HOW WELL DOES THE POFFENBERGER-SWART FORMULA APPLY TO HOMOGENEOUS COMPACT OVERHEAD LINE CONDUCTORS?

Experimental Analysis on an AERO-Z® 455-2z Conductor

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Abstract

This paper is an outcome of an experimental study on the bending strain vs. bending amplitude analysis of a homogeneous, compact overhead line conductor (Aero-Z® 455-2z), that was carried out at the Vibration Research &Testing Centre (VRTC) of the University of KwaZulu-Natal. The main task has been to determine the relationship between bending strain (stress) and bending amplitude of this conductor and to examine whether this relationship can be adequately expressed by the so-called Poffenberger-Swart formula, often used for standard conductors. For this reason four strain gauges have been applied on the conductor taking into account not only its tension but also its compression stress side and this tensioned at 15, 20 and 25% UTS (Ultimate Tensile Strength).

Keywords:

Homogenous compact conductor, bending amplitude, bending stiffness, vibration testing, stick-slip behaviour, strain gauge measurements

1. Introduction

Cyclic bending strain fatigue is one of the commonest causes of component failure in overhead transmission lines subjected to wind induced vibration. With variations in the conductor smoothness, wind velocity or when combined with the presence of ice on the conductor surface, the vibratory motion may take form of :(i) Aeolian vibration, (ii) conductor galloping , (iii) or wake-induced oscillations [1]. Although new conductor designs have been proposed in order to reduce the problems caused by vibration stress but cyclic bending strain fatigue is still one of the main concerns in overhead transmission lines in which damage often happens at the end fittings (clamps) [1-3] , especially when conductors are subjected to Aeolian vibration.

As mentioned, new approaches on conductor design i.e. material and shape, have been proposed in order to improve transmission efficiency, these are the so-called non-conventional conductors, among which are the homogenous compact conductors, such as Aero-z. The homogeneous compact conductor has been developed in Belgium since 1970, initially designed to solve the issues related to long spans across rivers. It's been noticed some improvements on mechanical and electrical characteristics: notably higher ampacity and lower drag vis-à-vis compared to the so-called conventional (round–strand) conductors [4]. On the other hand work present by Havard [6], stated that stresses developed in this kind of conductor may be higher than the ones verified in traditional conductors due to the significant contact between wires (contact stress). Many

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countries over the world, particularly in Europe and North America have chosen to carry electrical power using homogeneous compact conductors in their new electrical transmission line projects. In Africa, homogenous compact conductors are not yet disseminated. An attempt of exploring their adequation to African transmission line projects is being done in the Niamey (Niger)-Kebby (Nigeria) transmission line with about 132 kilometres.

Therefore quantifying the amount of mechanical damage caused by fretting fatigue on these conductors due to the exposition to the crude effect of Aeolian vibration becomes necessary for safe design and maintenance purposes. That empathises the importance of obtain a simple and reliable method (model) to evaluate mechanical strains (stresses) as an important fatigue criteria and furthermore life expectancy indicator.

The most disseminate approach to evaluate contact stresses, is the practical analytical method, the so-called Poffenberger-Swart formula (P-S), developed for round wire conductors. This method is widely recommended by the Institute of Electrical and Electronic Engineers (IEEE) [8], and adopted by the International Council on the Large Electric Systems (CIGRE) [3] and by the Electrical Power Research Institute (EPRI) [1]. The current work is an experimental analytical investigation on the bare compact conductor AAAC/ Aero-Z 455-A3F-261[2] steel, which presents complex shape for the calculation of minimum bending stiffness EI_{min} important parameter in the PS formula. The aims of this research are: i) To evaluate the correlation between the predicted and the measured mechanical tensions at cable-clamp region, by using the P-S formula at different ranges of tension, i.e. 15, 20 and 25% Ultimate Tension Stress (UTS), and ii) Analyse the obtained data to establish a comparison to conventional equivalent conductor as well as quantify the effect of different UTS levels on the mechanical static tension. The main characteristics are summarised in the table.1 and illustrated by the figure.1below

Table.1 characteristic of Aero-z 455-A3F-261

Overall Diameter [mm]	26.1
Number of round wires - Round: Steel/Aluminium - Z-Shaped	1+6/12 18+24
Diameter round wires [mm]	2.9
Height of Z-Shaped wires [mm]	2.9
Linear Mass [kg/m]	1.308
Rated Strength [kN]	150.1

Figure.1 Photo of Aero-z 455-A3F-261

2. Theory

2.1 Poffenberger-Swart Formula applied to Aero-z conductor

For almost half a century, Poffenberger and Swart [8] performed for the first time the analytical

[2]The notation Aero-Z 455-A3F-261 means: conductor made of A3F Z-shaped wires Aluminium alloy, its area is 455.sq.mm and the outer diameter is 26.1 mm (261× 0.1).

solution for the so-called conventional conductors. In this study, it was found how to quantify the stress at the fittings. However, it is important to affirm that Tebo [12] had initiated this work earlier. Therefore, it was found by Poffenberger and Swart that in the above method, the relationship between differential displacement, this measures at 89 mm (peak-to-peak) to the last point of contact (LPC) and conductor bending strain could provide a realistic measurement of the bending σ_a stress in the conductor tested, if the conductor tension and flexural rigidity EI_{min} were considered. The expression of the PS formula can be written as

$$\sigma_a = K_{ps} Y_b \tag{1}$$

Where K_{ps} is the P-S factor that depends on the characteristics of the conductor, conductor tension and the distance of the displacement measured at 89 mm to the LPC of the supporting clamp edge? The PS factor can be written as

$$K_{ps} = \frac{E_a d p^2}{4(e^{-xp} - 1 + px)} \tag{2}$$

In The Aero-z conductor, the diameter d in the P-S formula (used for round conductor) can be changed by the height h of the Z-shaped on the outer layer. Where Ea is the Young modulus of the aluminium (68.9 MPa), h is the thickness of the Z-shaped wire of the outer layer conductor, x is the IEEE recommended distance [9] equal to 89mm and $p = \sqrt{(H/EI_{min})}$, H is the static tension and EI_{min} is the flexural rigidity the so-called Bending Stiffness

2.2 Bending Stiffness of bare Compact AERO-Z conductor

Observation has shown that the z-shaped wires of the outer layer of the Aero-z, seem to act during the bending motions as being solidly connected to each other (a pipe) because of the geometrical configuration of these Z-shaped wires. Deeper analysis shows that each single wire is bending around its own neutral axis and not around the neutral axis of the conductor. This allows the PS formula on the Aero-z conductor to be applied. The evaluation of the minimum bending stiffness is mainly based on the moment of inertia of each wire. The flexural moment for the aero-z which is composed of cylindrical steel and, by round and Z-shaped Aluminium wires can be given by:

$$EI_{min} = n_s E_s I_{s,R} + E_a [n_{a,R} I_{a,R} + \sum_{i=1}^{n_{a,zi}} (I_{a,z_{i-j}})] \tag{3}$$

Where n_s the number of steel is wire $n_{a,R}$ and $n_{a,Zi}$ are respectively the number of aluminium wires in round denote by $I_{a,z_{i-j}}, i = 1,2 \ or \ 3 \ and \ j = 1,2,3 \dots n$ and Z-shaped. E_s and E_a are the respective Young modulus of steel and Aluminium, $I_{s,R}$ and $I_{a,R}$ are the area moment of inertia of the steel and aluminium round wires respectively ($I = d^4/64$), i and j represent the th number of layer in the strand conductor and the number of wires in different Z-shaped layers respectively. As a standard for overhead conductor, the Aero-z 455-2z is helical lay, concentric-lay and reverse-lay[13] for realizing fully the flexibility offered by multiple strand construction[3], and to improve the conductor's structural ability by defining the space of each layer and in addition improves the electrical characteristics (self-inductance and ac resistance) of the

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[3] Without it the shape of the conductor would distort badly when it is bending

conductor. Another parameter to consider in this case is the presence of grease found in between the layers of the conductor which is used in order to prevent corrosion of the steel wires (neutral to aluminium and zinc). The advantages of the grease are to improve the flexibility of the conductor by facilitating the slippage between layers (Al-Steel and Al-Al), and to improve the performance under the effects of Aeolian vibrations. However, the slippage between layers under static tension promotes dislocations of wires due to the stiffness variation. It is thus difficult to quantify the impact of the grease in the stiffness calculation and can be assumed there is dry sliding instead of an empirical factor induced by the grease. It was postulated by Scanlan and Swart [1], and later demonstrated by Papailiou [10] that the stiffness EI is between two values: EI_{min} and EI_{max} [4] and as well this is close to the EI_{min} . The geometry of the z-shaped wire does not allow the evaluation of its moment of inertia by simple calculation. This scheme could be simplified with the utilisation of package such as Abaqus/CAE® and SimXpert which can generate code meshed wires and include the problematic surfaces i.e. Surface friction (contact stress) and moment of inertia. By calculation, the moment of inertia I_{1-j} and I_{2-j} , measured in the X-Y direction relative to the centroid are different from each wire on the same layer and are in between 4.01 and 11.03 mm^4 for the outer layer, and for the second z-shaped layer, 3.24 and 11.48 mm^4 according to the z-shaped wire localisation with respect to its centroid and fixed axis. The stiffness EImin of the Aero-z 455-2z (30.25 N.m^2) is greater to its equivalent ACSR conductor especially Tern ACSR (21.60N.m^2).

Table.2 moment of inertia in the different wires

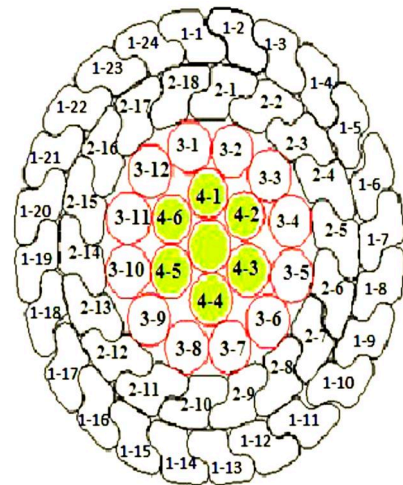| layer	Wire number layer/wire	Area [mm^2]	Izi-j [mm^4]
z1-j	1-24	8	181.94
z2-j	2-18	8.19	141.17
Round- Al	3-12	6.61	41.64
Round-St	4-7	6.61	24.29
total	61	465.01	
EImin[N.m2]			30.25

Figure 2. Aero-z 455-2z: cross section

3. Experimental procedures

The VRTC's Bench consist of 84.5 m span length of conductor, supported by rigid clamps which are fixed on two concrete blocks adequately designed to absorb the vibration during the test (figure5). The electrodynamic shaker was placed at 1.2m away from the tension end concrete block

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[4] EI_{min} and EI_{max} are assumed as the stiffness when the cable acts as a chain and rigid bar respectively. The stiffness model presented by Papailiou [10] takes account the interlayer friction force and interlayer slipping in the conductor during the bending process.
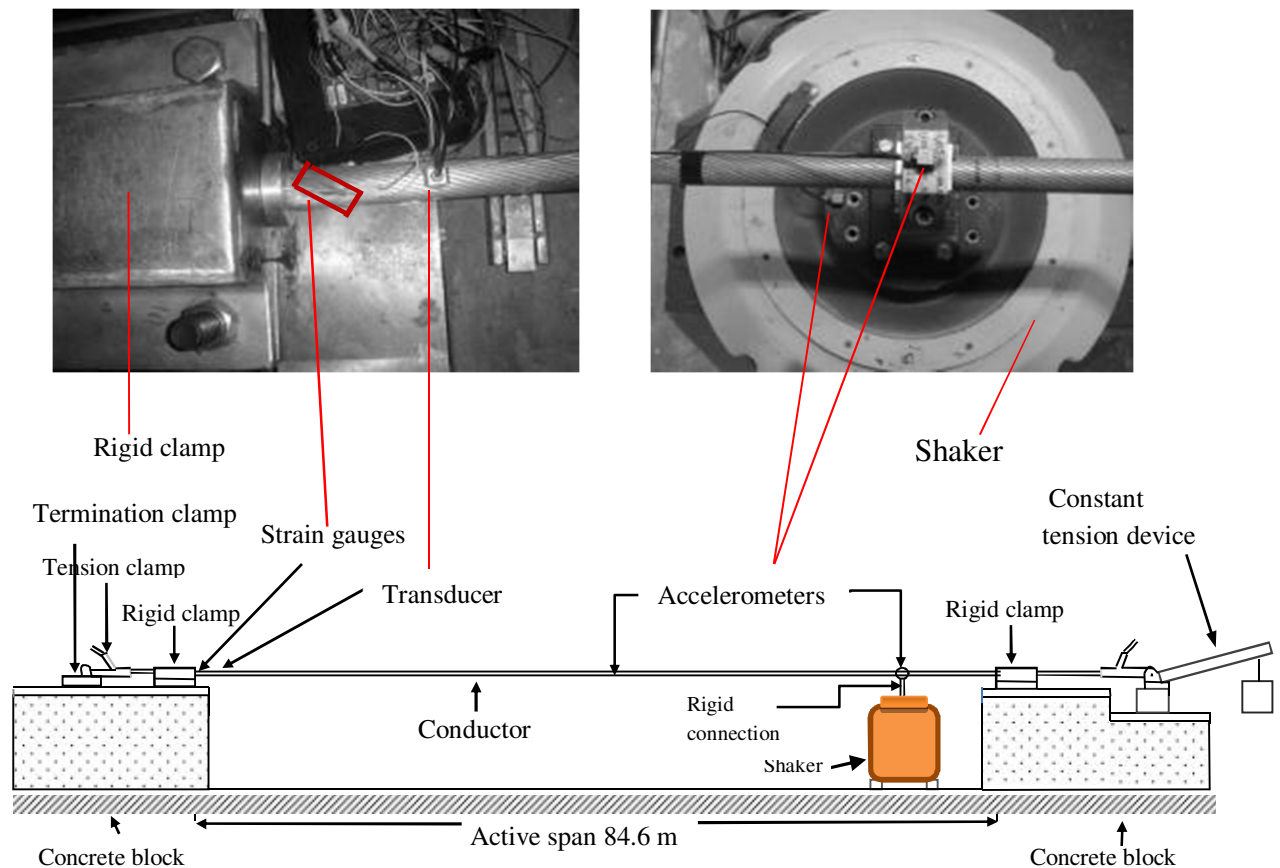
Figure 5.Test arrangement of conductor at VRTC

The rigid clamps are tightened with four bolts at a torque of ± 52 Nm and that rigidly fixes the conductor by compression of the keeper on the base of the rigid clamp. The ranges of amplitude levels used were between 0.2 and 1.2mm according to CIGRE safe design recommendation [3] which underlined the importance of the stress characterisation imposed and measured at 89 mm to the mouth of the clamp placed at the termination end by attaching an accelerometer & reading the amplitude as recommend by the IEEE standards [9]. The conductor was tensioned at three static loadings 15, 20 and 25% UTS (Ultimate Tensile Strength) and for each tension, natural frequencies (f) were determined by using the sweep method i.e. the suitable frequencies are those close to the resonance frequencies and in the range of 7 and 25 Hz (The range of Aeolian vibration is between 3 and 150 Hz).The lower frequencies of 3 and ±5 Hz are not used to avoid interference from the shakers own resonance because this may lead to excessive heating of the shaker drive system that short circuits between the electromagnet windings, and eventually leads to damage of the shaker. Six strain gauges with 120 Ω ± 0.75% and with Gauge factor K: 2.06±1%, were glued on at almost 1.5 mm from the mouth clamp (4 vertical and 2 horizontal axes). The four strain gauges were put in the vertical axis: two on top considered as the traction side when the conductor bend downward (conventional) and the two other on the compression side at the bottom of the conductor. The strains picked on the six wires were expressed in stress using the Hooke's law applied to the outer layer. This is made up of aluminium alloy wires and is given by the multiplication of measured strain by the young modulus (Ea. Ɛa).The graphs of strain vs. tension are shown below

4. Results and Discussions
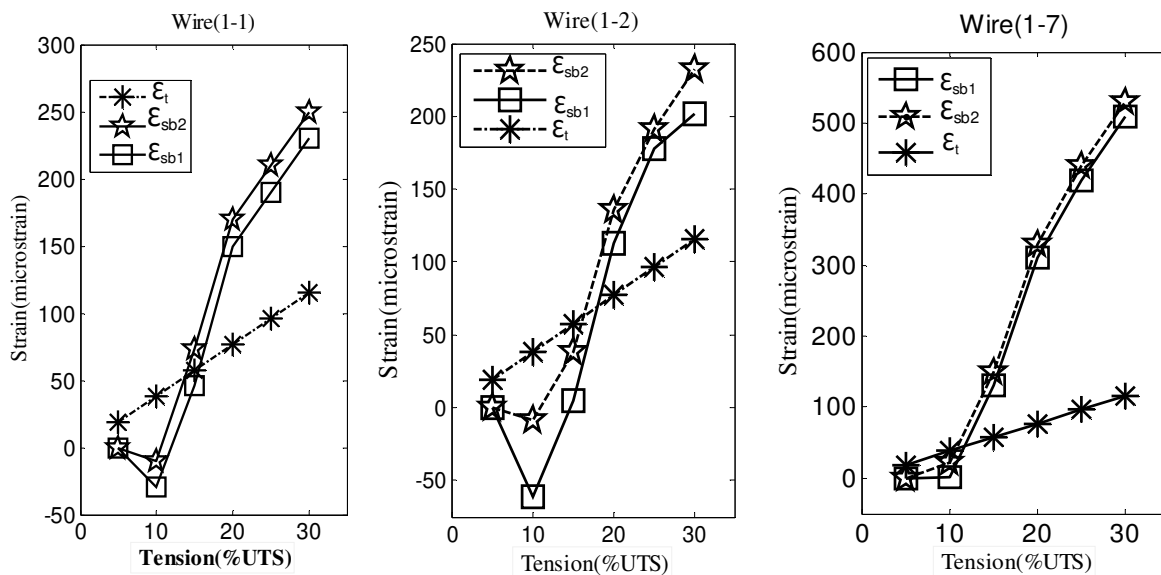
4.1 Static Calculations and Measurements

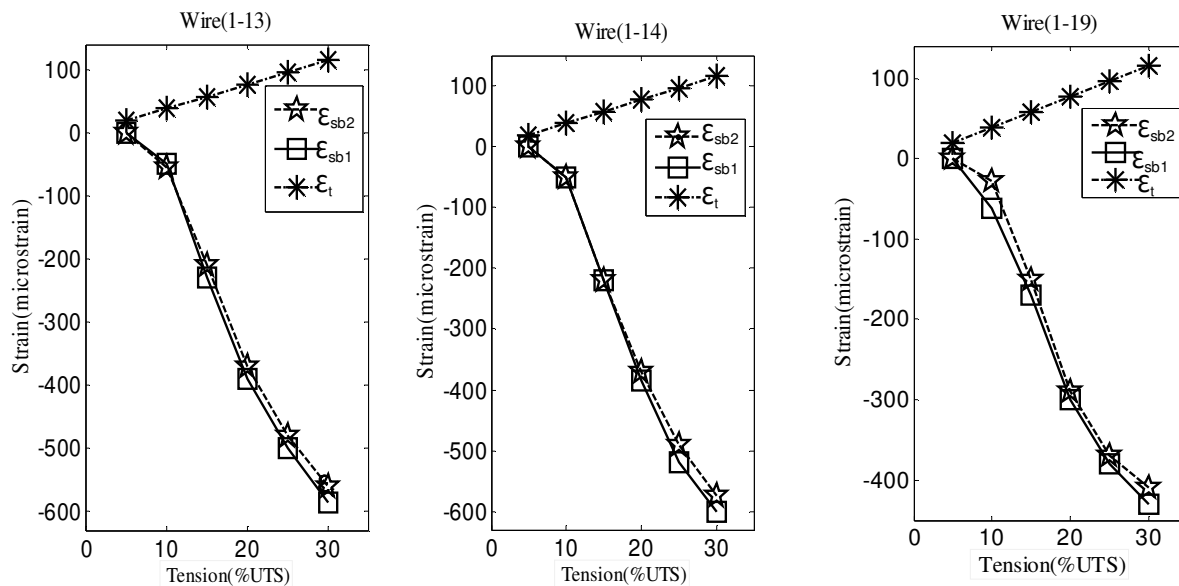Figure 6. Static bending strain in the traction zone(conventional considered positive)

Figure 7. Static Bending strains in compression Zone(conventional considered negative).

It is important to know the impact of the Every Day Stress (EDS) applied to the conductors dynamic stress (PS), since most of the overhead transmission line companies over the world impose tension around 20% EDS which gives the conductor a longer life which is an acceptable service tension of the Aero-z 455-2z. The strain gauges were instrumented on the conductor at 18% UTS (27.02 kN) with increments of 5% UTS (7.51 kN) till the highest achievable tension of 30%UTS (49.525 kN) in the lab without breakage to the strain gauges. When the conductor was at 5% UTS, the strain gauges were calibrated (zeroed). The static measurements were also performed in order to check if there is an eventual additional stresses impart on the conductor when the clamp was tightening (to investigate what the impact is due to the clamping pressure),

It was observed that when the tension was brought from the initial tension 5 to 30% UTS the strain increased at the uppermost wire (1-1) 250 microstrains (17.5MPa) and 230 microstrains (17.1MPa) in the lateral left wire (1-19) as illustrated by the figure 6. The first measurements were performed with clamp tightened (CT) and the second measurement with clamp loosened (CL), respectively illustrated by ε_{sb1} andε_{sb2} .For the distribution of strains collected in the so-called traction zone (TZ), it was also found that the looseness of the outer layer affected the elongation mostly on the uppermost wires and gives an additional stress of 1.4 MPa and the value of the strain on the wire (1-9) were the highest obtained in the left lateral side (clockwise), given by those variations of the tensions was 530 (37.1MPa) and 510 microstrains (35.7 MPa) respectively CT and CL (figure6). The strain variations with the tension in the compression zone (CZ) are higher than those measured in TZ due by stress combination i.e. the lowermost wire (1-13) 600 microstrains (42MPa) and in addition the difference between the variation of strains for CL and CT was less than 5% which is considered negligible. Tables 3 and 4 below give the different values obtain in the CL and CT. ε_t is the approximate longitudinal static strain due by the conductor axial tension which results from stringing the conductor established by Ramey and Townsend[15] and expressed as:

$$\varepsilon_t = \frac{T}{(3A_s + A_a)E_a} \tag{4}$$

Where T is the tension (N), A_s and A_a are values of the total area of the steel and Aluminium respectively, which is indicated in the table 2 above.

Table 3. The static bending strain from 5 to 30% in TZ and CZ

Tension		wire(1-1)		wire(1-2)		wire(1-7)	
UTS (%)	kN	CT	CL	CT	CL	CT	CL
5	7.51	zero-SG	Zero-SG	Zero-SG	zero-SG	Zero-SG	Zero-SG
10	15.02	-10.4	-29.2	-8.5	-61.1	21.7	1.4
15	22.52	73.4	45.8	38.3	5.2	150	130
20	30.02	170	150	136	113	330	310
25	37.53	210	190	191	178	440	420
30	45.03	250	230	232	202	530	510

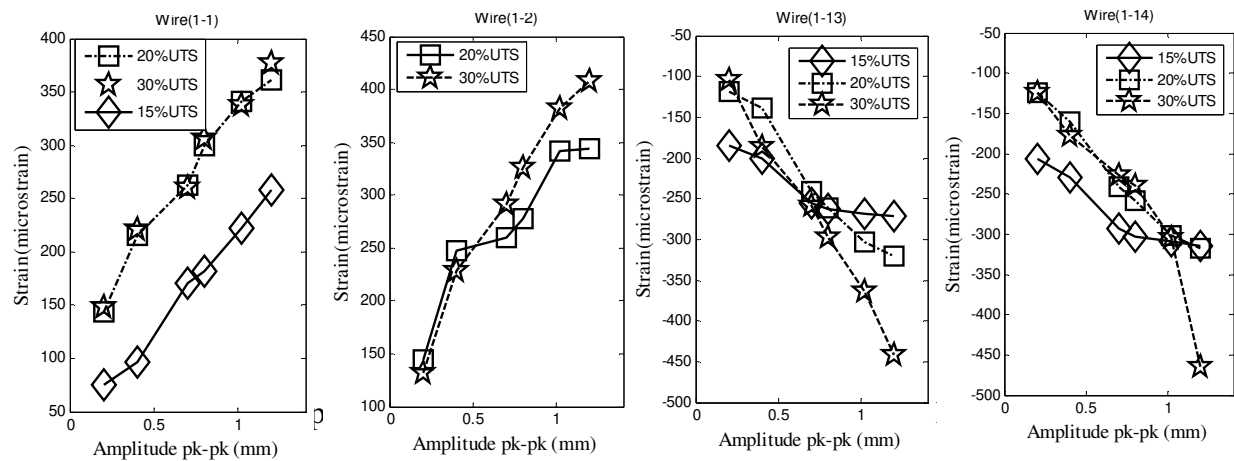| Tension		wire(1-13)		wire(1-14)		wire(1-18)	
UTS (%)	kN	CT	CL	CT	CL	CT	CL
5	7.51	Zero-SG	Zero-SG	Zero-SG	Zero-SG	Zero-SG	Zero-SG
10	15.02	-55	-50	-51.4	-51.5	-28.4	-62.4
15	22.52	-210	-230	-220	-220	-150	-170
20	30.02	-370	-390	-370	-385	-290	-300
25	37.53	-480	-500	-490	-520	-370	-380
30	45.03	-560	-585	-575	-600	-410	-430

4.1 Dynamic Measurements and P-S calculations

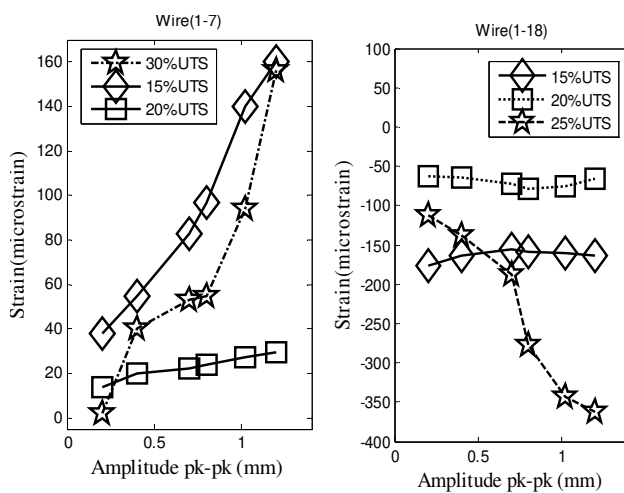
Figure 8. Dynamic Bending strain in vertical axis

Figure 9. Dynamic Bending strain in horizontal axis

Table.4 P-S Factor at EImin

| TENSION | | EImin | Kp-s |
uts%	kN	[N.m^2]	[Mpa.mm^{-1}]
15	22.515	30.25	24.52
20	30.02	30.25	26.64
25	37.525	30.25	28.45

The dynamic bending measurement has been done according to CIGRE recommendation on conductor clamp measurements [2]. The main variable is stress collected on the uppermost wire (1-1) where the strain is maximum. During the laboratory test it was difficult to impose small amplitudes .i.e. 0.2 to 0.4 mm at 15% UTS due to its high self-damping capability which resulted in beating motions of the conductor. The strain was collected by measuring the amplitude Y_b, at constant frequency and velocity of the conductor. The highest strain collected was 464 microstrains (322MPa). i) The comparison between the values of the measured dynamic strain values using the P-S formula is given below (figure 5, 6 and 7). The result obtained shown that there is a big discrepancy between the predicted (P-S formula) and the measurement. The values were about 45, 18 and 33% respectively at 15, 20 and 25 % UTS as it is shown on table 5, 6 and 7 below. Those discrepancies are the same in the compressions side, the strain gauges are supposed to be located at exactly on the LPC in order to collect the maximum strain possible (1.5mm from the LPC).ii) on several similar work on ACSR conductors, specifically on Ibis ACSR (diameter: 19.89 mm, EI$_{min}$: 11.07 N.m^2 and UTS: 70.3 kN) types which was done by Aida and co-worker [11] at the University of Brasilia (UnB) the P-S formula closely correlated with the measured stress (deviation was 2,5% between P-S formula and the actual stress) for

20%UTS i.e. at 0.8 and 1.21 mm peak to peak the stress equal to 25.76 and 37.2 MPa respectively with a variation of 12 MPa, whereas the Aero-z stresses which was recorded at the same amplitudes gave 21 and 25.27 MPa respectively with a variation of 4 MPa. the observed variation in stress between the two type of conductors can be accounted by: a) Ibis ACSR conductor has a smaller stiffness EI_{min} and wire diameter e (3.129 mm) than the Aero-z; b) it is observed that Aero-z conductors have less stress on the outer layer wires than the Ibis ACSR conductors which could be caused by the high friction that was noticed during bending between Aero-z wires due to the large contact surface area.

Table 5. P-S and measured stress 15% UTS

Amp	measured		PS	Δ
mm	strain	Mpa	Mpa	%
0.2	75	5.25	5.19	1.2
0.4	97	6.79	10.38	52.9
0.7	171	11.97	18.16	51.7
0.8	182	12.74	20.76	62.9
1.02	222	15.54	26.47	70.3
1.21	258	18.06	31.40	73.9
			Average	45.1

Table 6. P-S and measured stress 20% UTS

Amp	Measured		PS	Δ
mm	strain	Mpa	Mpa	%
0.2	144	10.08	5.99	40.6
0.4	216	15.12	12.0	20.7
0.7	263	18.41	21.0	12.2
0.8	300	21	24.0	12.4
1.02	341	23.87	30.6	21.9
1.21	361	25.27	36.3	30.3
			Average	18.3

Table 7. PS and measured Stress 25%UTS

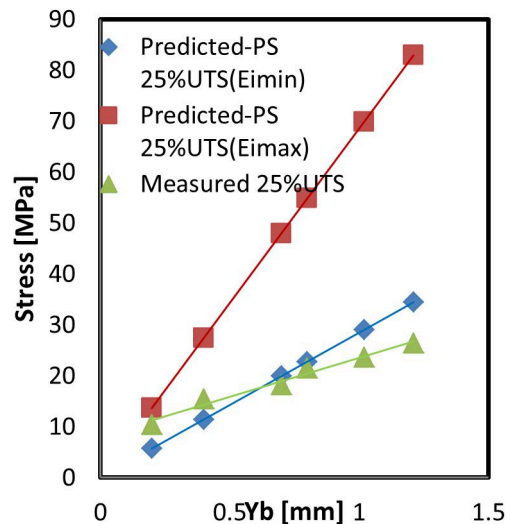| Amp	measured		PS	Δ
mm	strain	Mpa	Mpa	%
0.2	148	10.36	6.7	35.3
0.4	221	15.47	13.40	13.4
0.7	260	18.2	23.45	28.8
0.8	306	21.42	26.79	25.10
1.02	338	23.66	34.17	44.4
1.21	377	26.39	40.20	52.3
			Average	33.2

Figure10. Measured and P-S stress at 20%UTS

5. Conclusion.

The measurements have shown that the Poffenberger and Swart formula(P-S) is generally suitable also for compact conductors such as the aero-z, with the exception of low bending amplitudes, where gross sliding of the outer wires has not started(because of them being interlocked to each other). In this case measured stresses are up to 100% higher than the predicted stresses by PS with EImin and lie close to the predicted stress with PS with EImax.

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