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EFFECTIVE LIFETIME ESTIMATE OF CRIMPED POWERLINE SPLICE CONNECTOR OPERATED AT HIGH TEMPERATURE

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ABSTRACT

This paper addresses the thermal-mechanical properties and performance characteristics of full tension splice connectors under high temperature operation, in particular those used in overhead transmission and distribution lines. Due to the increase in power demand existing overhead power transmission lines often need to operate at temperatures higher than those originally considered for their design. This has led to the accelerated aging and degradation of splice connectors. The compressive residual stresses induced by the crimping process within the splice connector provide the clamping forces to secure the conductor and therefore, the determination of the state of compressive residual stresses in splice connectors is a necessary requirement to provide an accurate estimate of their service lifetime. This paper presents a protocol for integrating analytical and experimental approaches to evaluate the integrity of a full tension single-stage splice connector assembly.

Keywords–power delivery, single stage splice connector, thermal cycling, steel-reinforced core aluminum conductor

1. INTRODUCTION

Steel-reinforced core aluminum conductors (ACSR) are currently used in overhead transmission lines; the crimped type splice connectors are widely used in the power industry, including the two-stage splice connector (TSC) and the single-stage splice connector (SSC). However, the potential of failure of SSC fittings at higher operating temperatures is considerably higher than that of TSC fitting. For a normal operating temperature, the root cause of accelerated aging that causes failures is generally attributed to poor installation in the manufacturing process. For example, full tension splice connector fittings that do not have adequate crimping pressure or when the length of conductor that is pushed into the sleeve barrel prior to crimping is too short can cause accelerated degradation and lead to failure. Introducing higher operating temperatures, whether cyclic or steady state will accentuate weaknesses in the components and lead to incremental failures. Furthermore, annealed strands with an increased creep rate will flow away from the splice connector and will no longer experience to original residual stress against the splice connector. This situation is further worsened with thermal expansion/contraction cycles when the conductor power loading varies. Moreover, for a splice connector joint, the joint resistance does not remain constant but will increase during operation time. This long-term behavior of joint resistance can be influenced by different aging mechanisms, like stress relaxation, oxide layer built-up, corrosion processes, inter-diffusion, electromigration, and fretting. [1-8] The accelerated aging associated with the connector forming mechanism can be attributed to material creep, thermal-mechanical cycle fatigue, aluminum oxide film build-up and other microstructure evolution at the interfaces within the connector system. Therefore, it is expected that significant relaxation of the residual stress will occur during service, especially at higher operation temperature. The consequence of relaxation of the initial compressive stress is the reduction of connector initial rate tensile strength, which is evaluated according to ANSI C119.4. Therefore, the magnitude of the compressive residual stress within a compressive connector can serve as a good indicator of the effective lifetime of a conductor system during service.

This research project was dedicated to analyze single-stage splice connectors because they could potentially become the weakest link in current power transmission lines. The key factors that could affect the service life of SSCs include (1) geometry constraints, (2) material aging, and (3) axial tension loading of the conductor. SSCs can be divided into two sections, namely (a) conductor section and (b) core-grip section, as illustrated in Fig. 1, where the aluminum conductor, splice sleeve, and the core-grip are made from 1350-H19, 3003-H183, and 6061-T6 aluminum alloys, respectively. To gain a better understanding of the performance of SCCs, their potential failure mechanisms and long-term reliability during thermal cycling, unique computer

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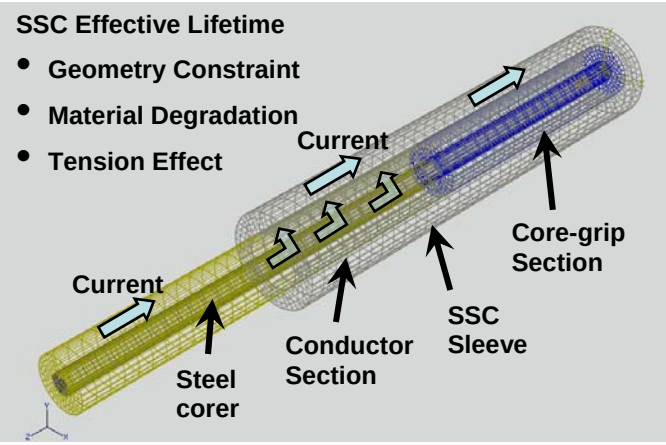

Fig. 1 Schematic diagram of a half SSC fitting.

simulations were performed. These analyzes have shown that large plastic deformations are experienced by the connector materials during the forming/crimping process, which result in large compressive residual stresses within the connector; thermal cycle simulation analyses have shown that the induced compressive residual stresses continue to relax during service, especially at high operating temperatures. Since these compressive residual stresses provide the clamping stress to confine and secure the conductor inside a splice connector, the magnitude of these residual compressive stresses could be used to predict the remaining service life of SSCs. If the compressive residual stress is not sufficiently high, the conductor system will fail during operation.

2. THE EFFECTIVE LIFETIME INVESTIGATION OF SSC CONNECTOR SYSTEM

Numerical simulations combined with experimental measurements were utilized in this investigation. To estimate the compressive residual stress field within a SSC system, finite element stress analyzes of the crimping forming process of a SSC system were carried out. To assess the fidelity of the finite element model (FEM) predictions, the magnitude of the residual stresses in a crimped SSC was determined experimentally using non-destructive neutron diffraction techniques [9]. This residual stress mapping experiment was carried out at the ORNL High Flux Isotope Reactor, Neutron Residual Stress Mapping Facility (NRSF2) [10]. The above work for the baseline SSC forming simulation and the associated residual stress investigation are detailed in reference 11. Residual strain determined by neutron diffraction revealed large compressive radial deformation at the core-grip region, but relatively small strains in the aluminum outer sleeve region. The radial compressive stress distribution is the key parameter to assess the clamping pressure strength to secure the conductor. In general, the FEM analysis results along the radial direction are in very good agreement with the neutron diffraction measurements. The bounds obtained from the neutron diffraction measurements also validate the FEM analysis results.

2.1 FINITE ELEMENT ANALYSIS OF SSC FORMING

A Drake conductor, consisting of three layers of wire bundles, two layers of aluminum wires (totals of 26 wires) and the core-steel bundle (7 wires) with the associated twisted angle for each layer of wires, an ALCOA aluminum splice sleeve with a core-grip, and a 60 tons 6012CD die set were used in the FEM to simulate the splice connector forming process and to determine the compressive residual stress fields. PATRAN mesh generator and ABAQUS Code were used in the finite element analyses. Due to a large number of contact surfaces involved during the connector crimping process, the FEM meshes were modified and optimized several times during the analyses in order to reach a better convergent solution at a reasonable time. The results of such simulation are shown in Fig. 2.

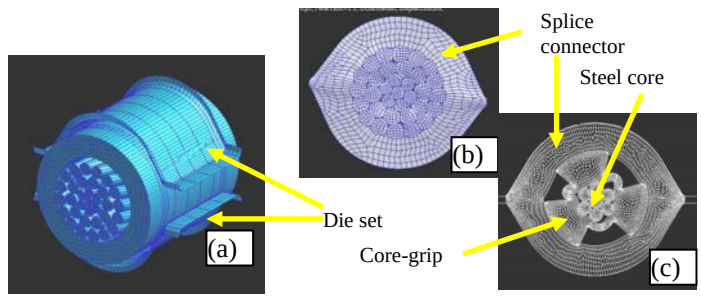

Fig. 2 SSC system FEM simulation: (a) before crimping with die set, (b) after crimping at conductor section, (c) after crimping at steel core-grip section.

- The core-grip section was analyzed using a 2-D plane stress model, where three crimped positions of the core-grip were investigated, each 15° apart. The ABAQUS code with quasi-static ramp load scheme was used for the analyses. To account for the severe distortion near the ring section of the core grip, the self-contact criterion was utilized in the analysis. The FEM forming simulation indicates that the contact areas between the core-grip and the steel core are quite limited, as shown in Fig. 3. The crimped load required to form the crimped connector fitting, with a 60-ton 6012CD die-set is estimated to be 54.6 tons, 56 tons, and 57.5 tons for the three core-grip positions.

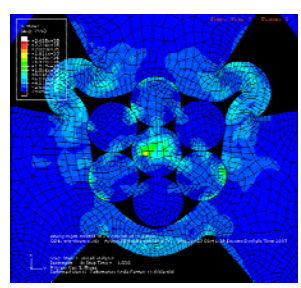

Fig. 3 The enlarged view of core-grip section.

- Due to the spiral configuration of the aluminum conductor wire bundle, a 3-D FEM analysis of the conductor section was performed. To address the large number of contact surfaces in Drake connectors the EXPLICT ABAQUS Code was used, and the dynamics analysis scheme was utilized with the "General Contact" approach. The time duration of

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dynamic loading for the 6012CD die during crimping was set to 1 sec with an unloading period of 0.1 sec. The calculated hydraulic load to form the splice connector in conductor section is about 54 tons.

- The residual stress analysis revealed that at the completion of crimping of the SSC the compressive residual stress at the crimped core-grip and conductor sections are sufficiently large to retain and confine the aluminum conductor for tensile loads as high as those used during a rated breaking strength test.

2.2. TENSILE LOAD TRANSFER IN A SSC SYSTEM

The tensile load transfer in a SSC system is illustrated in Fig. 4. In the middle section of the splice connector, where no conductor passes through, the load transfer mechanism is simply through the connector outer sleeve as shown in the top of Fig. 4. The free body diagram shown in the bottom of Fig. 4, illustrates the distribution of the frictional force induced by the compressive residual stress at the interface between the sleeve and conductor and interface between the core-grip and steel core. This friction force resistance provides constraint to confine the ACSR conductor within the connector sleeve when the conductor is subjected to tensile loads.

The shear force resistance between the SSC and the conductor has contributions from two interfaces: (1) interface between the sleeve and the outer layer of the conductor wires bundle and (2) interface between the core grip and the steel-core wires bundle as shown in Fig. 4. In order to maintain the integrity and prevent the failure of the splice connector, the summation of these friction shear forces needs to be greater than the tensile load experienced by the conductor. Due to the inherited forming mechanism of the splice connector, it is expected that such friction shear force resistance will relax progressively during service and the relaxation of the clamping residual stress could provide an indicator to predict the service life of SSCs.

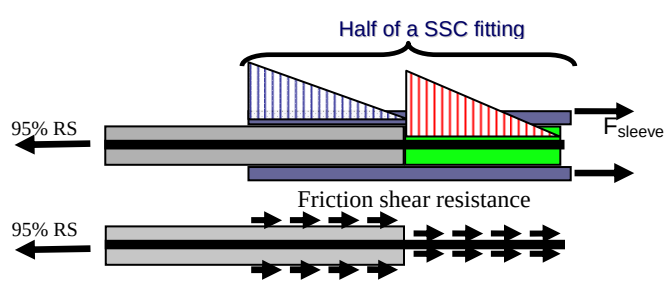

Fig. 4 Load transferring during rated breaking strength tensile test; (top) sleeve carry the full rated breaking strength at the middle section of the sleeve, the tensile stress distribution of the conductor and core steel within the SSC fitting are non-uniform as illustrated with two triangular blocks for conductor and core-grip sections, respectively; (bottom) shear force resistance at sleeve/conductor interfaces and core-grip/steel-core interface.

2.3. THERMAL MECHANICAL TESTING

A series of thermal mechanical tests were performed on test specimens of 1350-H19 aluminum conductor, 3003-H183 aluminum sleeve and the 6061-T6 core-grip materials. These tests include:

- True stress-true plastic strain curves to provide input data for FEM thermal cycling simulation of a SSC system. The tensile test data with the targeted temperature holding time, up to 10 hours was also included.
- Changes in yield and tensile strength as a function of thermal cycling were also investigated.
- It was found that the tensile strength of SSC component materials decreases with temperature. For example, at 260°C, the strength reductions are
    - 1350-H19: 77%;
    - 3003-H183: 67%
    - 6061-T6: 45%; w/ 10 hour holding: 60%.

  The data is consistent with the data listed in reference 12.
- The thermal-mechanical fatigue (TMF) testing was carried out with a total strain maintained at 0% and the cycle temperature ranges between 75°C and 175°C at 15 minutes interval. The TMF testing results indicate that the TMF induced material hardening seems to be balanced by the annealing during the thermal cycling and no obvious long term TMF damage or fracture after some 9000 TMF cycles.
- SEM postmortem examination on the fatigue tested samples of SSC component materials showed typical striation marks that are characteristic of fatigue-induced fracture, shown in Fig. 5. For 1350-H19 aluminum, the SEM image also shows large textures variation, this is due to cold drawing forming of 1350-H19 rod.

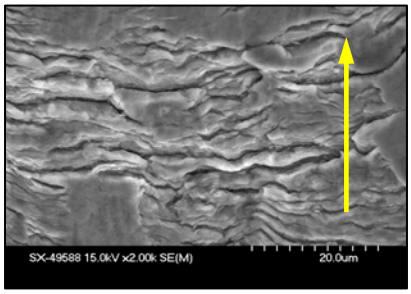

Fig. 5 1350-H19 aluminum fatigue fracture, arrow mark indicates the direction of the crack propagation.

2.4. TEMPERATURE PROFILES of A SSC SYSTEM

In collaboration with EPRI Solutions, a series of experiments were carried out to determine the temperature distribution during thermal cycling inside the connector fitting of an ACSR Drake conductor system. Temperature was cycled between ambient temperature and 150°C (6 cycles per day). The reference temperature corresponds to a location on the surface of the conductor about 5 meters away from the connector fitting. These experiments revealed that:

- The temperature of the SSC splice surface is lower than that of the aluminum wires underneath.
- The temperature of the steel core is normally higher than that of the aluminum wires, except at the core-grip region of the SSC.
- The temperatures of a SSC system increased continuously during thermal cycling; different temperature gradients were

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also observed from the embedded thermocouples (TC) in the SCC system. The majority of temperatures became greater than the 150°C reference temperature after about 50 cycles.

- The significant temperature increases are the direct result of the thermal cycle induced relaxation in compressive residual stresses in a SSC system, due to increased SSC resistivity.
- Significant tension loading drop of the tested conductor cables was also observed during the SSC thermal cycling aging. This may indicate that the slippage of conductor within SSC system occurred due to significant reduction in the compressive residual stress in SSC system.
- Water quench testing was also carried out on the SSC system in 100 thermal-cycle intervals. The occurrence of thermal spikes was observed in quench test data, but these thermal spikes were not observed in non-quench tests, as shown in Fig. 6.

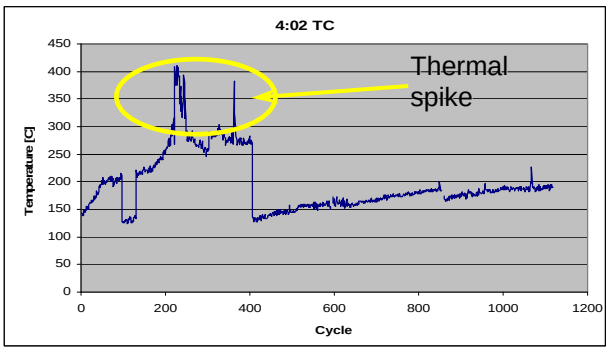

Fig. 6 Water quench was conducted in 100 thermal-cycle interval, where maximum cycle temperature history shows significant thermal spike events.

2.5 FEM THERMAL CYCLING SIMULATION

The FEM thermal cycle simulations for the SSC system were carried out with the heat-up temperature ranges from 70°C, 100°C, 125°C, 150°C, 175°C, 225°C, 250°C, 275°C, 290°C, 315°C and 350°C (at the SSC surface), and with the cool-down temperature at 20°C. The investigation of the impact of tensile loading and the water quench to the SSC integrity during the thermal cycling was also carried out. The FEM results of the middle section of the simulated SSC system was used for compressive residual stress degradation evaluation, as shown in shaded area of the crimped SSC in Fig. 7. The boundary conductions of the FEM models are that at the right end of the conductor the displacements in the axial direction are constrained but allow radial displacement, and no constraints are set for the left end portion of conductor. The measured temperature profiles of the thermal cycling experiments were used as the temperature input for the FEM thermal cycle simulations.

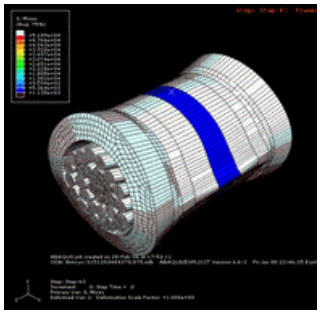

Fig. 7 FEM model for SSC thermal cycling simulation.

Simulation results show different temperature dependence for the core-grip and conductor sections. Whereas the conductor section shows significant reduction in the compressive stress when the thermal cycle temperature reaches 125°C, the core-grip section still retains a large compressive residual stress up to 200°C.

Thermal cycle simulation for conductor section

- Simulation without tensile loading show much less effect of the compressive residual stress degradation due to thermal cycling, and no significant reduction, both in compressive strength at ambient and heat-up temperature, till 250°C thermal cycling range.
- Significant relative movement of components within SSC system was observed from thermal cycle simulation with tension loading, such phenomenon was not observed for thermal cycling simulation without tension loading, as shown in Fig. 8. Where the marked center section of the SSC remains in the original order for non-tension simulation, but significant relative movement or disorder of the marked (or shaded) center section was observed for tension simulation.

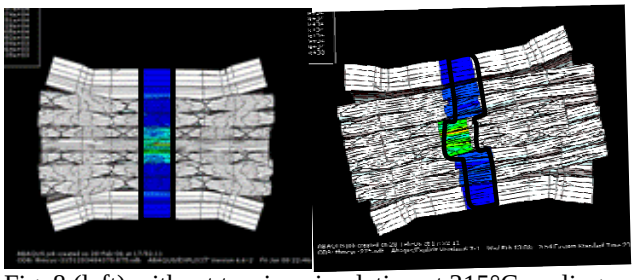

Fig. 8 (left) without tension simulation at 315°C cycling range, and (right) with tension at 275°C cycling range.

- Simulation with tension or/and water quench show severe reduction of the SSC compressive stress fields, both in the heat-up and cold down cycles, at or above thermal cycle range of 100-125°C, where 92-95% reduction was reached.

Thermal cycle simulation for core-grip section

- No significant difference of compressive residual stress relaxation was observed between FEM simulations with tension or without tension loading. Different compressive stress relaxation trends were also observed for the pair of the heat-up and cool down cycles. As shown in Figs. 9 and 10, where compressive residual stress at (cool down) room temperature is relaxed much slower than the corresponding heat-up cycle at the targeted thermal cycle range.

- Based on the above finding, the current ANSI requirement of room temperature tensile testing for evaluating the SSC reliability after thermal cycling needs to be modified to incorporate the tensile testing at the heat-up cycle of the targeted thermal cycling temperature.

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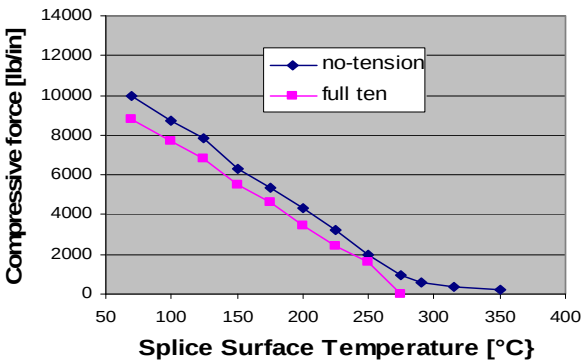

Fig. 9 The compressive force in core-grip section at heat-up cycles.

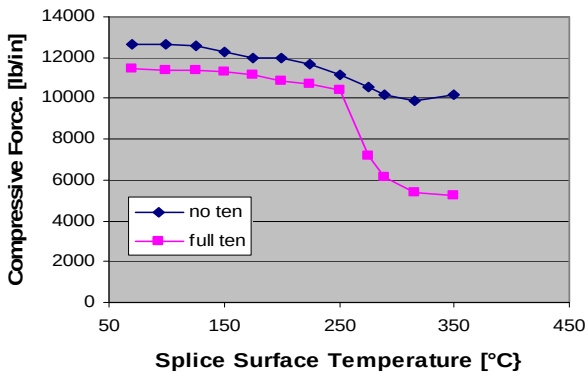

Fig. 10 The compressive force in core-grip section after heat-up at cool down (room temperature).

3. CONCLUSION

The integrity of SSC systems under thermal cycling at high operating temperature has been analyzed. A finite element simulation was also developed to provide guidance for effective lifetime estimate of SSC system performance. The results of FEM simulations for SSC forming were found to be in good agreement with experimental residual stress measurements obtained by neutron diffraction techniques. The main findings are

- Compressive residual stress field within SSC system can serve as good index for effective lifetime estimate.
- The thermal cycling has significant detrimental effect to SSC lifetime, especially under high temperature.
- Tension loading needs to be considered in SSC lifetime investigation, especially for the consideration in combining with dynamics tension loading.
- Both the compressive residual stresses at the ambient and at heat-up cycle temperatures need to be considered in evaluating the SSC system performance and lifetime.

4. ACKNOWLEDGEMENTS

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