

Improved conductor endurance limit by using a clamp with conical elastomers

J. PARADIS, P. VAN DYKE
Institut de recherche d'Hydro-Québec
Canada

SUMMARY

It is known that conductors subjected to aeolian vibrations tend to suffer damage close to where their movement is constrained, such as where they exit suspension clamps. Alternate bending causes strand breakage due to fretting fatigue in the absence of sufficient damping. For this reason, some years ago Hydro-Québec and Helix collaborated to develop a new type of suspension clamp. Equipped with tapered elastomer inserts at each end, they gradually reduce holding rigidity at the exit of the clamp and thereby reduce vibration-induced conductor bending severity.

To quantify the improvement in fatigue service life of a conductor in this new semi-rigid suspension clamp over a standard metal-to-metal clamp, experimental conductor fatigue tests under alternate bending were carried out at Hydro-Québec's research institute (IREQ) with the Crow conductor (ACSR 54/7). The conductor was installed on a 7.8-metre laboratory span and tensioned using weights on the end of a lever. It was vertically excited using an electrodynamic shaker to obtain the sixth mode of vibration of the span.

These tests were used to determine the S-N type curve, which is the vibration amplitude multiplied by the resonance frequency ($f_{Y_{max}}$) as a function of the number of cycles to rupture. The results were compared with the results of previous IREQ experiments on the metal-to-metal clamp, the results from the GREMCA [3] research group on the same conductor and clamp, and the results available in [4] for ACSR conductors with three layers of aluminum in a metal-to-metal clamp. It was also possible to calculate a safe fatigue endurance limit for infinite service life and compare it to the value in the literature for the metal-to-metal clamp [6].

The results show that the semi-rigid clamp significantly improves the conductor endurance limit. Theoretical alternating stress under which the conductor can vibrate for 500 million cycles without failure was increased by 68%. The fatigue endurance limit was increased by 71%. Statistical analysis using Student's t-distribution with a 95% confidence interval confirms that the increase in the alternating stress over 500 cycles is significant. The results were expressed regarding the amplitude at 89 mm from the final point of contact in the clamp and the $f_{Y_{max}}$ parameter to establish the reference level to use in damping system selection.

KEYWORDS

Endurance limit, fatigue, suspension clamp, elastomer, conductor

INTRODUCTION

The phenomenon of fretting fatigue caused by alternating bending of conductors is now well known [EPRI, 1979] [EPRI, 2009]. This type of fatigue of the conductor is primarily caused by aeolian vibrations but can also occur when in the presence of galloping or subspan oscillations. Aeolian vibrations can be controlled with the appropriate damping system and subspan oscillations with a system of adequate spacers properly positioned. Conductor galloping is more difficult to control, but it has been shown that in addition to preventing conductor clashing, interphase spacers reduce galloping amplitude. Fatigue can nonetheless occur and affect the sustainability of transmission lines [1].

To reduce the severity of conductor bending at the exit of suspension clamps, a new clamp was designed at Hydro-Québec's research institute (IREQ) in the 2000s. It has the following characteristics:

- Conserving a metal section in the middle of the suspension clamp for good conductor/clamp contact to meet the criteria for conductor slippage in the clamp
- Adding tapered elastomer insert at each end of the clamp (shown in blue in Figure 1) to gradually reduce the holding rigidity where the conductor exits the clamp and thereby significantly reduce bending severity at this location for the same level of antinode vibration amplitude and frequency.

In 2010, the design of the semi-rigid suspension clamp was completed jointly by Hydro-Québec and Helix Uniforme Ltd. (Figure 1). Hydro-Québec worked primarily on its geometry, while Helix created the prototypes and provided its industrial manufacturing expertise. The metal shell was designed to simplify the work of line workers, with an emphasis on live-line work.

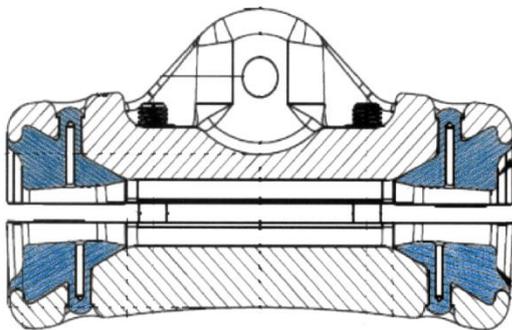


Figure 1: Cross section of the Helix 95-325-405 semi-rigid clamp being tested (elastomer inserts shown in blue)

This clamp is now systematically installed on all new Hydro-Québec's transmission lines or when replacing old ones for maintenance purposes. While it is known that the elastomer inserts reduce the severity of conductor bending at the exit of the suspension clamp, its effectiveness at extending conductor service life had not yet been quantified. The elastomer element might also introduce additional damping into the system, which would contribute to reducing the severity of vibrations. However, this study did not consider this effect.

EXPERIMENTAL SETUP

Hydro-Québec's research institute (IREQ) designed a testbed (Figure 2) of three laboratory spans following the guidelines of the IEC standard [2]. Three other spans were added later. For the present tests, the spans were set to a length of 7.83 m. An electromagnetic shaker was used to vertically excite every test span. Tension was applied and kept constant with weights at the end of a lever arm. Vibration amplitude was controlled with a displacement sensor located at a vibration antinode. The

conductor was thus excited at a set frequency and amplitude until three of its strands broke. After 500 million vibration cycles without breakage, a conductor was considered to have a virtually infinite service life. Because of the scatter in fatigue data, it is advisable to conduct three tests for every stress amplitude level [2,4,5]

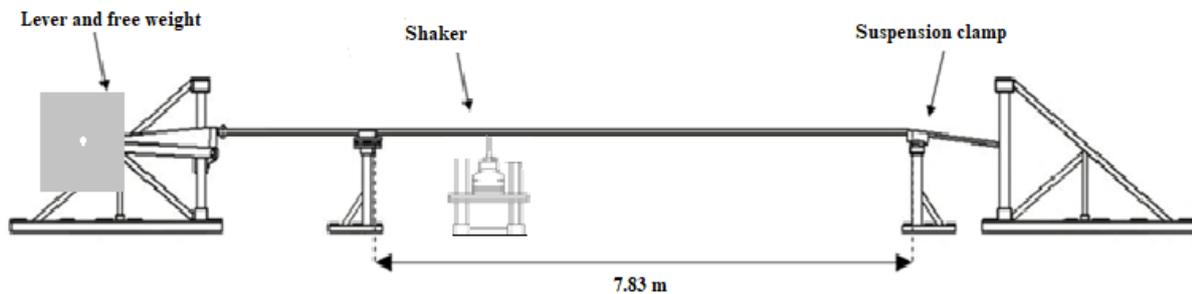


Figure 2. Diagram of the laboratory spans

Testing was performed on a Crow ACSR 54/7 conductor at a tension of 29 kN (25% RTS). Previous tests done with the Slacan 62065 metal-to-metal clamps on the same test setup were used for comparison (Figure 3). These tests were also compared with tests performed by GREMCA¹ on the same conductor with the same tension and suspension clamp to ensure that our results are comparable [3].

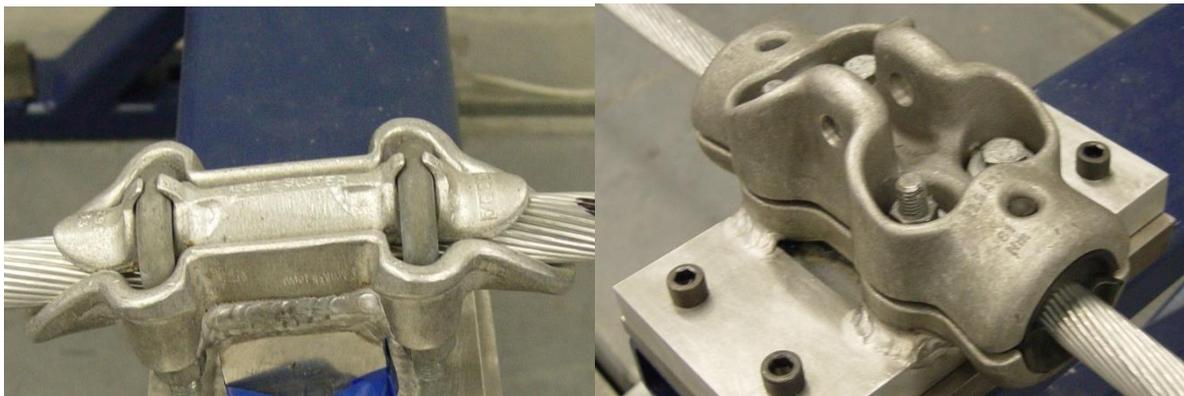


Figure 3. Suspension clamps (metal-to-metal Slacan 62065 on the left and semi-rigid Helix 95-325-405 on the right)

RESULTS

Figure 4 presents a comparison of the number of cycles prior to rupture for IREQ's testing of the metal-to-metal clamp (shown in blue) and the semi-rigid clamp (shown in red). For comparison, the series of white points represents the tests performed at the GREMCA laboratory on the same metal-to-metal clamp [3]. Points with arrows represent tests without breakage. It should be noted that the values expressed in stress represent a virtual stress calculated from the fY_{\max}^2 parameter. It does not correspond to the local stress causing rupture that would have been measured had a strain gauge been positioned at that location, as described in [4].

¹ GREMCA: Groupe de Recherche en Mécanique des Conducteurs Aériens

² fY_{\max} : Standard parameter that represents the product of frequency and amplitude at the antinode (peak).

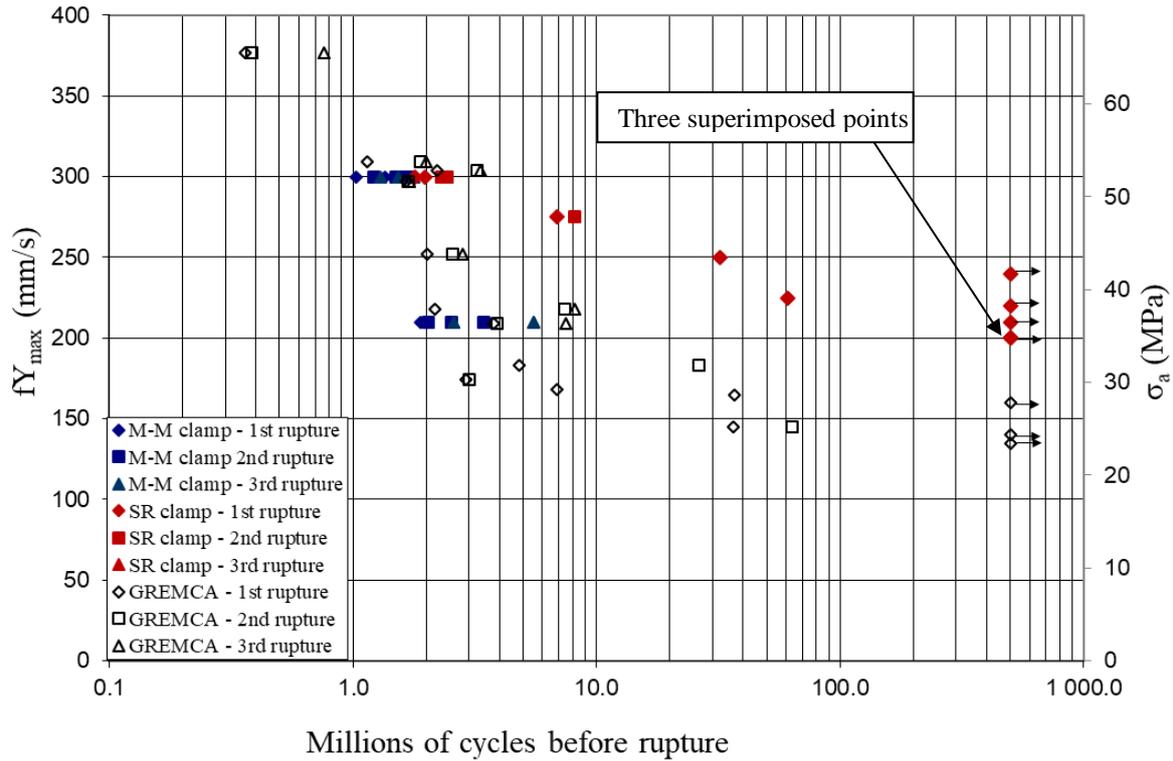


Figure 4. Comparison of the number of cycles prior to rupture for the two clamps being tested

FATIGUE ENDURANCE LIMIT

The fatigue endurance limit can be estimated in several ways. The most common method is the highest stress or amplitude without rupture at 500 million cycles. The results above show that the limit is 140 mm/s (24 MPa) for the metal-to-metal clamp (from the GREMCA data) and 220 mm/s (38 MPa) for the semi-rigid clamp. This represents an improvement of 58% in the fatigue endurance limit when using the semi-rigid clamp.

Hardy and Leblond [6] presented another method to calculate a “safe limit”. They first obtain the average curve by looking for the distribution’s best fit with the following equation:

$$\ln(\tilde{N}) = a + b \ln(\sigma_a - \sigma_d)$$

where σ_d is the actual fatigue endurance limit, \tilde{N} the number of cycles before the first rupture and a and b the constants to determine. However, the authors’ evaluation of this expression with several series of test data showed that the deviation from the experimental results was always smaller when $\sigma_d = 0$ since the number of cycles before rupture continues to increase as stress approaches zero. It will therefore be assumed to equal zero. Figure 6 compares the curve obtained from our testing of the semi-rigid clamp with that from GREMCA [3] testing of the metal-to-metal clamp on the same conductor. The limits of a 95% confidence interval using Student’s t -distribution are also shown. For comparison with a larger sample, the data for the semi-rigid clamp are also compared with the dataset presented by EPRI [4] that collects the experimental results of several tests of metal-to-metal clamps with various types of ACSR conductors with three layers of aluminum wires. Note that for all of these results, tests without rupture were not considered in the calculation and that the points from [4] were manually sampled from its Figure 3.2-13b.

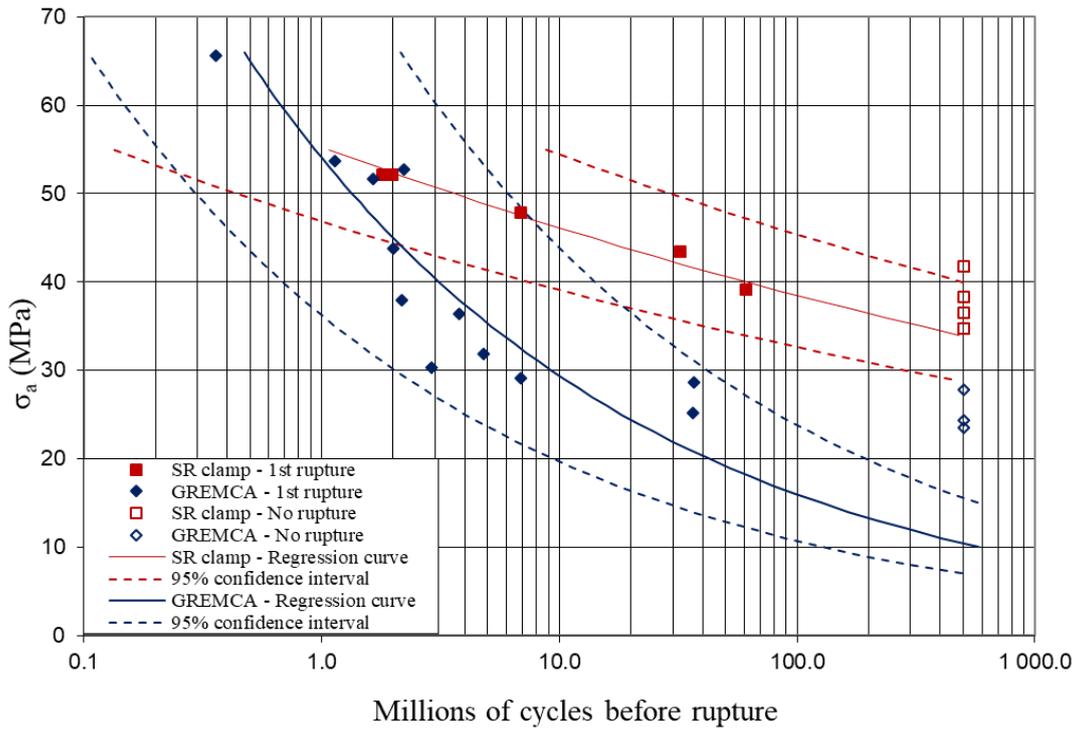


Figure 5. Comparison of the regression curves for a Crow conductor in the semi-rigid clamp and the metal-to-metal clamp from [3]

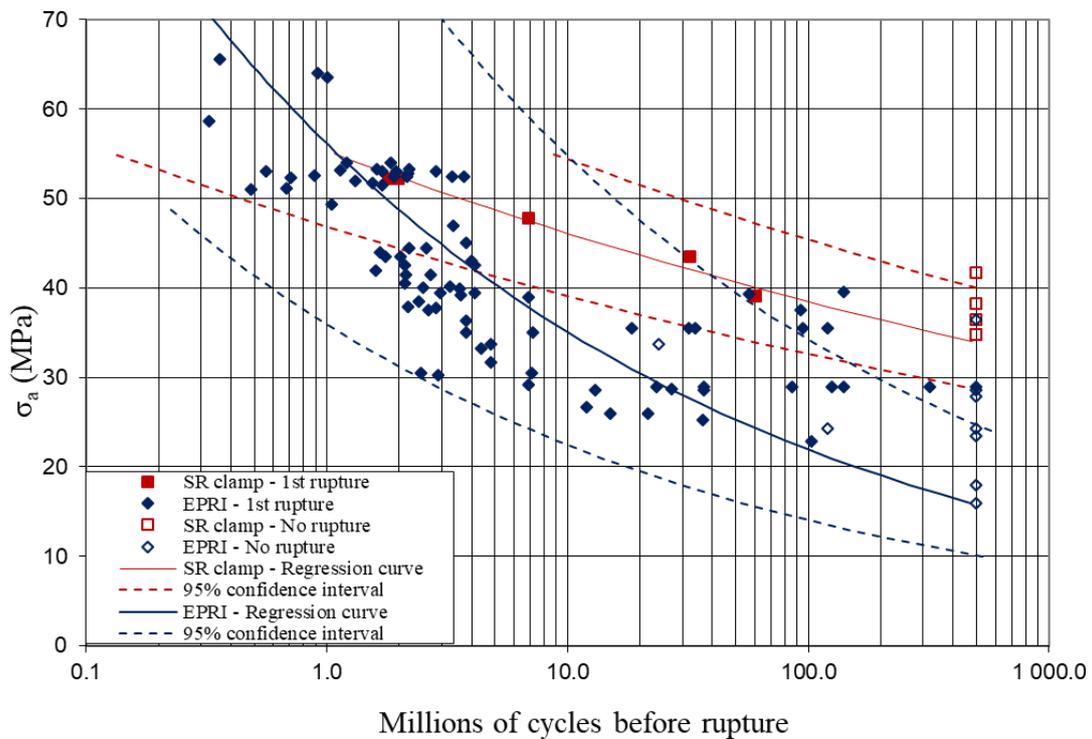


Figure 6. Comparison of the regression curves for a conductor with 3 layers of aluminum in the semi-rigid clamp and the metal-to-metal clamp from [4]

Despite the smaller number of data points for the semi-rigid clamp, the improvement in the fatigue service life can be observed, as can the increase in the stress without rupture after 500 million cycles. For comparison, Table 1 presents the relationship between the number of cycles to rupture for the two clamps at specific stress values along S-N curves. Greater improvement is evident at lower stress levels.

Table 1. Ratio of the number of cycles to rupture du number of cycles before breakage between the regression curves for different values of $\sigma_a(fY_{max})$

σ_a (MPa)	curve ratio (SR/m-m)
30	255
40	20
50	2.7

Another fatigue endurance limit σ_{al} presented in [6] is obtained by isolating it in the equation:

$$\ln(\sigma_{al}) = \frac{\ln(500 \cdot 10^6) - a + st_{0.05, n-2}}{b}$$

where s is the standard deviation and $t_{0.05, n-2}$ represents the *student* factor at 5% and for $n-2$ degrees of freedom. This limit corresponds to a 95% probability of no rupture at 500 million cycles. This gives a fatigue endurance limit of 8 MPa for the metal-to-metal clamp and 30 MPa (173 mm/s) for the semi-rigid clamp, an improvement of 275%. Another way to estimate the fatigue endurance limit would be to use the intersection of the average curve at 500 million cycles, which is 10 MPa for the metal-to-metal clamp and 34 MPa for the semi-rigid clamp, an improvement of 240%. Using the lower bound for a 95% interval, as shown in Figure 6, the limit is 7 MPa for the metal-to-metal clamp and 29 MPa for the semi-rigid clamp, an improvement of 314%.

According to Standard ASTM E739 [7] on the standard practice for representing the results of fatigue tests, the confidence interval is determined in another way with the following equation:

$$Y = \hat{A} + \hat{B}X \pm \sqrt{2F_p} \hat{\sigma} \left[\frac{1}{k} + \frac{(X - \bar{X})^2}{\sum_{i=1}^k (X_i - \bar{X})^2} \right]^{1/2}$$

where

$$\hat{B} = \frac{\sum_{i=1}^k (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^k (X_i - \bar{X})^2} \quad \text{and} \quad \hat{A} = \bar{Y} - \hat{B}\bar{X}$$

and where X represents $\log(\sigma)$, Y represents $\log(N)$, F_p is the coefficient for a 95% probability of Fisher distribution, $\hat{\sigma}$ standard deviation, k the number of tests, the symbol $(-)$ represents an average and $(\hat{ })$ an estimate. The points with the highest stress levels for the metal-to-metal clamp were not considered in order to have the same stress range for the two clamps. The result is shown in Figure 7. In this case, the 95% confidence interval lower bound is 1.3 MPa for the metal-to-metal clamp and 26 MPa for the semi-rigid clamp.

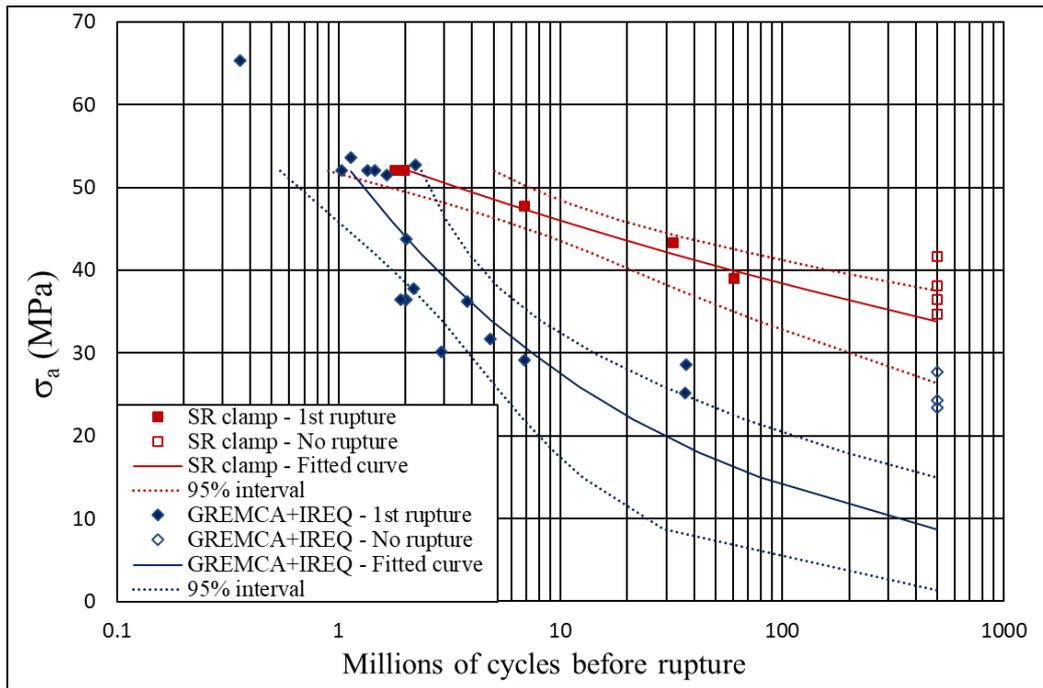


Figure 7: Comparison of normal distributions and their intervals for the semi-rigid and metal-to-metal clamps from [7]

For both Figure 6 and Figure 7, the curves were extended up to 500 million cycles to estimate the fatigue endurance limit. Note however that the ASTM standard does not recommend this practice as no test data is available for 500 million cycles and above. It would therefore be inadvisable to extrapolate the curve in that area. Limits calculated in this way should therefore be used with caution.

Table 2 summarizes the endurance limits obtained and the percentage of improvement of the semi-rigid clamp over the metal-to-metal clamp based on IREQ and GREMCA test results on the Crow conductor. It shows that these methods produce very scattered results. It is also clear that all the limits, with the exception of the highest stress level without rupture at 500 million cycles, are significantly different from the 24-MPa limit presented in [4] for ACSR conductors with three layers of aluminum in the metal-to-metal clamp.

Table 2. Comparison of fatigue endurance limits for the two clamps

		Highest 500 Mc without rupture	Fatigue endurance limit [6]	Average curve at 500 Mc	95% interval lower bound at 500 Mc	
					From [6]	From [7]
Metal-to-metal clamp	σ_a (MPa)	24	8	10	7	1.3
	fY_{max} (mm/s)	140	46	58	40	7.5
Semi-rigid clamp	σ_a (MPa)	38	30	34	29	26
	fY_{max} (mm/s)	219	173	196	167	150
		+58%	+275%	+240%	+314%	+1900%

CONCLUSION

Fatigue tests on the conductor-suspension clamp assembly were carried out to compare the performance of the semi-rigid clamp developed several years ago (Helix 95-325-405) with the Slacan 62065 metal-to-metal clamp. Testing was in compliance with the IEC standard [2] and the results were compared with GREMCA research laboratory results presented in [3] and with all results collected for ACSR conductors with three layers of aluminum presented in [4].

The fatigue endurance limit was determined using the method described in the CIGRE TB 429 [5] technical brochure, i.e. the highest stress or amplitude without rupture at 500 million cycles. This revealed an improvement of 58%.

The results showed a significant improvement in conductor fatigue service life with the semi-rigid clamp.

Other statistical analyses described in [6] were also used on the fatigue data to compare the performance of the two clamps. A fatigue endurance limit corresponding to a 95% probability of no rupture at 500 million cycles was determined. An improvement of 275% was observed. Lastly, the intersection of the average curve with the 95% confidence interval lower bound, calculated as per [6] or [7], produced an improvement of 240%, 314% and 1900%, respectively. There are wide variations in the calculated endurance limits, which are generally far from the 24 MPa endurance limit for the metal-to-metal clamp presented in [4]. It would be worthwhile to obtain data from testing above 500 million cycles to more accurately estimate this limit.

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