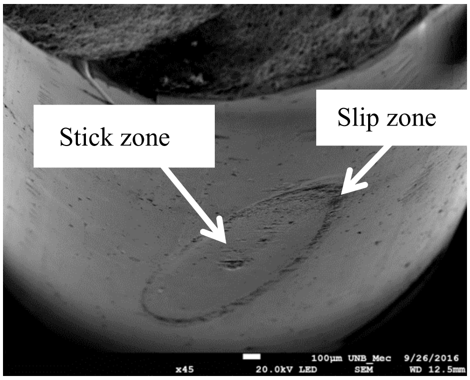

Fig. 10. Elliptical fretting mark on the conductor broken wire with two zones: the slip and stick zone.

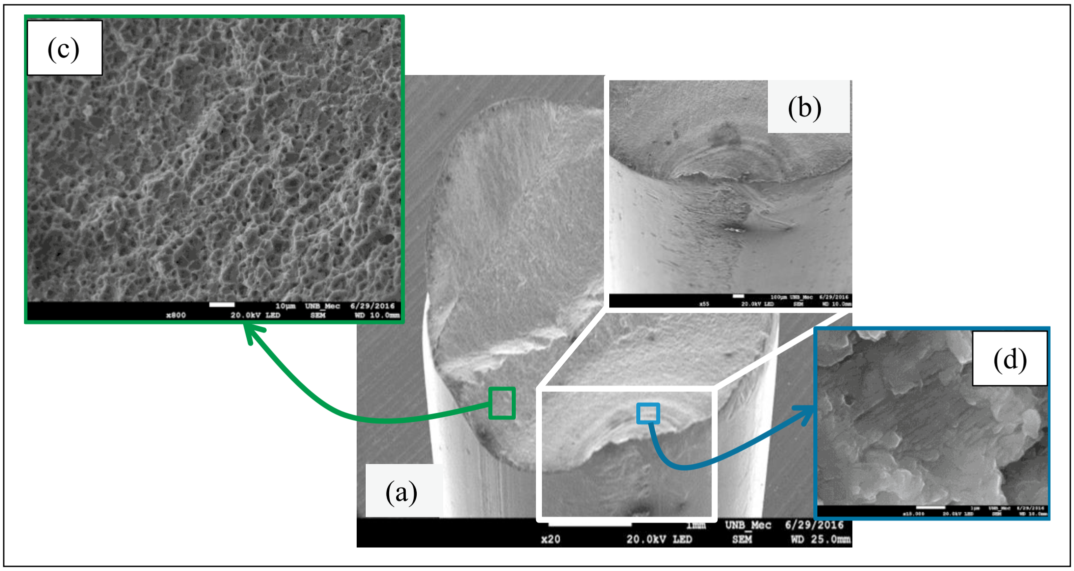

Fig. 11. Fracture surface of an AAAC 900 MCM strand: (a) crack initiated in the fretted region and beach marks; (b) zoom of the crack initiation point; (c) dimples; and (d) striation mark.

Figure 11 illustrates the fracture surface of a wire of the AAAC 900 MCM. Beach marks can clearly be seen in the crack initiation site within a fretting damaged area. The crack then propagates to the interior of the wire, and finally, the failure arises when the remaining section could not sustain the static load (Fig. 11). However, it was not possible to find beach marks in the wires broken from the ACSR Tern (Fig. 12) and AAC Orchid conductors (aluminium 1350-H19) (Fig. 13). This difference could be justified by the fact that the conductors made of the pure aluminium (1350 H19) present a small zone of crack initiation as compared to the one conductor made by the aluminium alloy (6201-T81). In the crack initiation zone, striation and micro cracks were observed for samples from ACSR Tern (Fig. 12) and AAC Orchid conductor (Fig. 13), previous researchers reported the same fatigue marks on the broken wires [2].

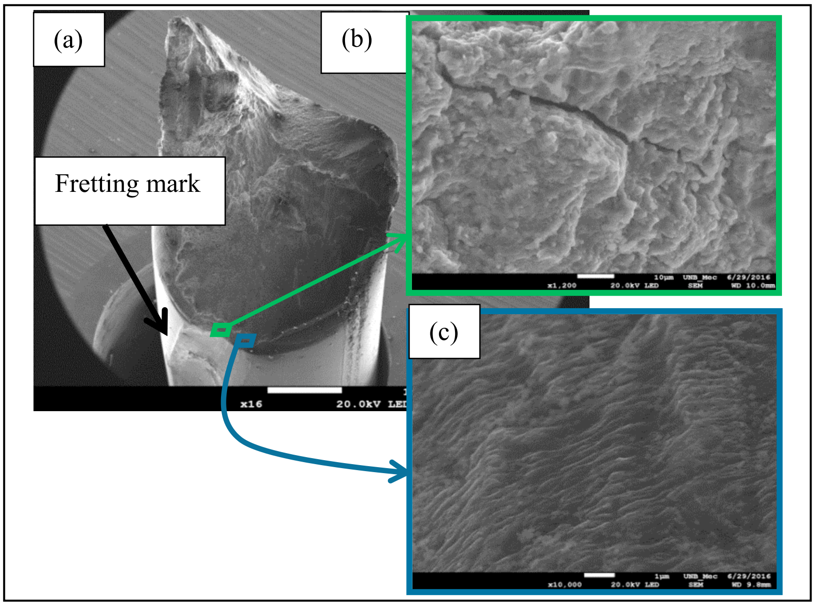

Fig. 12. Fracture surface of an ACSR Tern conductor showing (a) the fretting mark, (b) the micro crack and (c) the striation.

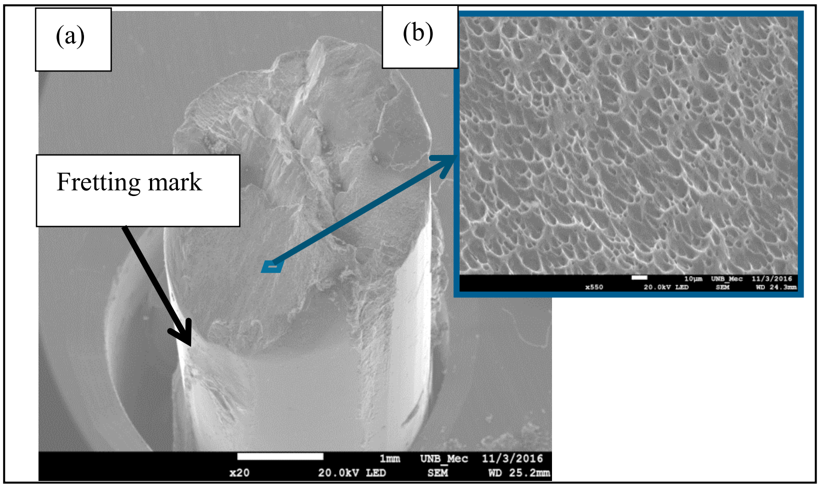

Fig. 13. Fracture surface of an AAC Orchid conductor showing the fretting mark (a) and (b) the dimples.

5. Conclusions

Based on the results and discussion presented in this study, the following conclusions can be drawn:

- For the same value of *H/w* parameter, the life ratio is four and two, respectively, for ACSR Tern and AAC Orchid compared to the AAAC 900 MCM conductor.
- For the same fatigue life, the ACSR Tern and the AAC Orchid can hold a stress amplitude 35% and 17% higher than the AAAC 900 MCM conductor, respectively.
- Conductor strands always break within the suspension clamps where visual inspection is not possible.
- Cracks always initiated in the fretted regions and propagated through the conductor strand.

- To optimize the design of transmission power lines, one should establish a different limit value of *H/w* for each family of conductors.
- Numerical analysis, as well as the wind load data are needed for the development of more refined fatigue design procedures for overhead conductors.

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