

Fracture Analysis of Composite Insulators

Technical Report

Fracture Analysis of Composite Insulators

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REPORT SUMMARY

Non-ceramic (composite) insulators for high-voltage applications are a relatively new product, and their structural integrity and expected life is of great interest to both utilities and manufacturers. This research contributes to the understanding of complex macro- and micro-fracture mechanisms in non-ceramic composite high-voltage insulators (NCIs).

Background

A high-voltage non-ceramic insulator consists of a pultruded glass-fiber reinforced polymer (GRP) rod as the principal load-bearing component, with weathersheds bonded to the outside. This assembly has metallic end fittings that permit its attachment to the transmission tower and to the cable. Compared to traditional ceramic insulators, they are lighter, have improved damage tolerance and impact resistance, and are generally easier to install. In recent years, non-ceramic insulators have been replacing ceramic insulators, but there are still questions related to their lifetimes in service. A specific problem has been brittle fracture failures. The brittle fracture process is caused by stress corrosion cracking of the insulators' GRP rods, cracks developing inside or near the energized end and growing perpendicularly to the fibers. The brittle fracture process in suspension composite insulators results from the combined effect of low mechanical tensile stresses and nitric acid solutions generated in-service as a consequence of electrical activities. During the brittle fracture process, cracks are formed in the composite insulator rods and lead to premature failure of composite insulators. The process is catastrophic and unpredictable at present. Since composite insulators are a relatively new product, very few published studies have examined their mechanical performance and design. This research addresses the most important issues regarding mechanical performance of composite suspension and substation insulators.

Objectives

To improve the design and in-service mechanical performance of composite insulators and to develop non-destructive evaluation methods that will lead to an early indication of incipient failure (or remaining life) in service.

Approach

The initial research on brittle fracture between July 1992 and June 1994 was jointly sponsored by the Bonneville Power Administration, Western Area Power Administration, and EPRI. From 1994-1998, brittle fracture research was continued in two separate programs sponsored by EPRI and a consortium of utilities at OGI and the University of Denver. In the consortium's program, major efforts were made to design a composite rod material with the highest resistance to brittle fracture. In the EPRI project, macro- and micro-fracture mechanisms in composite insulators were studied. In this research, the most important issues regarding the mechanical performance

of composite suspension and substation insulators were addressed. These two complementary programs have been separately managed without any duplication of research efforts.

Results

Several issues regarding mechanical performance of composite high-voltage insulators were addressed in this project. First, comprehensive failure analyses of suspension composite insulators were performed. Three major designs of composite insulators were evaluated. The most important brittle fracture failure mechanisms were identified. The effect of static and fatigue loading conditions on brittle fracture was analyzed. Second, a comprehensive testing methodology was proposed for evaluating mechanical strength properties of crimped composite insulators. Third, effects of moisture and internal defects on electric field distributions and the possibility of brittle fracture failures of composite suspension insulators were determined. Fourth, the critical chemical composition of corrosive environments responsible for brittle fracture failures of composite insulators was established. This document contains synopses of research performed between 1994 and 1998 and a complete list of publications, dissertations, and major reports based on EPRI's project.

EPRI Perspective

Compared with traditional porcelain insulators, NCIs offer significant advantages such as a high mechanical strength-to-weight ratio, improved damage tolerance, flexibility, impact resistance, and ease of installation. However, there are many aspects regarding materials, designs, applications, specifications, testing, maintenance, and aging that are not so well established. This research has helped to clarify these issues and made major contributions to the entire composite insulator technology.

Keywords

High-voltage insulators
Non-ceramic insulators
Glass-fiber reinforced polymers
Environmentally induced brittle fracture
Failure mechanisms
Failure analyses of insulators

ABSTRACT

Several issues regarding the mechanical performance of composite high voltage insulators have been addressed in this project. First, comprehensive failure analyses of suspension composite insulators have been performed. Three major designs of composite insulators have been evaluated. The most important brittle fracture failure mechanisms have been identified. The effect of static and fatigue loading conditions on brittle fracture has been analyzed. Second, a comprehensive testing methodology has been proposed for the evaluation of the mechanical strength properties of crimped composite insulators. Third, the effects of moisture and internal defects on the electric field distributions and the possibility of brittle fracture failures of composite suspension insulators have been determined. Fourth, the critical chemical composition of the corrosive environments responsible for the brittle fracture failures of composite insulators have been established. Based on the research performed in this project, major contributions to the entire composite insulator technology have been made.

GOAL

Non-ceramic (composite) insulators for high voltage applications are a relatively new product. Therefore, their structural integrity and expected life is a subject of great interest to both utilities and manufacturers. The aim of this project was to improve the design of composite insulators and improve their in-service mechanical performance.

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1

RESEARCH OBJECTIVES (IMPORTANCE OF RESEARCH)

The main objective of this research was to contribute to the understanding of complex macro and micro-fracture mechanisms in non-ceramic composite high voltage insulators (NCIs). Compared with the traditional porcelain insulators, NCIs offer significant advantages such as a high mechanical strength-to-weight ratio, improved damage tolerance, flexibility, impact resistance, and ease of installation. However, there are many aspects regarding materials, designs, applications, specifications, testing, maintenance and aging that are not so well established.

2

INTRODUCTION

If non-ceramic insulators are not protected against moisture penetration into their end-fittings they can fail in-service by brittle fracture. The brittle fracture process is caused by stress corrosion cracking of the glass reinforced polymer (GRP) rods of the insulators, wherein cracks develop inside or near the energized end, and grow in the direction perpendicular to the fibers. The brittle fracture process in suspension composite insulators results from the combined effect of low mechanical tensile stresses and nitric acid solutions generated in-service as a consequence of electrical activities. During the brittle fracture process cracks are formed in the composite insulator rods leading to the premature failure of composite insulators. The process is catastrophic and unpredictable at present. The first research project in this country on brittle fracture was initiated at the Oregon Graduate Institute of Science and Technology in 1992. The initial research on brittle fracture between July 1992 and June 1994 was jointly sponsored by the Bonneville Power Administration, Western Area Power Administration and the Electric Power Research Institute. Over the last four years the brittle fracture research has been continued in two separate programs sponsored by EPRI and a consortium of utilities (Bonneville Power Administration, Western Area Power Administration, Alabama Power Company, Pacific Gas and Electric and the National Rural Electric Cooperative Association) at OGI and the University of Denver. In the EPRI project the macro and micro-fracture mechanisms in composite insulators have been studied. In the program sponsored by the consortium, major efforts have been made to design a composite rod material with the highest resistance to brittle fracture. These two complementary programs have been separately managed without any duplication of research efforts.

Since composite insulators are a relatively new product, very few published studies have examined their mechanical performance and design. In this research major efforts have been undertaken to address the most important issues regarding the mechanical performance of composite suspension and substation insulators. Three of the most important designs of composite insulators have been evaluated. In particular, the epoxy cone and crimped end-fitting designs have been investigated both numerically and experimentally. The epoxy cone end fitting design has been widely used in the US and abroad. Despite the fact that this particular design was abandoned a few years ago, mostly due to the numerous brittle fracture failures at the Western Area Power Administration, there are still several hundred thousand of these insulators in-service. Based on the research performed in this project the brittle fracture failures at the Western Area Power Administration have been explained. This research also helped explain the failures of the 500 kV insulators at Pacific Gas and Electric.

The crimped end-fitting design has become a common method of joining the GRP-rods to the fittings. The insulator manufacturers have adopted the crimped end-fitting design apparently due to a lower cost of assembly. In the crimped design, the end-fittings are radially compressed onto the ends of the rod. Contrary to the epoxy cone design, in the crimped end-fitting design the

bonding between the rod and fitting is purely mechanical in nature. During crimping large internal stresses are generated inside the composite rod which in some cases can cause severe cracking of the rod inside the fitting. It has been found in this research that the insulator manufacturers do not possess high quality testing techniques for the evaluation of their crimping technologies. In this research program the crimped end-fitting design has been carefully evaluated in order to help the insulator manufacturers to optimize the crimping process. A comprehensive testing methodology has been proposed for the investigation of the mechanical strength properties of crimped composite insulators.

In the programs sponsored by the consortium, stress corrosion experiments using constant K_I specimens have been performed. The most important composite rod materials have been evaluated for their brittle fracture properties. In order to make the stress corrosion experiments more realistic, closer to the actual brittle fracture process in a composite suspension insulator, new testing techniques have been developed in this program to investigate the process in composite rods.

One of the most important discoveries regarding brittle fracture was the identification of the corrosive environment responsible for brittle fracture. It has been shown in this research that brittle fracture of suspension insulators can be caused by nitric acid solutions formed in-service due to corona activities and moisture. For the first time nitride has been found in the brittle fracture zone of a 115 kV suspension insulator. This major discovery clearly shows that composite suspension insulators can fail in-service by brittle fracture even if environmental contaminants are not present. Since the nitric acid formation process is dependent on the amounts of ozone and moisture it can be speculated that the most critical conditions, with the highest possibility of brittle fracture will occur if a composite insulator is subjected to ozone and a small amount of moisture. Under this condition nitric acid solutions will be highly concentrated causing brittle fracture failure of a composite insulator, especially if the insulator is not well protected against moisture ingress into its end-fittings.

3

RESEARCH PERFORMED BETWEEN JULY 1, 1994 AND FEBRUARY 28, 1998

Based on the research performed in this project, between July 1, 1994 and February 1998 nine papers have been published in several major international journals. In addition, two Ph.D. dissertations, three MS theses and six major reports have been prepared. A complete list of the publications, dissertations and reports based on this project is presented in the last section of the report. In addition, the abstracts and major conclusions of the published manuscripts are also included.

3.1 Failure Analysis of Composite Insulators (by Q. Qiu and M. Kumosa)

The most important macro and micro-failure mechanisms related to the brittle fracture failures of composite suspension insulators have been identified in this project. Three types of composite suspension insulators have been investigated. The first design is based on the epoxy cone end-fittings (Qiu, 1995 and Kumosa et al., 1997) whereas the second type is based on two metal wedges inserted into the composite rod inside the fitting (Kumosa and Qiu, 1996). The epoxy cone end fitting design has been widely used over the last two decades by many utilities in this country and abroad. Due to numerous brittle fracture failures of these insulators at the Western Area Power Administration (14 brittle fracture failures in 1991/92 and 2 in 1997 on 345 kV lines) and other utilities this particular design has been gradually replaced with crimped insulators. However, according to our estimations there are approximately 300,000 composite suspension insulators with epoxy cone end-fittings still in-service on high voltage transmission lines. The metal wedge design seems to be less “popular”. Several brittle fracture failures of the suspension composite insulators based on this design on 161 kV and 500 kV lines at PG&E, FPL and in Israel have created a very negative impact regarding the successful application of composite insulators in high voltage situations.

3.1.1 Brittle Fracture of Non-Ceramic Suspension Insulators with Epoxy Cone End-Fittings

The purpose of this research was to establish the critical loading conditions that could promote brittle fracture in suspension composite insulators with epoxy cone end-fitting (Qiu, 1995 and Kumosa et al., 1997). Several issues have been addressed in this research. A suspension composite insulator with epoxy cone end-fittings has been modeled by finite element techniques. Local and global deformations of the end-fitting have been determined assuming different frictional properties of the interface between the fitting and the rubber sheath and the epoxy cones as a function of external tensile loads. In addition, internal stresses inside the fitting have been evaluated for different frictional properties of the interface and applied loads. Results from

this study clearly show that excessive tensile loads applied to the composite insulators either during manufacturing or in-service can cause severe internal cracking of the epoxy cones. The cracks, in combination with interfacial gaps at the rubber-sheath/metal end-fitting interface can allow easy access of moisture and environmental contaminants to the surface of the GRP rod. In this project, a detailed explanation has been given of the numerous brittle fracture failures of 345 kV composite insulators based on the epoxy cone design at the Western Area Power Administration (Kumosa et al., 1997).

3.1.2 Analysis of Brittle Fracture Failures at PG&E

Using the experience gained in the EPRI project, brittle fracture failures of 500 kV suspension composite insulators at the Pacific Gas and Electric Company have been explained (Kumosa and Qiu, 1996). A detailed report, based on the PG&E failures, has been prepared and submitted to EPRI and several EPRI member utilities (per agreement between EPRI, PG&E and M. Kumosa). A major portion of this work was sponsored by PG&E with small funding from the EPRI contract to support the research.

3.1.3 Finite Element Analysis of Brittle Fracture Cracks in the GRP Rods

In this part of the study, three dimensional finite element analyses of brittle fracture cracks in composite insulators have been performed (Kumosa et al., 1997). An attempt has been made to establish a critical size of brittle fracture cracks in suspension non-ceramic insulators. The finite element computations of the cracks showed that the numerically determined stress intensity factors are significantly higher than the critical stress intensities required to generate brittle fracture. Numerical evaluation of a critical size of brittle fracture cracks in the GRP rod was therefore not possible.

Conclusions/Recommendations

1. The most important failure mechanisms related to the brittle fracture process in suspension composite insulators have been identified (Qiu, 1995, and Kumosa and Qiu, 1996). The brittle fracture failures of composite suspension insulators are caused by the stress corrosion cracking of the GRP rods. In this process, both calcium and aluminum are leached out of the E-glass fibers used in the GRP insulator rods. It appears, however, that calcium depletion is more severe than aluminum depletion. This finding strongly suggests that the acid corrosion of E-glass fibers in the brittle fracture process is controlled by an ion-exchange mechanism.
2. All of the insulator brittle fracture surfaces examined in this study were free from any post-failure damage (Qiu, 1995, and Kumosa and Qiu, 1996). The fractured fibers retained their initial fracture markings (mirror and hackle zones) without further visible deterioration. This phenomenon strongly indicates that the in-service acidic environments may not be highly concentrated or they may stay in contact with the fracture surface temporarily during the fracture process.
3. In composite insulators with the galvanized cast iron end-fittings, zinc and iron can be detected in the deposits on the brittle fracture surfaces away from the high voltage end (Qiu,

1995). It is believed that the zinc and iron corrosion products of the fittings are transported by water migrating along the insulators in-service. The zinc and iron transportation process can be used to determine the extent of water migration in composite insulators affected by brittle fracture.

4. It has been shown in this research (Kumosa et al., 1997) that in-service gaps can develop at the rubber-sheath/metal interface in epoxy cone end-fittings, allowing rain water to penetrate into the fittings. The size of the gaps is dependent on the mechanical loads applied to the insulators in-service. It is strongly recommended that the fittings with the epoxy cones should always be protected with a high quality sealant placed on the top surface of the hardware.
5. The numerical results of internal mechanical stresses inside the epoxy cone end-fittings indicate that under excessive tensile loads, cracks can develop in the potting material (Kumosa et al., 1997). The cracks will be formed by high compressive stresses in the cones generated by sliding of the cone along the internal surface of the end-fitting, when subjected to high tensile loads. Since the gaps at the sheath/metal interface can allow water penetration, water may penetrate to the surface of the GRP rod through the cracks in the epoxy potting material. If the water is sufficiently acidic, a brittle fracture crack will be formed in the rod inside the hardware.
6. Since most of the insulators based on the epoxy cone design evaluated in this study did not have any protection against water penetration into their fittings (no sealant) it can be stated that this particular design is absolutely unacceptable for high voltage applications. The numerous brittle fracture failures of the epoxy cone suspension insulators at the Western Area Power Administration and other utilities clearly support the above two conclusions.
7. The metal wedge design of suspension composite insulators has also been evaluated (Kumosa and Qiu, 1996). The brittle fracture failures of the metal wedge suspension insulators at PG&E (500 kV) and other utilities have been explained. The failures were caused by brittle fracture and resulted from the combined effect of poor design, quality control, and the inappropriate selection of materials.
8. It has been observed that the size of brittle fracture cracks in several field-failed insulators examined in this and other projects over the last four years can range from 30 to 90% of the cross-sectional area of the rod. The planar nature of the cracks could not be explained by numerically evaluating the stress intensity factors at the tip of a transverse elliptical crack in a unidirectional composite rod subjected to uniaxial tension along the fibers (Kumosa et al., 1997). These factors seem to be significantly higher in comparison with the critical stress intensities for axial debonding along the fibers. Taking into account the numerical data of the factors obtained in this study, brittle fracture cracks in suspension composite insulators should be much smaller than the size of the cracks observed so far in the field-failed insulators. In addition, the planar nature of the cracks should be highly dependent on the crack size since larger cracks will generate higher stress intensity factors promoting axial splitting along the fibers.

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3.2 Experimental and Numerical Studies of Composite Insulators with Crimped End-Fittings (by A. Bansal, M. Kumosa, S. H. Carpenter and D. Armentrout)

During the assembly of insulators with the crimped end-fitting design, bonding between the GRP rod and metal end-fittings is achieved by radially compressing the end-fittings onto the rod until the onset of plastic deformation in the metal. This process can introduce large residual compressive stresses in the GRP-rod. Clearly, excessive radial compression applied to the GRP-rod during crimping can lead to radial and tangential stresses large enough to initiate debonding and crushing failures in the GRP-rod. On the other hand, a low value of radial compression during crimping, coupled with large axial loads, can cause internal sliding failures (rod pull-out) in the crimped end-fitting design. In the past, field failures of crimped suspension insulators have been blamed on both of these mechanisms.

In this part of the EPRI project the possibility of short-term mechanical failures of crimped substation and suspension composite insulators has been addressed. Detailed two and three-dimensional non-linear finite element analyses have been performed (Bansal et al., 1995, Bansal, 1996, Bansal and Kumosa, 1997, and Han, 1997) to evaluate the axial load bearing capacity and stress distributions in the compressed GRP-rods of composite insulators as a function of the magnitude of radial compression, shape of the compression profile introduced during crimping, coefficient of friction at the GRP-rod/metal interface, and the radius of the GRP-rod. In addition, the effect of the plastic deformation of the end-fitting on the stress distribution and the mechanical strength of suspension insulators has been evaluated (Han, 1997). Several destructive mechanical tests have been performed on substation and suspension insulators by subjecting them to either push-out or pull-out tests (Bansal et al., 1995, and Kumosa et al., 1997).

3.2.1 Finite Element Modeling of Crimped Composite Insulators

Two and three-dimensional finite element models of crimped composite insulators have been constructed. This research has been performed in the following three stages:

1. Investigation of the effect of perfectly bonded and frictional interfaces on the internal stress distributions in crimped composite insulators (linear and non-linear two-dimensional modeling).
2. Investigation of the effect of various compression profiles and the frictional properties of the GRP rod/metal end-fitting interfaces on the mechanical strength properties of crimped composite insulators (two and three-dimensional modeling).
3. Investigation of the elasto-plastic properties of metal end-fitting materials on the mechanical strength of the insulators (non-linear modeling).

In the initial stages of our research the insulators were modeled without any collaboration with the insulator manufacturers. Therefore, important information regarding their design such as the actual internal dimensions of the fittings and the frictional properties of the rod/fitting interfaces were not available at that time. Therefore, our initial finite element models were very sophisticated but not very realistic. In the final year of the EPRI contract the two and three-dimensional models of crimping were significantly modified. This was possible thanks to a collaborative research program with NGK-Japan. The actual dimensions of the fittings and the elasto-plastic properties of the fitting materials were introduced into the models making them much more realistic. Subsequently, the improved numerical models have been experimentally verified. Excellent agreement between the numerical and experimental load displacement diagrams from the pull-out tests performed on the NGK insulators has been obtained. At present, we can numerically simulate crimped composite insulators as a function of:

- crimping profiles, magnitude of crimping,
- friction between the fitting and the GRP-rod,
- geometry of the fittings,
- elastic and elasto-plastic properties of the fitting materials
- external loads (axial tension, compression, combined loading).

Since the finite element simulations of crimped composite insulators can be accurate, it is possible at present to determine numerically the actual crimping conditions on the surface of the rod inside the fitting by comparing the numerical and experimental load-displacement diagrams. If the friction coefficient at the rod/metal interface is known the magnitude of compression on the rod surface inside the fitting can be very accurately determined by combining the numerical simulations with the experimental data.

3.2.2 Experimental Studies

A new non-destructive manual contact pulse-echo ultrasonic technique has been developed in this project to measure the magnitude of radial compressive displacements applied to the GRP-

rod with crimped end-fittings. This technique is capable of determining the magnitude and shape of the radial compression profile with an accuracy of ± 0.025 mm provided the GRP-metal interface is smooth with no interfacial voids. This technique has been used to evaluate the crimping deformations in several different substation and suspension insulators. The limitations of the ultrasonic technique have been determined.

Suspension composite insulators with a rod diameter of 16 mm have been subjected to excessive tensile axial loads. In addition, a series of push-out tests have been performed on substation insulators with large GRP-rods. The resistance to sliding of the insulators has been determined. The possibility of using acoustic emission techniques for the monitoring of insulator failure has also been evaluated. The purpose of this test series was:

- to verify finite element models from the experimental load-displacement response of the insulators subjected to axial compression (substation insulators) and axial tension (suspension insulators),
- to establish the mode of failure and maximum loading capacity of the insulators under axial compression and axial tension,
- to evaluate the frictional properties of the GRP-rod/metal interface and the magnitude of crimping in conjunction with finite element models,
- to evaluate the application of acoustic emission as a monitoring system in the rod push-out and pull-out tests.

Most Important Conclusions/Recommendations

1. The mechanical strength properties of crimped composite insulators subjected to either axial tensile, compressive or multiaxial loads can be predicted using finite element techniques (Bansal et al., 1995, Bansal, 1996, Bansal and Kumosa, 1997, and Han, 1997). The load-displacement diagrams from the pull-out and push-out test can be numerically simulated. The global deformations of the insulators when subjected to axial tension, axial compression and multiaxial loads can also be very accurately determined using finite elements.
2. Under excessive monotonic axial compression and axial tension composite substation and suspension insulators exhibit a non-linear structural response, and usually encounter failure due to interfacial sliding of the GRP-rod within the end-fitting (Bansal et al., 1995, Bansal 1996, and Bansal and Kumosa, 1997). In some cases, however, the rod can fracture under axial tension (Han, 1997).
3. The axial loads at the onset of sliding in crimped insulator end-fittings can be increased by (Bansal and Kumosa, 1997):
 - decreasing the radius of the GRP rod for insulators loaded under axial compression and increasing the radius for insulators loaded under axial tension
 - increasing the average magnitude of radial compression and consequently the amplitude of radial compression applied during crimping
 - increasing the coefficient of friction at the GRP-metal interface
 - increasing the length of the fitting.

4. The biaxial compressive stresses (radial and tangential) will be increased by a decrease in the radius of the GRP rod, and an increase in the average magnitude (and amplitude) of radial compression (Bansal and Kumosa, 1997). This will enhance the risk of compressive intralaminar damage in the rod during crimping. An increase in the coefficient of friction at the GRP-rod/metal interface will have no influence on the stress state in the rod.
5. The shape of the radial compression profile will not affect the axial load at the onset of sliding, provided that the average magnitude of radial compression remains the same (Bansal and Kumosa, 1997). The shape of compression profile affects the stress distribution in the GRP rod. However, the maximum values of the biaxial compressive stresses in the rod will not be significantly affected, provided that the amplitude of radial compression remains constant.
6. It has been clearly shown in this research that uniform crimping generated during manufacturing provides the best stress conditions in the GRP-rods with the lowest possibility of internal cracking (Han, 1997). Non-uniform crimping conditions on the rod surface inside the fitting generate significantly higher stresses in the rod in comparison with the uniform crimping condition.
7. The elasto-plastic properties of the fitting materials do not significantly affect the load/displacement diagrams and the internal stresses in the GRP rods for the insulators loaded under axial tension until failure (Han, 1997). It appears that the linear elastic models with contact elements placed along the GRP-rod/metal interfaces can very accurately predict the mechanical strength properties and internal stresses for the crimped composite insulators subjected to various loading conditions.
8. A manual contact pulse-echo ultrasonic technique has been used to evaluate the compression profiles of several types of suspension and substation crimped composite insulators (Bansal et al., 1995, Bansal, 1996, Bansal and Kumosa, 1997, and Kumosa et al., 1997). It has been shown that the ultrasonic method can be successfully used to determine the shape and magnitude of radial compression on the rod surface inside the crimped end-fittings of substation insulators. In the case of crimped suspension insulators the proper application of the ultrasonic technique can be difficult, even impossible, if the crimping deformations on the rod surface are small.
9. The mechanical strength properties of crimped composite suspension and substation insulators can be determined by performing the rod pull-out and push-out tests, respectively (Bansal et al., 1995, Bansal, 1996, Bansal and Kumosa, 1997, and Kumosa et al., 1997). The resistance to sliding of the rod inside the fitting can be evaluated from these tests using acoustic emission. The acoustic emission data such as the total number of events will be proportional to the magnitude of crimping for the same insulator design.
10. A comprehensive testing methodology has been proposed for the evaluation of the mechanical strength properties of crimped composite insulators (Bansal et al., 1995, Bansal, 1996, Bansal and Kumosa, 1997, Kumosa et al., 1997, and Han, 1997).

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3.3 Moisture Absorption Research (by M. V. Balakrishnan, Y. Zhao and M. Kumosa)

Brittle fracture of composite suspension insulators can occur either inside (internal failure) or outside (external failure) the energized end-fittings (Qiu, 1995, Kumosa and Qiu, 1996, Kumosa et al., 1997). The most common mode of the brittle fracture process is the initiation of brittle fracture cracks outside the fitting, usually just above the grading rings. It has been shown in our research that this type of brittle fracture failure is associated with moisture penetration into the end-fitting and then its migration along the rod into the high electric field above the grading rings. If grading rings are not used the external failure will occur just above the hardware. In the failure process outside the fittings, nitric acid solutions are formed inside the insulators due to the presence of moisture and internal partial discharges. Moisture in composite suspension insulators migrates near the GRP rod/rubber sheath interface inside the composite. The nature of this process has not yet been investigated and therefore is not well understood. It can be assumed however, that the internal moisture propagation process along the insulators will depend on the following two factors;

1. The quality and type of bonding of the GRP rod/rubber housing interface,
2. The moisture absorption properties of the composite rod materials used in composite insulators.

No research has been done on the effect of different GRP rod/housing interfaces on moisture migration in composite insulators; therefore, it is difficult to provide any viable recommendations as far as the proper chemical/mechanical properties of the rod/housing interfaces are concerned. Since the major portion of brittle fracture failures (according to our estimates approximately 90%) have occurred above the fitting the moisture propagation phenomenon in composite insulators cannot be ignored and should be investigated in the future.

By preventing moisture propagation along the insulators the rate of brittle fracture failures could be drastically reduced. In this research, the second issue regarding the moisture absorption properties of the most important composite rod materials has been addressed.

The purpose of this research was to evaluate the moisture absorption properties of the most widely used insulator rod materials, namely E-glass/modified polyester, E-glass/epoxy and E-glass/vinyl ester. The moisture properties of three new composite systems based on ECR fibers with the same polymer resins have also been studied. The tests have been performed according the ASTM standard D5229/D5229M. In addition to the moisture absorption tests several shear tests were also performed in order to determine the effects of absorbed moisture on the intralaminar failure properties of the composites.

Tests performed:

1. E-glass/modified polyester, E-glass/epoxy and E-glass/vinyl ester unidirectional composites supplied by Glasforms, Inc. were tested in distilled water at 50°C. The diffusivity and maximum moisture content of the composites were determined. Subsequently, Iosipescu shear testes were performed to determine the shear strength properties of the composites as a function of moisture content (Kumosa at al., 1995, Balakrishnan, 1995).
2. E-glass and ECR-glass fiber unidirectional composites with modified polyester, epoxy and vinyl ester resins (also supplied by Glasforms) were tested at 50°C in humid air (relative humidity of 80%). The diffusivity and maximum moisture content of the composites were determined (Zhao, 1997)

For the composites tested in distilled water at 50 °C the maximum moisture contents were 0.26 0.58 and 1.13% for the E-glass/vinyl ester, E-glass/epoxy and E-glass/modified polyester, respectively. The normalized times required to attain the maximum moisture contents for the composites were 1100, 1400 and 1600 hours.

For the E-glass composites tested in humid air the maximum moisture contents were 0.18, 0.21 and 0.25% for the composites based on vinyl ester, epoxy and modified polyester, respectively. The ECR based composites absorbed slightly less moisture with the maximum moisture contents 0.123, 0.18 and 0.18% for the vinyl ester, epoxy and modified polyester resins, respectively.

The ECR-glass is manufactured from a single end roving versus an assembled roving for the E-glass. This means that the glass content is higher in the ECR-glass composites, and conversely, the E-glass composites have a higher resin content. Since moisture is absorbed much more by the resin, than the glass, it is not surprising that the ECR-glass composites absorbed less moisture in comparison with the E-glass based composites.

The results from the moisture absorption tests have not yet been published.

Most Important Conclusions/Recommendations

1. The unidirectional E-glass based composites absorbed more moisture in distilled water than when exposed to humid air at 50°C. The highest moisture absorption has been found in the modified polyester composites, whether it is E-glass or ECR-glass.
2. It has also been found in this research that absorbed moisture significantly reduces the intralaminar shear strength properties of the composites.
3. A vast majority of the brittle fracture failures over the last several years have occurred in the insulators with the GRP-rods based on the E-glass/modified polyester composites (WAPA, APC and others) with the external failures above the hardware. Therefore, it can be speculated that the rate of these failure (as well as their location above the hardware) might be related to the large maximum moisture content of the composite. To better understand the relation between the moisture absorption and migration process in unidirectional glass fiber/polymer composites more research is required. Especially, the effect of high voltage fields on the moisture migration process along the GRP-rod needs to be investigated.

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3.4. Electric Field Calculations (by Y. Zhao and M. Kumosa)

The purpose of this study was to understand the brittle fracture process in composite insulators by examining the effects of electrical stress and moisture on the failure process. Numerical macro- and micro-field calculations have been performed using finite element methods to determine the electrical stresses in insulators with and without internal damage (Zhao, 1997). The macroscopic field calculations are important in order to understand such mechanisms as the direct damage to the sheath, weather sheds, and the GRP-rod by the field as well as the aging process of the weather sheds due to corona activities (for example, water drop corona). The macro-field calculations can also provide useful information about the effect of the field on the nitric acid generation process in-service. The micro-field computations, on the other hand, can provide data concerning the field intensification due to the presence of voids and cracks inside a composite insulator. The intensification of the electric field inside these defects might explain the nature of the nitric acid formation process inside the insulator.

A series of field calculations have been performed using the Maxwell Field Simulator (Zhao, 1997). The overall field distributions along the long axis of a composite suspension insulator

have been determined considering the presence of the grading ring at the energized end. The position and geometry of the grading rings are expected to have a profound influence on the field distributions both inside and outside of composite insulators, therefore, these grading effects on the field distributions were evaluated. If an insulator has an internal damage zone and if the conductivity of the zone increases due to moisture this should change the field distribution outside the insulator. If the change in the field distribution is significant it might be used to detect damage in composite insulators in-service. The effect of damage on the change in the field distributions was investigated by modeling various internal damage zones, simulating as closely as possible the actual damage zones which might be present in the insulators in-service.

Subsequently, microscopic field calculations have been performed (Zhao, 1997). The internal fields near cracks and voids positioned inside a composite insulator close to the energized end-fitting have been calculated for different void geometries and electrical properties. The main purpose of this part of the study was to find out if the field intensification near the voids is high enough to cause partial discharges and thus, the formation of nitric acid.

Most Important Conclusions/Recommendations

The following conclusions can be drawn based on the electric field computations:

1. The Maxwell Field Simulator is an acceptable tool for the electric field computations inside and outside composite insulators (Zhao, 1997). The verification of the software by comparing the numerical results of several simple electrical problems with the available analytical solutions showed good agreement for the dielectric and perfectly conductive materials. However, the software does not satisfactorily handle materials with finite conductivity.
2. The electric field close to the end-fitting for a composite suspension insulator without any internal damage is high enough to cause ionization of air for most high voltage loading conditions even when grading rings are used to reduce the electrical stresses (Zhao, 1997). Nitric acid is very likely to be generated at this location.
3. The geometry and position of the grading rings affect the macro-field distributions (Zhao, 1997). The position of the ring, however, has a more pronounced influence on the field reduction than the size of the ring.
4. A conductive damage zone inside a composite insulator alters the external field distributions if the size of the damage zone is significant (Zhao, 1997). The field disturbance caused by the conductive damage depends on the length and position of the damage zone inside the GRP rod. However, the in-service detection of the field disturbance will be difficult at present.
5. The electric field at the ends of a longitudinal void placed at the center of a composite insulator along the fibers is significantly intensified (Fujimoto et al., 1995, and Zhao, 1997). The intensification at the top of the void is strong enough for partial discharges to occur for most in-service voltage levels when the void is filled with conductive materials or water. The diameter of the void, however, was found to have no effect on the field distribution at the ends of the void. A strong field intensification was also observed at the end of a conductive void inside the hot end-fitting.

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3.5. Chemical Analysis of Composite Insulators (by Q. Qiu, A. Chughtai, D. Smith and M. Kumosa)

The purpose of this research was to establish the type of corrosive environment responsible for brittle fracture of suspension composite insulators. A detailed study of brittle fracture failures of composite insulators has been conducted by Q. Qiu (1995). It was speculated that the process is caused by the formation of nitric acid solutions in-service. The acid is formed either inside the insulators (close to the energized end-fitting) or outside (on the hardware, weathersheds and the rubber sheath). Several field failed insulators from 115 kV, 345 kV and 500 kV lines have been examined (Qiu, 1995, and Kumosa and Qiu (1996). The most important failure mechanisms have been established; however, the presence of nitric acid on the brittle fracture surfaces in the insulators has not been shown (despite the fact that major efforts were undertaken to show the presence of nitric acid using standard SEM techniques). In this study, an attempt has been made to determine the chemical composition of a corrosive environment which was responsible for the in-service failure of a 115 kV suspension insulator with epoxy cone end-fittings.

A Fourier transform infrared spectroscopy (FTIR) study has been performed (Chughtai et al., 1998) to identify chemical functionalities formed during the degradation process of composite insulators affected by brittle fracture. Small quantities of material were scraped from composite fracture surfaces of a field failed 115 kV suspension insulator. Two types of samples were collected. The first sample was collected from the fracture surfaces along the fibers far away from the brittle fracture zone (mechanical failure). The second sample was taken from the surface within the brittle fracture damage zone. By comparing the FTIR spectra from the two fracture surfaces the chemical composition of the corrosive environment for the insulator failure could be determined. In the specimen collected from the brittle fracture zone a sharp absorption band, due to either symmetric stretch of the C-NO₂ linkage and/or the asymmetric stretch of nitrate, was found at 1386 cm⁻¹. To confirm this identification, several additional experiments were carried out on clean (as supplied) composite samples exposed to HNO₃, NO₂/N₂O₄. In each case, the same absorption band produced by HNO₃ was detected.

It is clear from the results presented in this study that oxides of nitrogen and thus nitric acid solutions can be formed in-service in the presence of corona discharges, air and small amounts of water.

Most Important Conclusions/Recommendations

1. It has been shown in this research that, independent of the presence of environmental pollutants, brittle fracture of suspension composite insulators is caused by nitric acid formed through corona discharges. Nitrate has been identified in a 115 kV composite suspension insulator inside its brittle fracture zone (Chughtai et al., 1998).
2. Since corona discharges frequently occur in the immediate vicinity of the end-fittings of suspension composite insulators, oxides of nitrogen and nitric acid are formed in-service in the presence of ozone and moisture. The acid can also be formed inside an insulator if moisture and internal discharges are present.

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3.6 Stress Corrosion Investigation (M. Kumosa, Q. Qiu, S. Carpenter, T. Ely and D. Armentrout)

A major portion of the research regarding the brittle fracture failures of composite insulators has been supported at the Oregon Graduate Institute and the University of Denver by a consortium of utilities consisting of the Bonneville Power Administration, Western Area Power Administration, Pacific Gas and Electric, Alabama Power Company and the National Rural Electric Cooperative Association (Kumosa et al., 1998). However, several complementary research efforts have been undertaken in the EPRI contract regarding the stress corrosion cracking of unidirectional E-glass fiber/polymer composite materials (Qiu and Kumosa, 1997 and Ely and Kumosa, 2000). In particular, the effect of different acids on the damage initiation in E-glass fibers has been investigated (Qiu and Kumosa, 1997). In addition, significant efforts have been made to determine the effects of static and fatigue loading conditions on the stress corrosion cracking of the composite rod materials (Carpenter and Kumosa, 1998 and Armentrout et al, 1998).

3.6.1 Corrosion of E-Glass Fibers in Acidic Environments

This study has been concerned with the corrosion behavior of E-glass fibers exposed to oxalic, hydrochloric, nitric and sulfuric acids (Qiu and Kumosa, 1997). Acid-immersion tests were performed on E-glass fibers in nitric, oxalic, sulfuric and hydrochloric acids. The fiber weight loss was significantly affected by both the acid type and concentration; however, the influence of

acid type seemed more pronounced. Of the four acids tested, oxalic acid led to the highest weight loss. The fiber weight loss in nitric acid and hydrochloric acids were similar to one another but insignificant compared with those in either oxalic or sulfuric acid of the same concentration. As a general trend, the fiber weight loss became more severe as the acid concentration increased.

The results reveal that acid corrosion of E-glass fibers is primarily attributed to calcium and aluminum depletion. The leachability of these metallic ions is not only determined by the hydrogen ion concentration but also strongly affected by the anions in the acids. The formation of insoluble salts or complex ions between the anions in oxalic and sulfuric acids and calcium and aluminum ions leached out from the glass accelerates fiber corrosion considerably. Furthermore, acid corrosion may generate axial or spiral cracks on the fiber surface, depending on acid type and acid concentration. An ion-depletion-depth model has been proposed to explain the mechanisms of fiber surface cracking.

3.6.2 An Investigation of Brittle Fracture of Composite Insulator Rods in an Acid Environment with either Static or Cyclic Loading

In this research the effect of static and cyclic loading conditions on the stress corrosion cracking (brittle fracture) of unidirectional E-glass/modified polyester rods has been investigated (Carpenter and Kumosa, 2000). A series of stress corrosion experiments on the rods has been performed by subjecting them to mechanical tensile static and fatigue stresses in the presence of a nitric acid solution. The loading conditions simulated possible loading conditions of composite suspension insulators in-service. The morphology of the brittle fracture damage zones was investigated. The brittle fracture process in the rods was monitored by acoustic emission.

There were a number of goals for this investigation: First, it was hoped that the brittle fracture process in an actual composite rod could be generated with conditions at least somewhat like those that might be encountered in-service. Second, assuming successful generation of brittle fracture, it would be important to monitor its development and determine if information about the mechanical mechanisms involved could be obtained. Third, it was important to examine both static and fatigue loading to establish if the brittle fracture mechanisms are the same in both of these loading arrangements. Fourth, it was hoped that the measurement of acoustic emission would provide insight both to the mechanisms of brittle fracture in the composite rods and to a possible technique for the prediction and detection of brittle fracture in composite insulators in-service.

Results obtained in this study showed that the brittle fracture process can be generated in the rods when subjected to relatively low tensile stresses in the presence of a nitric acid solution. The morphology of the brittle fracture cracks in the rods closely resemble the fracture zones in composite suspension insulators failed in-service by brittle fracture. It has also been shown in this research that low frequency, low amplitude vibrations in tensile loads can significantly accelerate the fracture process. It has also been found that the acoustic emission generated during the stress corrosion fracture process in the rods is sensitive to the placement of the transducer.

3.6.3 Stress Corrosion Experiments in Flat Composite Coupons

Corrosion testing has resulted in considerable acoustic emission data from constant K_I specimens (Ely and Kumosa, 2000). In these tests, a good correlation has been obtained between the number of fractured fibers and the number of acoustic emission signals. Stress corrosion experiments in GRP rods show a more complicated relation between the number of signals and the number of fractured fibers. Since the application of acoustic emission for the monitoring of the stress corrosion process in the rods has only been partially successful experiments using flat composite coupons were proposed (Armentrout et al., 1998). The stress corrosion experiments on the flat specimens loaded in tension in the presence of a nitric acid solution generated stress conditions at the crack tip significantly closer to the rod experiments. In both cases the stress intensity factors at the crack tip increase as a function of crack length for a constant applied load (contrary to the constant K_I specimens). Moreover, the application of acoustic emission as a monitoring system of the brittle fracture process proved to be more successful in comparison with the rod experiments. This research is in progress and will be continued in the next stage of the EPRI research.

Most Important Conclusions/Recommendations

1. Acid corrosion of E-glass fibers is primarily attributed to calcium and aluminum depletion, the severity of which is highly dependent on acid type and concentration for a given glass composition and fiber fabrication process (Qiu, 1995, and Qiu and Kumosa, 1997).
2. Oxalic and sulfuric acids are much more damaging to E-glass fiber than hydrochloric and nitric acids. This behavior results from different acid-leaching mechanisms: leaching is controlled by acid concentration in hydrochloric and nitric acids but dominated by the formation of insoluble salts or complex ions in oxalic and sulfuric acids (Qiu and Kumosa, 1997).
3. Axial and spiral crack morphologies are observed in fiber acid corrosion. Based on the internal stress analysis, an ion-depletion-depth model is established to explain fiber cracking mechanisms; the axial crack formation is probably associated with a larger ion-depletion depth relative to the spiral crack formation (Qiu and Kumosa, 1997).
4. The susceptibility of fiber surface cracking in acids suggests the tendency to form significantly more post-failure damage in oxalic and sulfuric acids than in hydrochloric and nitric acids (Qiu and Kumosa, 1997).
5. Brittle fracture of real composite insulator rods can be repeatably obtained in controlled laboratory conditions. Brittle fracture can be generated by either static or cyclic loading conditions in a liquid nitric acid environment (Carpenter and Kumosa, 2000).
6. The morphology of the brittle fracture damage zones in the rods is distinctly different for static and cyclic loading (Carpenter and Kumosa, 2000). The differences obtained are due to the fatigue and not due to the stress overload that occurs in fatigue. Time to failure seems to be significantly smaller for the specimens tested under cyclic than under static loadings.

7. The acoustic emission generated during the brittle fracture process in the composite rods seems to be strongly dependent on the position of the acoustic emission transducers (Carpenter and Kumosa, 2000). The application of acoustic emission for the monitoring of stress corrosion cracking in the rods has only been partially successful.
8. The stress corrosion experiments performed using the flat composite specimens have shown that the time to failure of the specimen is more dependent on the specimen quality than the either static or cyclic loading (Armentraut et al., 1998). Moreover, splitting along the fibers significantly affects the crack propagation rate. It appears that the stress corrosion crack propagation rate increases with the amount of splitting along the fibers which is consistent with the results from the static and fatigue stress corrosion experiments on the GRP-rods.

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4

GENERAL COMMENTS

The most important issues regarding the mechanical performance of composite insulators, both suspension and substation have been addressed in this project. Major research contributions to the entire composite insulator technology have been made. Despite this more research is still needed to understand the complex failure mechanisms in the insulators affected by brittle fracture and, in particular, the critical mechanical, chemical, and electrical conditions which can cause brittle fracture.

A

PUBLISHED PAPERS

Finite Element Analysis of Substation Composite Insulators

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Abstract

Composite insulators are rapidly replacing their porcelain counterparts in electrical substation applications. These insulators consist of a glass-reinforced polymer (GRP) rod, with two metal end fittings radially crimped onto the ends of the rod during assembly. In this paper, axisymmetric finite element models are developed to evaluate the mechanical performance of composite insulators under externally applied axial compression. The analyses are performed by assuming both a perfectly bonded interface between the composite rod and the end fittings, and an imperfect interface which permits large relative sliding with Coulomb friction. Results indicate that the perfect interface model is unrealistic since it predicts singular stresses at the interface corner and an overall linear structural response. On the other hand, the imperfect interface model is found to simulate accurately the structural non-linearity caused by relative sliding of the GRP rod within the end fittings. The imperfect interface model has therefore been used to evaluate the effects of interface friction, and the extent of crimping, on the maximum load-bearing capacity of substation composite insulators.

Conclusions

The following conclusions can be drawn from the results presented in this study.

1. 1. The finite element model with a perfectly bonded GRP/Al interface shows that stresses at the interface corner decrease with an increase in the fillet radius (ρ). However, the magnitudes of stress concentrations computed from this model can be misleading since they are highly mesh sensitive.
2. Application of the finite element iterative method has shown that the stresses at the perfectly bonded GRP/Al interface corner are, in fact, singular in nature.
3. The imperfect interface model, employing general axisymmetric contact elements at the GRP/Al interface, can be used to accurately simulate the structural non-linearity, and to predict the onset of failure due to interfacial sliding of the GRP rod.
4. Composite substation insulators subjected to excessive monotonic axial compression, in combination with the pre-existing radial compression applied during assembly, will encounter failure due to interfacial sliding of the GRP rod within the end fittings.
5. Under externally applied axial compression, the load at the onset of interfacial failure can be increased by either increasing the coefficient of friction at the GRP/Al interface, or by increasing the magnitude of radial compression applied during crimping. An increase in the coefficient of friction does not affect the internal stresses in the GRP rod; however, an increase in the magnitude of radial compression will significantly enhance the risk of compressive intralaminar damage and matrix cracking in the rod.
6. The shape of the radial compression profile does not affect the loads at the onset of sliding, provided that the magnitude of radial compression applied during crimping remains the same. The shape, however, does affect the internal stresses in the GRP rod close to the interface.

Brittle Fracture of Non-Ceramic Suspension Insulators with Epoxy Cone End-Fittings

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Abstract

The purpose of this research is to establish the critical loading conditions that could promote brittle fracture in suspension insulators with epoxy cone-type end-fittings. Two issues have been addressed in this paper. First, a suspension composite insulator with epoxy cone end-fittings has been modeled by finite element techniques. Local and global deformations of the end-fitting have been determined by assuming different frictional properties of the interface between the fitting and the rubber sheath as a function of external tensile load. In addition, internal stresses in the glass-reinforced polymer (GRP) composite rod and epoxy cone have been evaluated for different frictional properties of the interface and applied loads. Second, a transverse brittle crack in the GRP rod has been modeled by performing three dimensional finite-element computations. An attempt has been made to establish a critical size of brittle fracture cracks in suspension non-ceramic insulators.

Results obtained in this study showed that excessive tensile loads applied to composite insulators either in service or during manufacturing can cause internal cracking of the epoxy cones. The cracks, in combination with interfacial gaps at the rubber-sheath/metal-end-fitting interface, might allow easy access of moisture and environmental contaminants to the surface of the GRP rod, causing brittle fracture. The finite-element computations of brittle fracture cracks in the GRP rod showed that the numerical stress intensity factors determined at the tip of the crack appear to be significantly higher than the critical stress intensities required to generate brittle fracture. Numerical evaluation of a critical size of brittle cracks was not therefore possible.

Conclusions

The following conclusions can be drawn from the results presented in this study.

1. Non-ceramic composite insulators are a relatively new product. In comparison with the traditional porcelain insulators, NCIs offer significant advantages such as a high mechanical strength-to-weight ratio, improved damage tolerance, flexibility, impact resistance, and ease of installation. However, there are many aspects regarding materials, designs, applications, specifications, testing, maintenance and aging which are not so well established. Caution

should be observed when NCIs are used in the applications which could promote their failures by brittle fracture.

2. If non-ceramic suspension insulators are not protected against moisture penetration into their end-fittings they can fail in-service by brittle fracture. The brittle fracture process is caused by stress corrosion of the GRP-rod of the insulators, wherein cracks develop inside or near the energized end, and grow in the direction perpendicular to the fibers. The fracture surfaces associated with brittle fracture are essentially planar in nature.
3. The brittle fracture process in suspension NCIs is the combined effect of low mechanical tensile stresses and environmental stresses caused by nitric acid solutions generated in-service due to electrical activities. Therefore, non-ceramic suspension insulators should always be protected against moisture penetration into their end-fittings. It has been shown in this study that, in-service, gaps can develop at the rubber sheath/metal interface in the epoxy cone type end-fittings allowing rain water to penetrate into the fittings. The size of the gaps is strongly dependent on the mechanical loads applied to the insulators in service. It is strongly recommended that the fittings with the epoxy cones should always be protected with a sealant placed on the top surface of the hardware.
4. The numerical results of internal mechanical stresses inside the epoxy cone end-fittings strongly indicate that under excessive tensile loads, cracks can develop in the potting material. The cracks will be formed by high compressive stresses in the cones generated due to the sliding of the cone along the internal surface of the end-fitting, when subjected to high tensile loads. Since, the gaps at the sheath/metal interface can allow water penetration, water may penetrate onto the surface of the GRP-rod through the cracks in the epoxy potting material. If the water is acidic, a brittle fracture crack will be formed in the rod inside the hardware.
5. It has been observed that the size of brittle fracture cracks in several field-failed insulators examined at OGI over the last four years can range from 30 to 90% of the cross-section area of the rod. The planar nature of the cracks could not be explain by evaluating the stress intensity factors at the tip of a transverse elliptical crack in a unidirectional composite rod subjected to uniaxial tension along the fibers. The SIFs seem to be significantly higher in comparison with the critical stress intensities for axial debonding along the fibers. Taking into account the numerical data of the factors obtained in this study, brittle fracture cracks in suspension composite insulators should be much smaller than the size of the cracks presented either in this paper or other publications. In addition, the planar nature of the cracks should be highly dependent on the crack size, since larger cracks will generate higher stress intensity factors promoting axial splitting along the fibers.

Corrosion of E-Glass Fibers in Acidic Environments

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Abstract

This study is concerned with the corrosion behavior of E-glass fibers exposed to oxalic, hydrochloric, nitric and sulfuric acids. The results reveal that acid corrosion of E-glass fibers is primarily attributed to calcium and aluminum depletion. The leachability of these metallic ions is not only determined by the hydrogen ion concentration but also strongly affected by the anions in the acids. The formation of insoluble salts or complex ions between the anions in oxalic and sulfuric acids and calcium and aluminum ions leached out from the glass accelerates fiber corrosion considerably. Furthermore, acid corrosion may generate axial or spiral cracks on the fiber surface, depending on acid type and concentration. In this study, an ion-depletion-depth model is proposed to explain the mechanisms of fiber surface cracking; the axial crack formation is most likely associated with a larger ion-depletion depth than the spiral crack formation.

Conclusions

This study leads to a better understanding of acid-corrosion mechanisms of E-glass fibers. The most important conclusions may be summarized as follows.

1. Acid corrosion of E-glass fibers is primarily attributed to calcium and aluminum depletion, severity of which is highly dependent on acid type and concentration for given glass compositions and fiber fabrication processes.
2. Oxalic and sulfuric acids are much more corrosive to E-glass fiber than hydrochloric and nitric acids. This behavior results from different acid-leaching mechanisms: leaching is controlled by acid concentration in hydrochloric and nitric acids but dominated by the formation of insoluble salts or complex ions in oxalic and sulfuric acids.
3. Axial and spiral crack morphologies are observed in fiber acid corrosion. Based on the internal stress analysis, an ion-depletion-depth model is established to explain fiber cracking mechanisms; the axial crack formation is probably associated with a larger ion-depletion depth relative to the spiral crack formation.
4. The susceptibility of fiber surface cracking in acids suggests that the tendency to form post-failure damage in E-glass fibers is much greater in oxalic and sulfuric acids than in hydrochloric and nitric acids.

Mechanical Evaluation of Axially Loaded Composite Insulators with Crimped End-Fittings

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Abstract

Composite materials consist of a glass reinforced polymer (GRP) rod with two metal end-fittings attached to the ends of the rod during assembly. This paper aims to evaluate the strength and design of mechanically crimped insulator end-fittings subjected to axial tensile or compressive loads during service. A non-destructive ultrasonic technique has been used to measure the extent of radial shortening applied to two composite substation insulators during crimping. The axial compressive strength of these insulators have been determined from destructive mechanical tests. In addition, detailed non-linear axisymmetric and three dimensional finite element analyses have been performed to evaluate the effects of several design variables on the mechanical performance of the crimped joints subjected to axial loads. Results obtained from this study demonstrate that the insulators are likely to encounter failure due to sliding of the GRP rod (within the end-fitting) under excessive axial loads. Based upon the finite element results, semi-empirical relationships have been presented to predict the axial loading capacity of the crimped insulator ends, and the maximum internal stresses on the GRP rod surface.

Conclusions

1. The radial shortening profiles of crimped composite insulators can vary significantly among insulators. In some insulators, they are highly non-uniform in both the axial and tangential directions.
2. The fifth order regression polynomial, and the sinusoidal wave-function, can be used to individually simulate variations in the shape or magnitude of radial shortening in the axial and tangential directions respectively.
3. Under excessive monotonic axial compression, composite substation insulators exhibit a non-linear structural response, and encounter failure due to interface sliding of the GRP rod within the end-fittings. The same mode of failure is expected in suspension insulators subjected to excessive tensile loads.

4. The axisymmetric and three-dimensional finite element models, employing general surface-to-surface contact elements at the GRP-metal interface, can be used to simulate the structural non-linearity of insulators caused by internal sliding of the GRP rod.
5. The axial loads at the onset of sliding in crimped insulator end-fittings can be increased by:
 - decreasing the radius of the GRP rod for insulators loaded under axial compression, and increasing the radius for insulators loaded under axial tension,
 - increasing the average magnitude of radial shortening, and consequently the amplitude of radial shortening applied during crimping,
 - increasing the coefficient of friction at the GRP-metal interface.
6. The biaxial compressive stresses in the GRP rod will be increased by a decrease in the radius of the GRP rod, and an increase in the average magnitude (and amplitude) of radial shortening. This will enhance the risk of compressive intralaminar damage in the rod during crimping. An increase in the coefficient of friction at the GRP-metal interface will have no influence on the stress state in the rod.
7. The shape of the radial shortening profile will not affect the axial load at the onset of sliding, provided that the average magnitude of radial shortening remains the same. The shape of the shortening profile affects the stress distribution in the GRP rod. However, the maximum values of the biaxial compressive stresses in the rod will not be significantly affected, provided that the amplitude of radial shortening remains constant.

Chemical Analysis of a Field Failed Composite Suspension Insulator

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Abstract

The purpose of this research is to establish the type of corrosive environment responsible for brittle fracture of suspension composite insulators. A series of Fourier transform infrared spectroscopy (FTIR) experiments has been performed to identify chemical functionalities formed during the degradation process of composite insulators affected by brittle fracture. It has been shown that the brittle fracture process is caused by the formation of nitric acid either outside or inside an insulator leading to the stress corrosion cracking of the glass/polymer composite rod material. Nitrate has been detected on the composite fracture surfaces inside a 115 kV suspension composite insulator which failed in service by brittle fracture.

Conclusions

It has been shown in this study that, independent of the presence of environmental pollutants, brittle fracture of suspension composite insulators is caused by nitric acid formed through corona discharge. Nitrate has been identified in a suspension 115 kV insulator inside its brittle fracture zone. Since corona discharges frequently occur in the immediate vicinity of the end fittings of suspension composite insulators oxides of nitrogen and nitric acid are be formed in-service in the presence of ozone and moisture. The acid can also be formed inside an insulator if moisture and internal corona discharges are present.

The Stress Corrosion Experiments on an E-Glass/Epoxy Unidirectional Composite

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Abstract

A series of stress corrosion experiments were performed on a pultruded E-glass/epoxy composite system commonly used in high voltage composite insulators. The tests were performed in nitric acid solutions (pH 1.2) using constant K_I specimens specifically designed for stress corrosion testing of unidirectional fiber-polymer matrix composites. The effect that the magnitude of the applied loads had on the stress corrosion fracture process was investigated. The process was monitored using acoustic emission (AE) techniques. It was found that when the specimens were subjected to static loads (ranging from 71.2 to 124.6 N) in the presence of nitric acid planar cracks formed and propagated perpendicular to the fiber direction without generating a significant degree of fiber debonding or pullout. In addition, for various stress intensity factors at the crack tip both the normal and log-normal distribution functions were accurately used to model the peak amplitude data generated by stress corrosion induced fiber fracture. Both the AE data and mechanical compliance results clearly indicated that the specimens used in this project provided consistent constant K_I conditions over the entire range of loads considered. The results from the tests performed in this project clearly demonstrated that the constant K_I stress corrosion experiments are simple and informative evaluation methods for monitoring stress corrosion cracking in unidirectional composites.

Conclusions

The stress corrosion fracture process in a pultruded E-glass/epoxy composite was investigated using the constant K_I specimen geometry and acoustic emission techniques. It was shown in this research by using both the compliance technique and AE data that this specimen geometry provides a high quality constant K_I region for cracks up to 12 mm in length. The stress corrosion fracture process in the E-glass/epoxy constant K_I specimen was accurately monitored using acoustic emission. Most importantly, the peak amplitude distribution of AE signals generated by fiber fracture were described by the normal (versus dB) and log-normal (versus voltage) distributions. The mean amplitude values of the normal and log-normal distributions from fiber fracture were determined to be linear functions of the applied load and the stress intensity factors at the stress corrosion crack tip.

An Investigation of Brittle Fracture of Composite Insulator Rods in an Acid Environment with Either Static or Cyclic Loading

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Abstract

The effect of static and cyclic loading conditions on the stress corrosion cracking of unidirectional glass reinforced polymer (GRP) rods used in composite high voltage insulators has been investigated. A series of stress corrosion experiments has been performed on unidirectional E-glass/modified polyester composite rods. The rods have been subjected to mechanical tensile static and cyclic stresses in the presence of a nitric acid solution. The stress corrosion fracture process in the rods was monitored using acoustic emission techniques. The experimental loading conditions simulated possible in-service loads for composite suspension insulators. The results obtained in this study showed that the brittle fracture process can be generated in the rods when subjected to relatively low tensile stresses in the presence of a nitric acid solution. The morphology of the experimentally generated brittle fracture cracks in the rods closely resembles those from in-service failed composite suspension insulators. It has also been shown in this research that low frequency, low amplitude vibrations in tensile loads can significantly accelerate the fracture process. It appears that the brittle fracture cracks in the rods generated under cyclic loads are less planar in nature in comparison with the cracks formed under static conditions. It has also been found that the acoustic emission generated during the stress corrosion fracture process in the rods is sensitive to the placement of the transducers. However, a reasonably good correlation between the stress corrosion crack growth rates and acoustic emission has been attained.

Conclusions

Brittle fracture of composite insulator rods can be repeatably obtained in controlled laboratory conditions. Brittle fracture can be generated by either static or cyclic loading in a liquid nitric acid environment. The crack morphology of the brittle fracture damage zones in the rods is distinctly different for static loading and cyclic loading. The difference obtained are due to the fatigue and not due to the stress overload that occurs in fatigue. The main difference in the crack morphology is the size and depth of the first transverse planar crack. The crack is much larger for static loading than it is for cyclic loading. Other minor differences in crack morphology also occur as discussed earlier. The application of acoustic emission for the monitoring of stress corrosion cracking in the rods has been partially successful. Good correlation between the number of acoustic emission signals from the transverse crack propagation process and the size of the planar crack has been shown. However, a precise monitoring of the process by counting individual fibers from acoustic emission signals has not been possible. Moreover, the acoustic emission generated during the brittle fracture process in the composite rods seems to be strongly dependent on the position of the AE transducers.

An Investigation of Mechanical Strength Properties of a Crimped Composite Suspension Insulator

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Abstract

Experimental studies of a suspension composite insulator with crimped end-fittings have been performed. The compression profiles of the insulator for three different magnitudes of crimping have been obtained using a non-destructive pulse echo ultrasonic technique. In the second part of this study, the insulators with low, normal and high crimping deformations have been subjected to the mechanical pull-out tests. It has been shown that the ultrasonic technique can be used to evaluate the shape of the compression profiles as well as the magnitude of crimping for this particular type of a suspension composite insulator. Results obtained from the pull-out tests demonstrate that the magnitude of crimping influences the strength of the insulators when subjected to the tensile loads. Under excessive axial loads the insulators have failed by sliding of the glass reinforced polymer composite (GRP) rods out of the end-fittings. It has been found that the resistance to sliding of the GRP rods within the fittings is proportional to the magnitude of crimping determined by the ultrasonic technique.

Introduction

Composite insulators consist of a unidirectional E-glass reinforced polymer (GRP), with two metal end-fittings attached to the rod during assembly (Fig. 1). In order to prevent electrical degradation of the GRP rod and electrical leakage currents, the entire surface of the GRP rod is protected by a layer of rubber alloy with multiple weathersheds. In previous designs the end-fittings were attached to the GRP rod either by an epoxy adhesive (epoxy cone design) [1] or by metal wedges inserted into the rods inside the fittings (wedge design) [2]. However, due to a lower cost of assembly, all insulator manufacturers have adopted the crimped end-fitting design (Fig.2) [3-6]. In the crimped design, the end-fittings are radially compressed on to the ends of the rod. This results in a purely mechanical bond caused by residual compressive stresses at the interface between the GRP rod and the end-fittings.

Despite the fact that crimping has become the common method of joining the rods to the fittings, severe problems may occur if improper crimping procedures are used during assembly. It has been shown that the surface compression of the GRP rods inside the fittings, caused by crimping, can vary significantly among the insulators [3]. In some insulators, the compression profiles are highly non-uniform in both the axial and tangential directions. Also, the magnitude of radial

compression on the rod surface can be very high, depending the manufacturing process. If the magnitude of surface compression is too high, the GRP rod can be severely crushed during the manufacturing process (see Fig. 3) [3]. This might lead to in-service failures by either rod pull-out or brittle fracture. The effect of damage in the rods on the short and long-term in-service strength properties of crimped composite insulators is not yet known. Undercrimping can significantly reduce the axial strength of an insulator leading to in-service failure by rod pull-out.

The mechanical strength of a composite crimped insulator will depend on the internal stresses in the composite rod. These stresses are a function of the crimping deformations, frictional properties of the rod/hardware interface, rod diameter, geometry of the fittings and the type of external loading. The internal stresses in the GRP rods and the strength properties of crimped composite insulators subjected to axial loads have been studied by Bansal and Kumosa [6]. It has been shown that in suspension insulators (subjected to in-service tensile loads) the biaxial compressive stresses (radial and tangential) in the rods inside the fittings will be increased in the GRP rod as the radius of the rod decreases, and as the average magnitude and amplitude of radial compression increases (Fig. 4). This will enhance the risk of compressive intralaminar damage in the rod during crimping. An increase in the coefficient of friction at the GRP-metal interface will have no influence on the stress state in the rod [3-6]. The increase in the compressive stresses is especially significant in small rods, which is the case of suspension insulators. On the other hand, the resistance to sliding (pull-out failure) can be increased by increasing the rod radius for insulators loaded under axial tension (see Fig. 5) [6]. Small rod insulators will exhibit lower sliding loads than large rod insulators for the same crimping conditions and design. Obviously, the resistance to axial sliding under tension will increase with an increase in the average magnitude of surface compression, and consequently the amplitude of radial compression applied during manufacturing, as well as with an increase in the coefficient of friction at the GRP-metal interface [6].

All the above factors make the manufacturing process of crimped insulators extremely difficult to optimize. Insulator manufacturers would like to keep the strength of suspension crimped insulators as high as possible by applying, in some cases, excessive compressive loads to the fittings during their manufacturing process. This, however, can lead to very high compressive stresses in the rods causing intralaminar damage.

This paper utilizes the techniques developed in references 3,4 and 5 to evaluate the design of crimped end-fittings of substation composite insulators. Substation insulators [3] have a similar design compared to suspension insulators. There are however, two significant differences. One is in the diameter of the GRP rod which is significantly smaller in suspension insulators (16 mm, 0.6 in) than in substation insulators (60 mm, 2.5 in). The other difference is the type of loading applied to the insulators in service. Suspension insulators are subjected to predominantly tensile loads with possible small bending and torsional loads, whereas substation insulators work mainly under axial compression, bending and torsion.

Since the small rod suspension crimped insulators are much more susceptible to the rod crushing during manufacturing and the rod pull-out failures in service than substation insulators, the understanding of the effect of different crimping technologies on the long and short term strength properties of crimped suspension insulators is especially important. In this study, one type of suspension composite insulator with crimped end-fittings was investigated. Three sets of the insulators with low, normal, and high crimping deformations (as specified by the manufacturer)

were evaluated. The crimping deformations of the GRP rods inside the fittings were evaluated for different magnitudes of crimping and subsequently correlated with the mechanical strength results of the insulators obtained from the mechanical pull-out tests.

Examined Composite Insulators

The crimped insulators examined in this project had the SML rating of 15,000 lbs. Before submitting the insulators for the mechanical analysis, the manufacturer had specified the following crimping conditions on the insulators:

1. High crimping deformations (approximately 20% above normal)
2. Normal crimping deformations
3. Low crimping deformations (approximately 20% below normal).

The name of the manufacturer and the exact design of the insulators will be treated in this paper as proprietary information.

Analysis of Crimping Deformations

A manual contact pulse-echo ultrasonic technique [3-6] was used to determine the extent of radial compression exerted on the GRP rods of three insulators with low (sample #6), normal (sample # 1) and high crimping (sample #8) (as specified by the manufacturer).

Before measuring the internal compression the external surfaces of the fittings were machined off in order to remove the surface marks generated during the crimping process. The external surfaces of the end-fittings were discretized into 16 lines in the circumferential direction (ϕ) and 6 lines in the axial direction (z). This created a grid with 96 data points. The distance between the points was 0.2 inch (approximately 5 mm).

An ultrasonic transducer (Parametric 26DL plus, Dual Element Transducer, 10MHz) with a diameter of 5 mm was acoustically coupled to each of the 96 grid points, and the interface depth x , was measured. The internal radius of the compressed rods was measured as [3-5]

$$r_{in} = r_{ef} - x \quad (1)$$

where r_{ef} is the measured external radius of the end fitting. r_{ef} was measured mechanically. From the outer radius of the uncompressed GRP rod, r_{out} , the extent of radial compression, u , of the rods was determined from

$$u = r_{out} - r_{in} \quad (2)$$

Figures 6a, 7a and 8a present the three-dimensional compression profile for the insulators with the low, normal and high crimping deformations generated during manufacturing. Points A, C and F indicate the position in the beginning, middle and the end of the fitting, respectively. In Fig. 6b, 7b and 8b the two dimensional profiles are shown for sections A (beginning), C (middle)

and F (end). It can be seen in Figures 6, 7 and 8 that the compression profiles of the rod surface inside the fittings are not uniform. There are six maxima and minima along the circumference, along any particular length in the z direction. The maximum values of the compression on the surface of the rod inside the fitting of the insulators with low, normal and high crimping deformations are approximately 0.3 mm, 0.4 mm, and 0.65 mm, respectively. It is also evident that at any particular angle ϕ , along the circumference the magnitude of compression is more or less uniform.

The magnitude of crimping (M) for each insulator was subsequently estimated using the compression test data from the ultrasonic analysis. The magnitude of crimping is defined as the average compression on the rod surface inside the fitting. The following average magnitudes of crimping were determined:

1. High crimping deformations (sample #8) $M = 0.1437$ mm
2. Normal crimping deformations (sample #1) $M = 0.1209$ mm
3. Low crimping deformations (sample # 6) $M = 0.0803$ mm.

Mechanical Testing

Nine mechanical pull-out tests were performed on the insulators with the normal, low and high crimping deformations. Three insulators from each group were tested. The insulators were tested in a standard MTS-880 deformation machine. The samples were deformed in stroke control at a rate of 0.254 mm/min. The acoustic emission generated during deformation was also monitored using a resonant (150 kHz) transducer placed near the end where pull-out was expected. A 40 dB preamplifier was used in our experiments.

The deformation machine used in this investigation has been significantly modified for use in acoustic emission measurements. The modifications include: (1) The hydraulic pump and the motor which drives it are located in a separate room some 15-10 feet from the test stand. The room has been sound proofed with acoustic tile to minimize any acoustic emissions from the hydraulic pump. (2) The servo valves which control the flow of hydraulic fluid have been disconnected from the main test frame and have been connected to the test frame by high pressure hoses. The servo valves are located approximately 5 feet from the test frame. Noise from the servo valves are damped out by the rubber hoses before it reaches the test frame. (3) Hydraulic grips are used to grip the sample for the application of loads. The grips are loaded to the appropriate pressure and can then be valved off so that the pump does not have to keep working to maintain the grip pressure. This eliminates noise from the grips. (4) The test frame, its control panel, and all of the AE equipment are attached to a real ground (copper rod driven ten feet into the earth). This eliminates any stray electromagnetic radiation spikes which could be misinterpreted.

The load versus displacement diagrams, as well as the acoustic emission data for the two sets of insulators with different magnitudes of crimping subjected to the pull-out tests, are shown in Figures 9a, 9b and 9c, respectively. An examination of these figures shows that the load/displacement curves exhibit very similar features for all of the insulators tested. They start out with a linear region, bend slightly, come to a maximum and continue to maintain a

significant load for a long period of time. All insulators subjected to the pull-out test failed by the rods simply pulling out of the fittings. The maximum loads coincided with the visible sliding of the GRP rods out of the fittings. Figure 10 shows the scatter in the maximum load for the six tests run. It can be seen in Figure 10 that the insulators with the high crimping conditions exhibit the highest loads whereas the insulators with the low crimping deformations started pulling out of the fittings at the loads lower than the insulators with the high and normal crimping conditions.

Acoustic emission generated during the deformation of the insulators was also measured and found to be significantly dependent on the crimping conditions (see Figures 9a,9b and 9c). The onset of acoustic emission corresponded to the onset of nonlinearity of the load/displacement diagrams (very close to the maximum load) and appeared to be almost the same for all the insulators investigated. However, the rate of emission and the total number of events were significantly different for each crimping condition. The highest rates of emission and with the largest total number of acoustic emission events were recorded for the insulators with the high crimping magnitudes. Since the onset of sliding of the rods within the fittings must generate a significant number of acoustic emission signals due to the friction between the rod and the fitting it is not surprising that the start of AE coincides so well with the onset of sliding and the maximum loads. The friction coefficient in the examined insulators was found to be very high.

Discussion

It can be seen from the results of the average crimping magnitudes and the specifications of the manufacturer that the ultrasonic method quite accurately determined the crimping conditions in the insulators examined. The average magnitude of crimping, from the ultrasonic measurements, of the insulator with high crimping is approximately 18.8% higher than the magnitude of the normal crimping deformations. The insulator with low crimping (20% below normal) has the average magnitude of crimping deformation 33% below the normal crimping condition.

The above results clearly demonstrate that the ultrasonic technique can be a useful and relatively simple tool for evaluating surface deformations of insulators with crimped end-fittings. The only problem is that the method is extremely sensitive to the quality of surface machining of the fittings. Since the surfaces of the fittings have to be machined off in order to remove the surface marks caused by crimping, significant problems can occur relating to the potential misalignment of the surface of the machined end-fittings with respect to the rod surface outside the fitting. This problem can be quite severe if the fittings are made of hard materials (such as steel or cast iron). During machining the rod is clamped and the surfaces of the fitting is machined off. This can cause severe bending of the GRP rod leading to a significant misalignment of the fitting surface with respect to the rod axis. If the misalignment is high an experimental error related to surface compression (using equations 1 and 2) can also be quite high, in some cases even higher than the magnitude of crimping especially in insulators with relatively small crimping deformations.

The resistance to sliding of the GRP rods out of the fittings in the insulators with crimped end-fittings depends on the magnitude of crimping [5,6]. There are also other factors significantly affecting the strength of the insulators such as the friction coefficients at the rod/metal interface and the length of the fitting. Since all of the insulators examined in this study have the same friction coefficient and the length of fittings, only the magnitude of compression should affect the mechanical response of the insulators to the tensile loads in the pull-out experiments. Thus,

the average compression determined by the ultrasonic technique should be proportional to the maximum load from the pull-out tests. The following maximum loads were determined from the mechanical tests (see Fig. 10):

1. Low crimping deformations (three specimens) 14,383 lbs (64 kN), 13,771 lbs (61.3 kN) and 13,306 lbs (59.2 kN) with the average max. load 13,820 lbs (61.5 kN).
2. Normal crimping conditions (three specimens) 15,485 lbs (68.9 kN), 15,990 lbs (71.15 kN) and 14,734 lbs (65.56 kN) with the average max. load 15,403 lbs (68.54 kN).
3. High crimping conditions (three specimens) 16,851 lbs (74.98 kN), 16,404 lbs (73.0 kN) and 16,042 lbs (71.39 kN) with the average max. load 16,432 lbs (73.12 kN).

It should be mentioned here that the loads at sliding might be affected by the machining of the end-fittings prior to the ultrasonic measurements. The lowest loads at sliding for each crimping condition were determined for the insulators subjected to the ultrasonic tests (59.2 kN, 65.56 kN and 71.39 kN for the low, normal and high crimping conditions respectively). Most likely the machining of the surface of the fitting relieved some stresses in the fitting generated during crimping and thus reduced the pull-out strength of the insulators. However, for the insulators examined in this study the reduction in the tensile strength of the insulators due to the surface machining is relatively slow.

The average maximum load for the insulators with the normal crimping conditions can be taken as the reference point and compare with the other average maximum loads for the insulators with the low and high crimping deformations as a function of the average magnitudes of crimping. It can be noticed that the average maximum load for the insulators with normal crimping is approximately 10% higher than the average maximum load for the insulators with low crimping. The average maximum load for the insulators with high crimping is approximately 6.6% higher than the maximum load for the insulators with normal crimping. The maximum loads obtained from the pull-out experiments are a linear function of the magnitude of compression generated during manufacturing (see Figure 11). Similar relation has been found between the maximum loads, from the push-out experiments of substation insulators, and the magnitude of compression [6]. The linear behavior of the loads at sliding as a function of crimping has also been numerically simulated, using finite elements, in both substation and suspension composite insulators [6,7]. There is, however, a strong effect of the friction coefficient at the rod/metal interface, which determines the slope of the max. load/magnitude of compression curve [6,7]. Since the insulators examined in this project had the same friction coefficient (identical design) this effect can be neglected in the analysis.

The linear relation between the loads at sliding and crimping can be used to determine the magnitude of crimping of a composite insulator with the crimped end-fittings from the mechanical pull-out tests providing that the exact design of the insulator is known, and in particular, the friction coefficient at the rod/fitting interface is established. However, it can be expected that if the rod is significantly crushed by excessive crimping deformations generated during manufacturing the linear proportionality between the loads at sliding and the magnitude of crimping will be lost.

It can be seen from Figures 9a, 9b and 9c that the onset of sliding of the rods inside the fittings can be monitored by acoustic emission. The onset of non-linearity in the load/displacement diagrams, just before the maximum loads, corresponds to the onset of acoustic emission. Moreover, the total number of events recorded during the pull-out tests also correspond to the magnitude of crimping. The highest number of acoustic emission events was recorded for the insulators with high crimping, whereas the insulators with low crimping exhibited the lowest number of events during the tests. This is not surprising since acoustic emission generated during the tests was most likely caused by the frictional effects at the rod/hardware interface. Since the magnitude of crimping is proportional to the normal forces at this interface, the insulators with high crimping generated more signals than both the insulators with normal and low crimping.

Conclusions

A manual contact pulse-echo ultrasonic technique has been used to evaluate the compression profiles in one type of crimped suspension composite insulators. It has been shown that the ultrasonic method can be successfully used to determine the shape and the magnitude of radial compression on the rod surface inside the crimped end fitting. The results from the mechanical pull-out tests clearly demonstrate that the magnitude of compression, determined using the ultrasonic technique, corresponds to the tensile strength of the insulators. There is a linear relationship between the maximum loads and the magnitude of compression generated during manufacturing.

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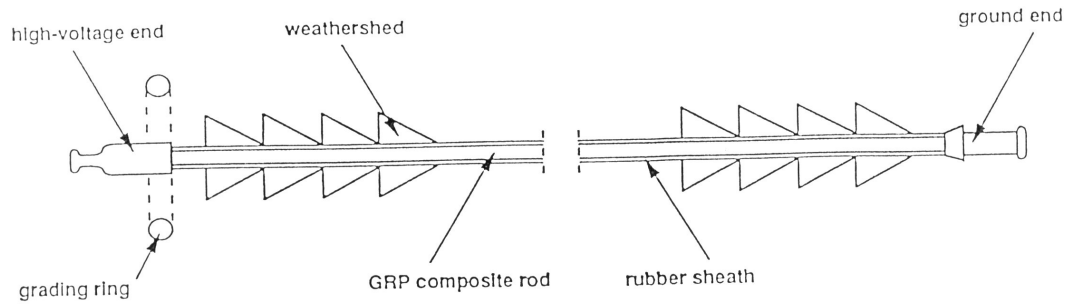


Figure 1: Composite suspension insulator

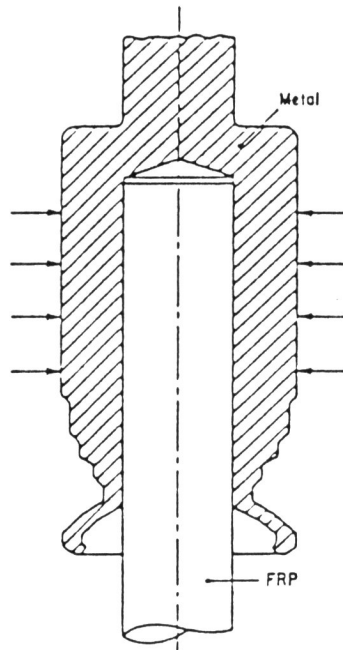


Figure 2: Crimped composite end-fitting

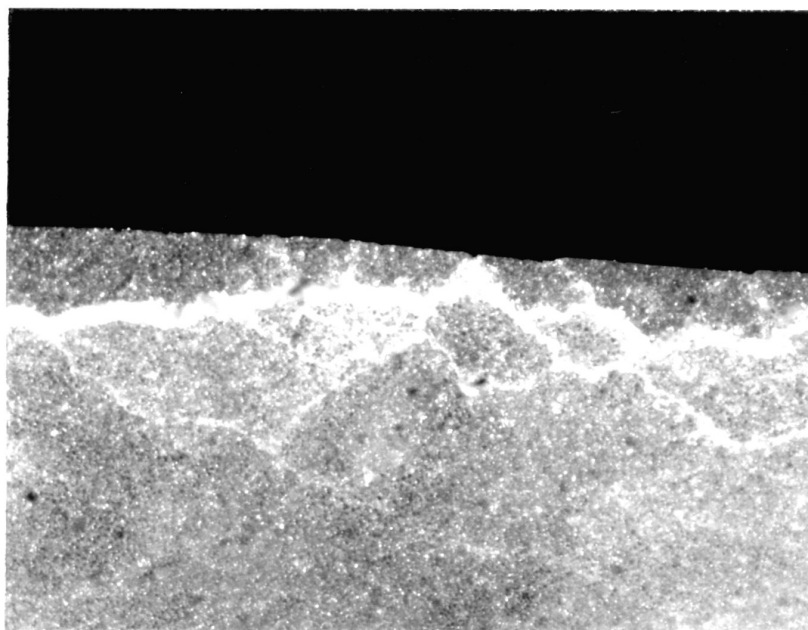


Figure 3: Network of circumferential cracks in GRP rod caused by improper crimping detected in a suspension composite insulator

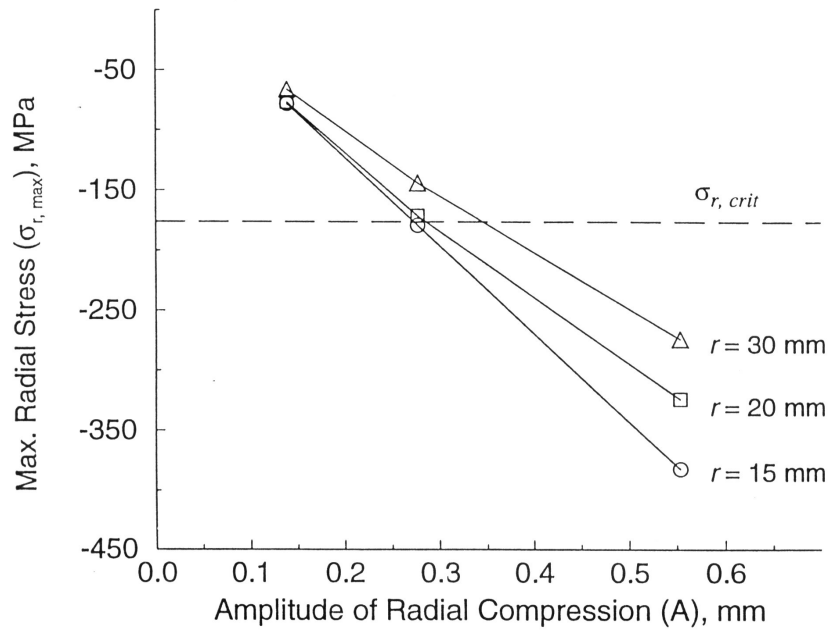


Figure 4a: Relationship between applied amplitude of radial compression and maximum stresses on the surface of the GRP rod; maximum radial stress

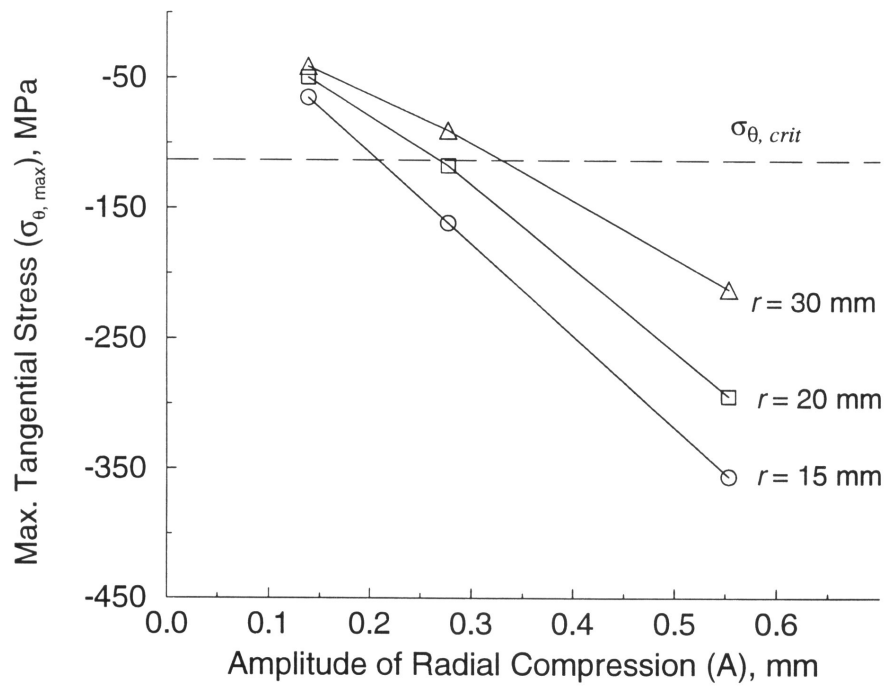


Figure 4b: Relationship between applied amplitude of radial compression and maximum stresses on the surface of the GRP rod; maximum tangential stress

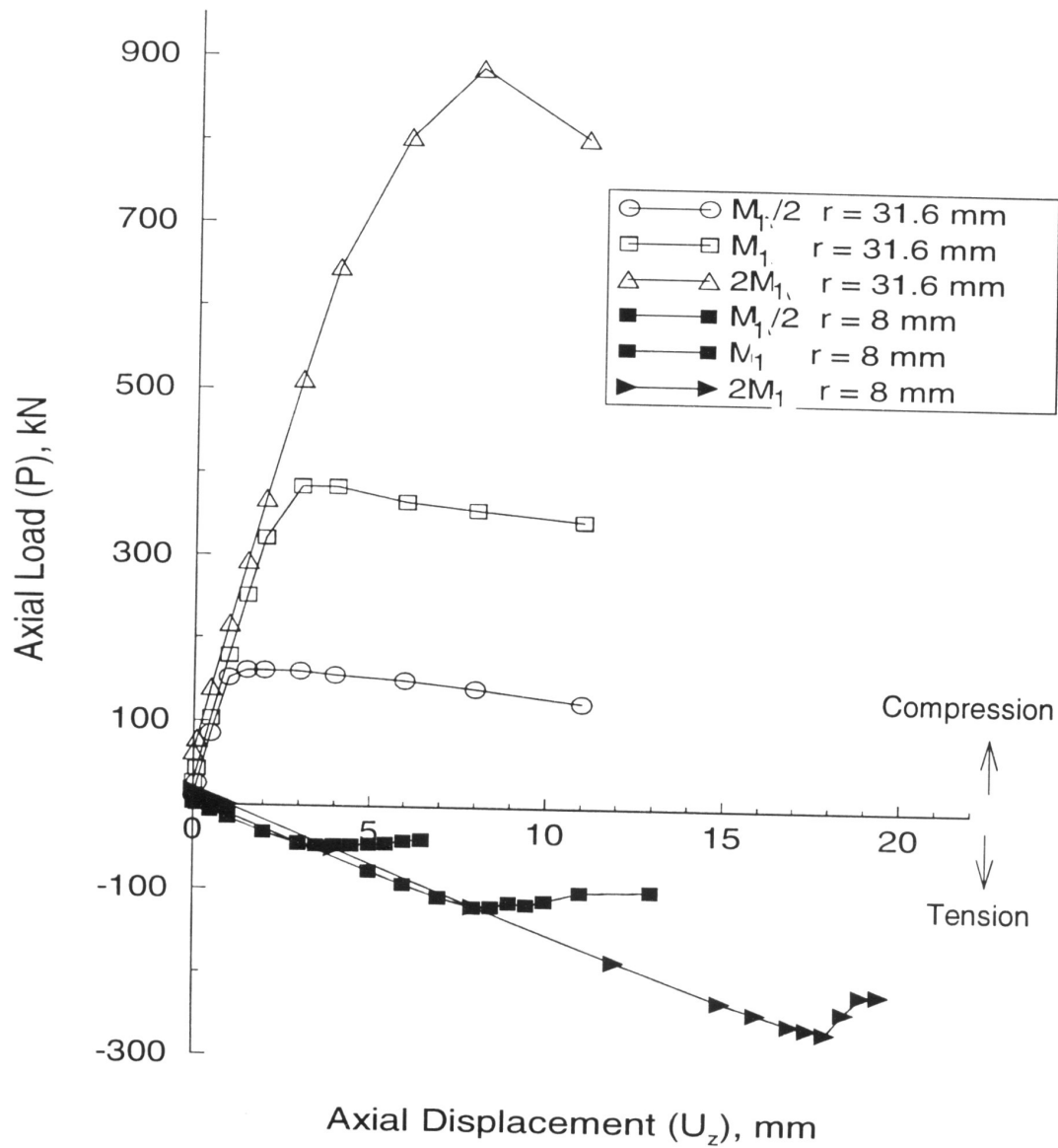


Figure 5: Numerical load/displacement diagrams for crimped composite insulators subjected to axial tension (pull-out) and axial compression (push-out) with two rod diameters (16 mm and 62.2 mm) and three different magnitudes of crimping

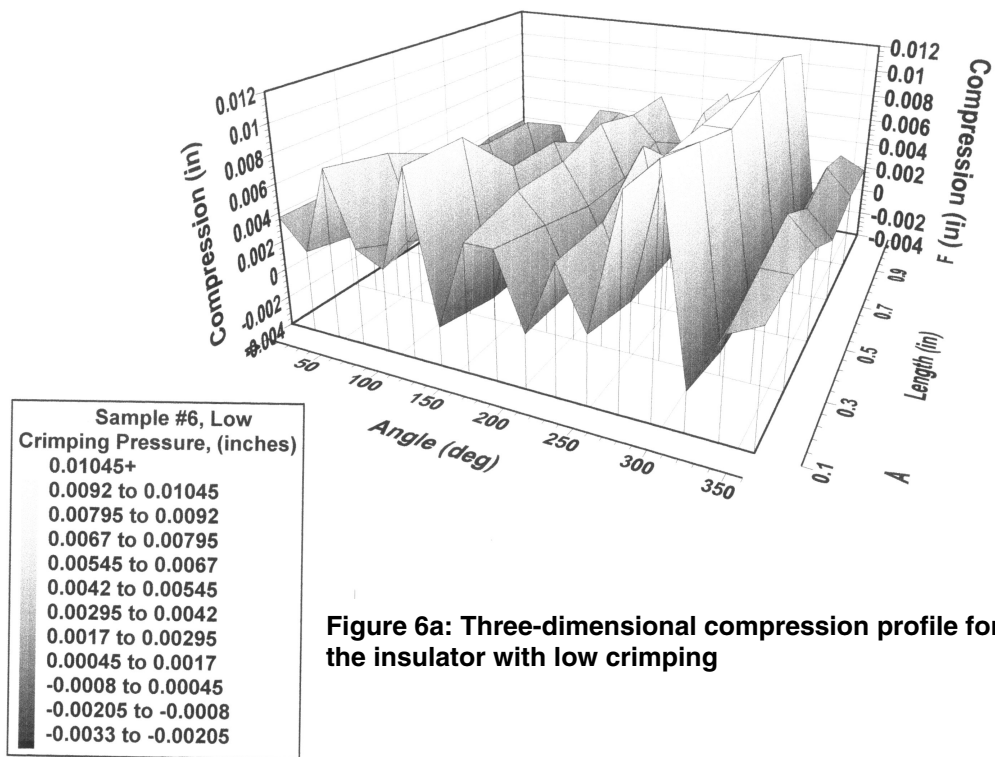


Figure 6a: Three-dimensional compression profile for the insulator with low crimping

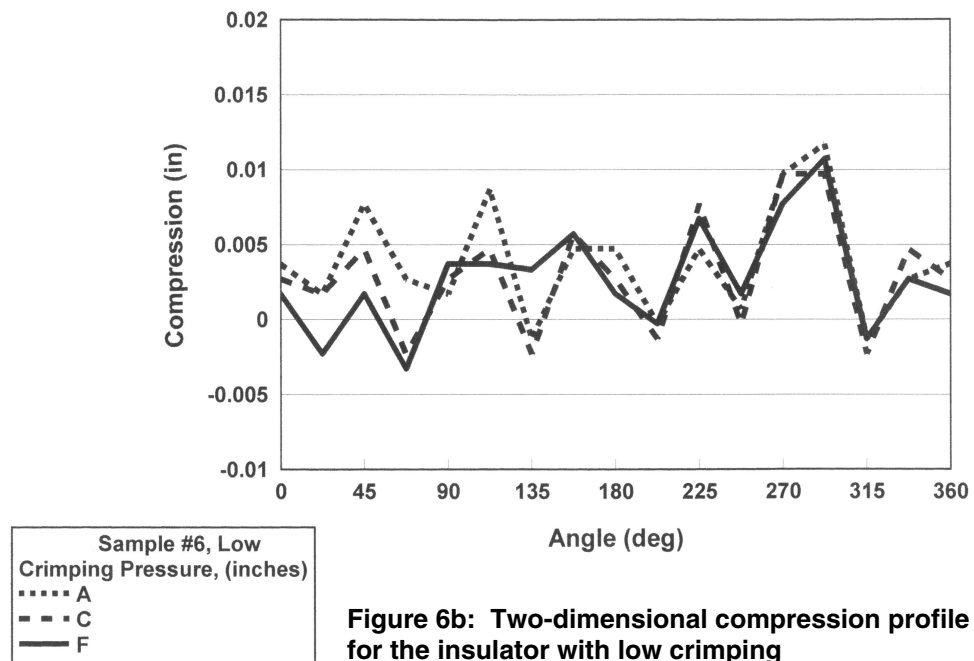


Figure 6b: Two-dimensional compression profile for the insulator with low crimping

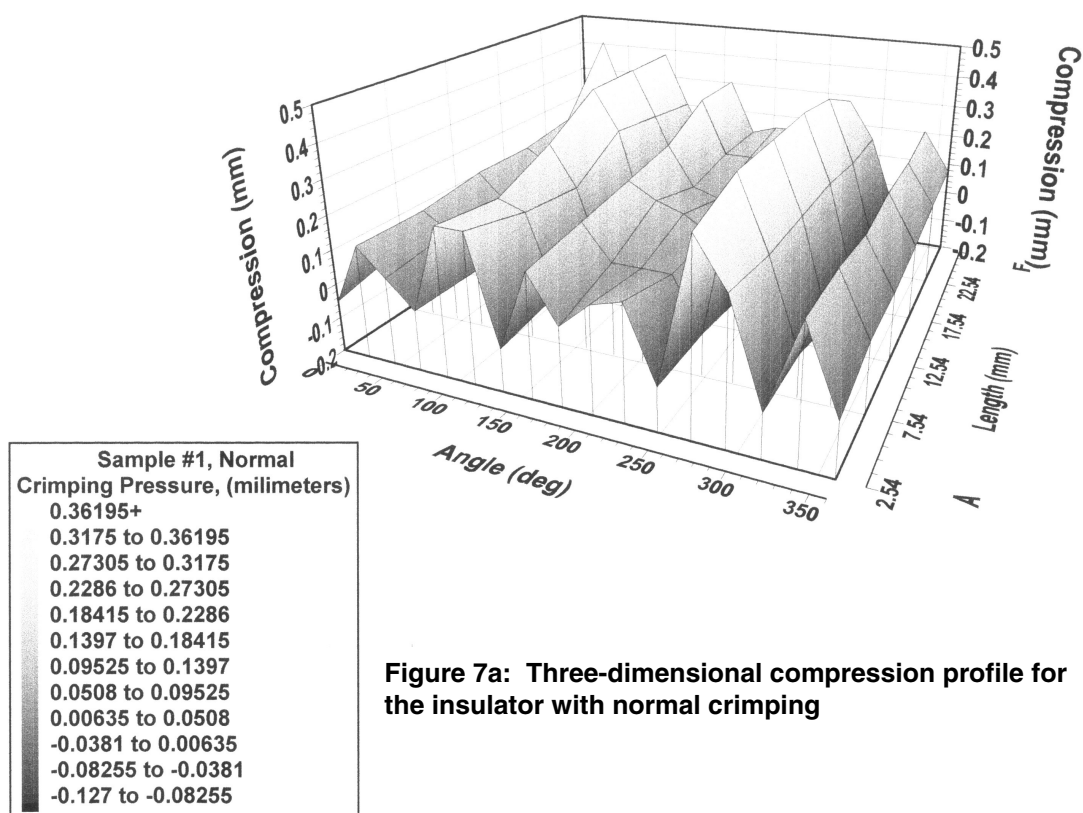


Figure 7a: Three-dimensional compression profile for the insulator with normal crimping

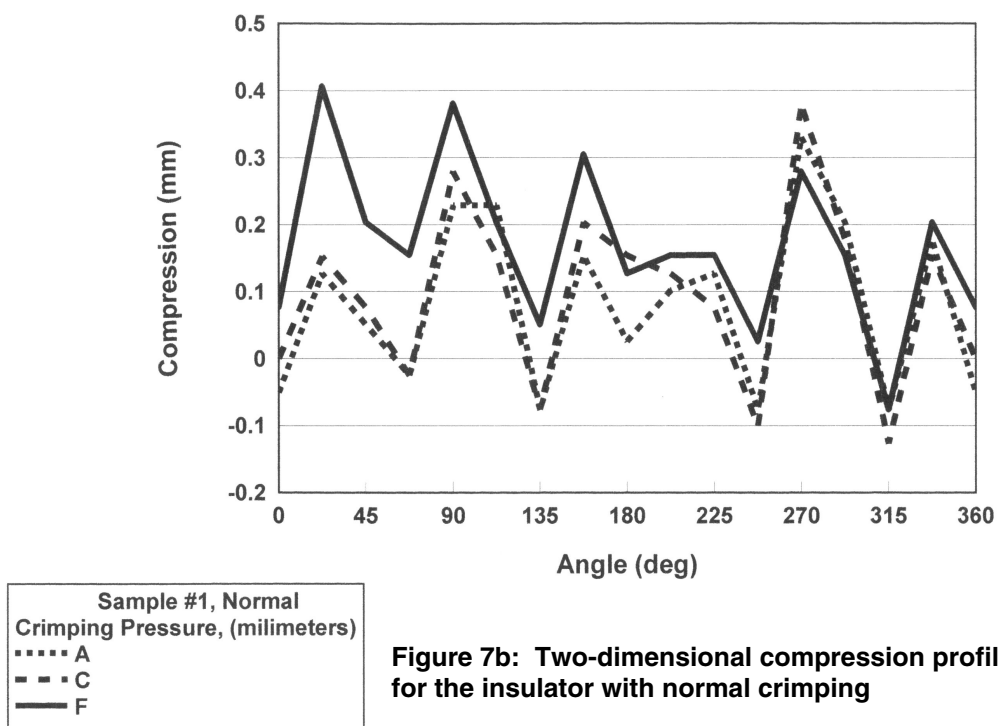


Figure 7b: Two-dimensional compression profile for the insulator with normal crimping

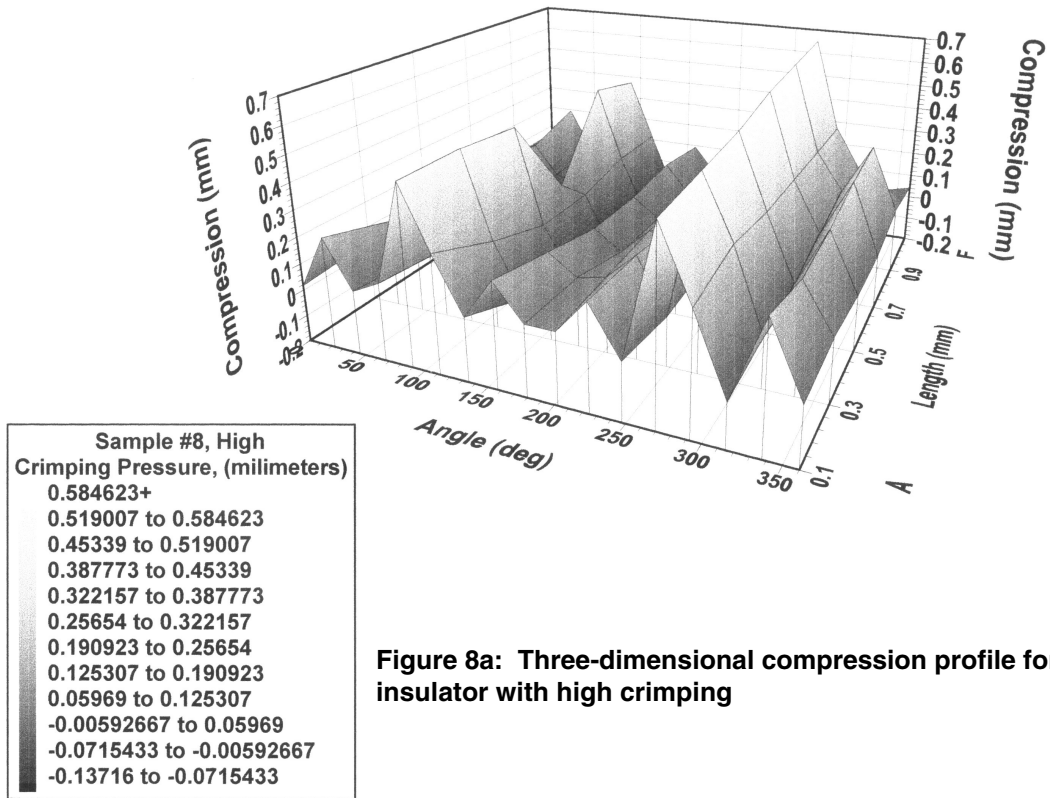


Figure 8a: Three-dimensional compression profile for the insulator with high crimping

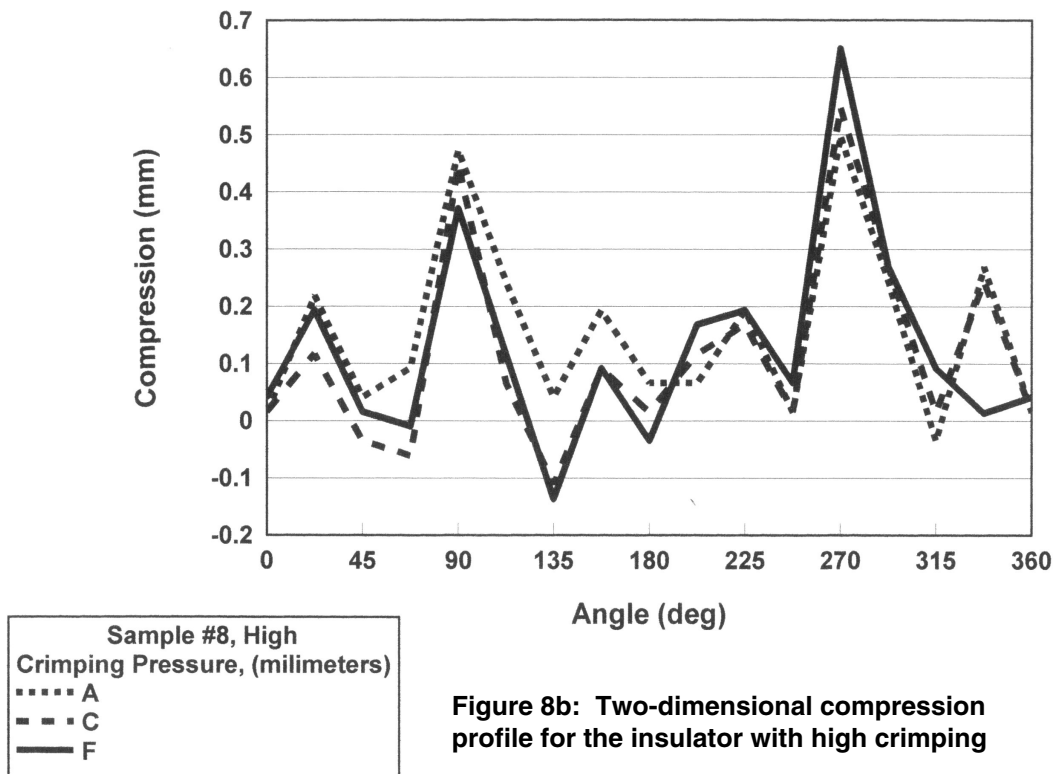


Figure 8b: Two-dimensional compression profile for the insulator with high crimping

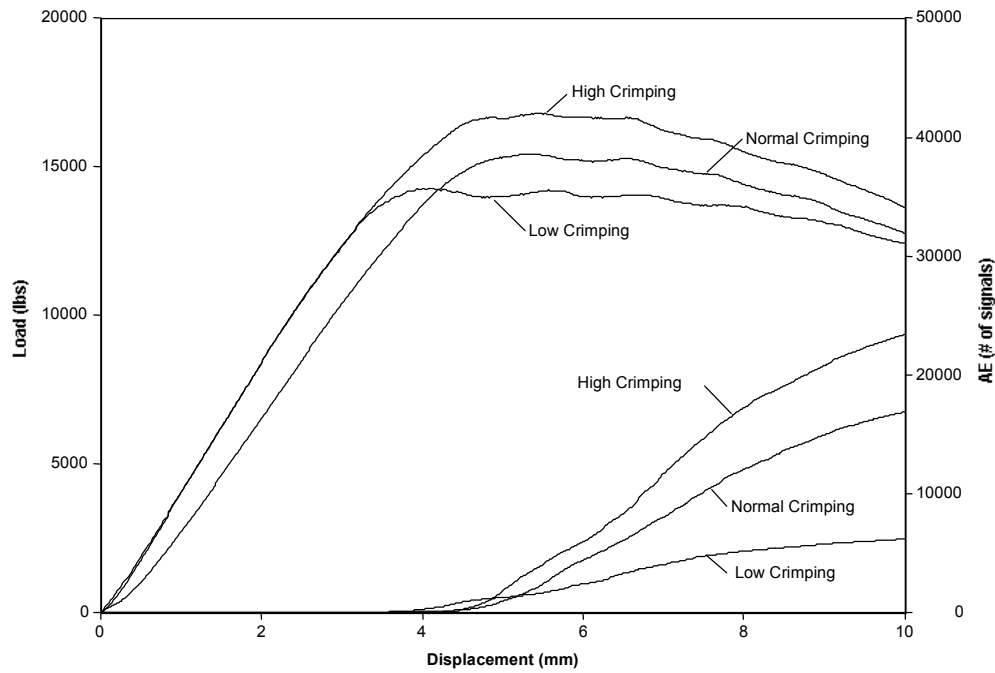


Figure 9a: Load/displacement diagram and acoustic emission for the insulators with low, normal and high crimping deformations; first set.

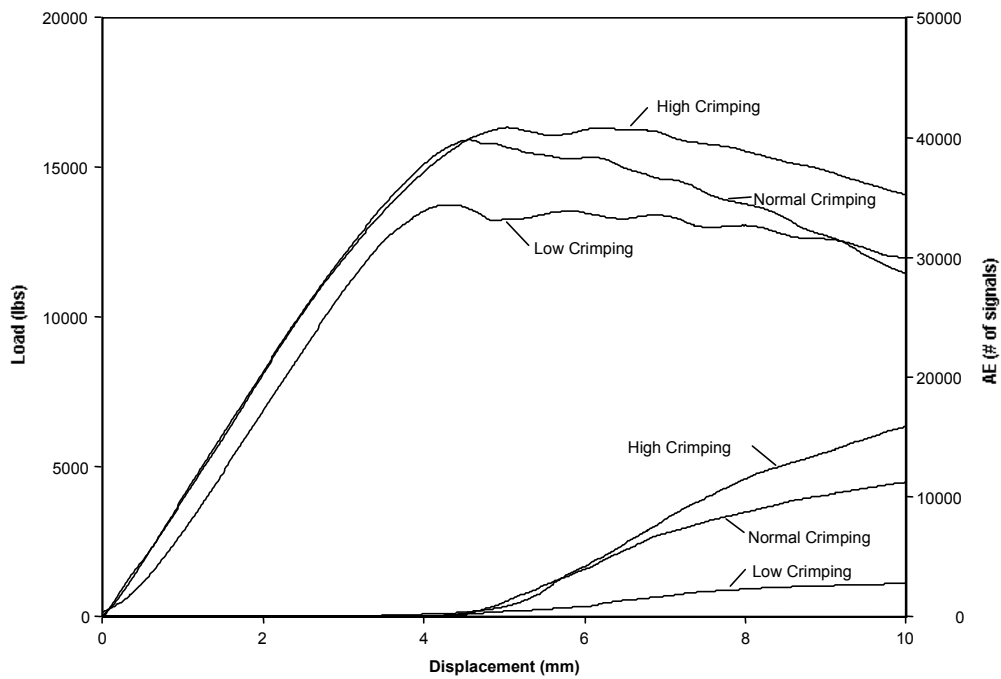


Figure 9b: Load/displacement diagram and acoustic emission for the insulators with low, normal and high crimping deformations; second set

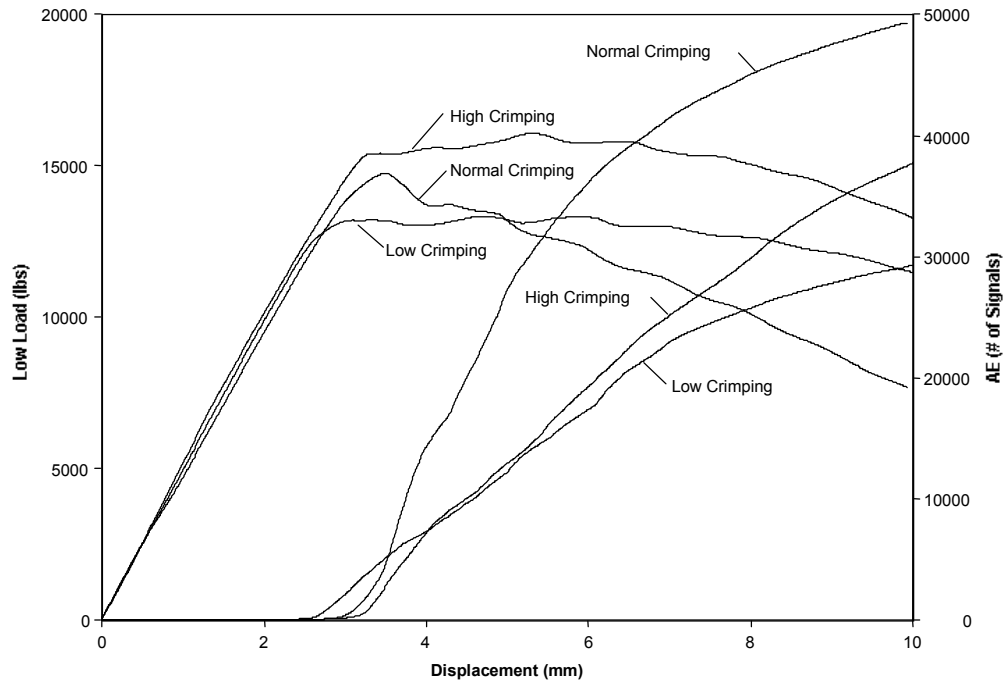


Figure 9c: Load/displacement diagram and acoustic emission for the insulators with low, normal and high crimping deformations; third set.

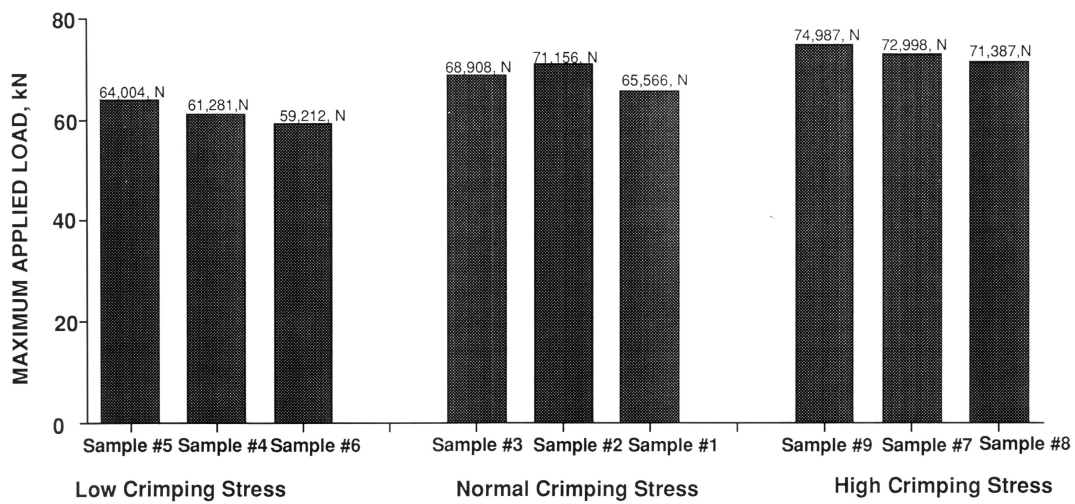


Figure 10: Maximum loads obtained from the pull-out experiments

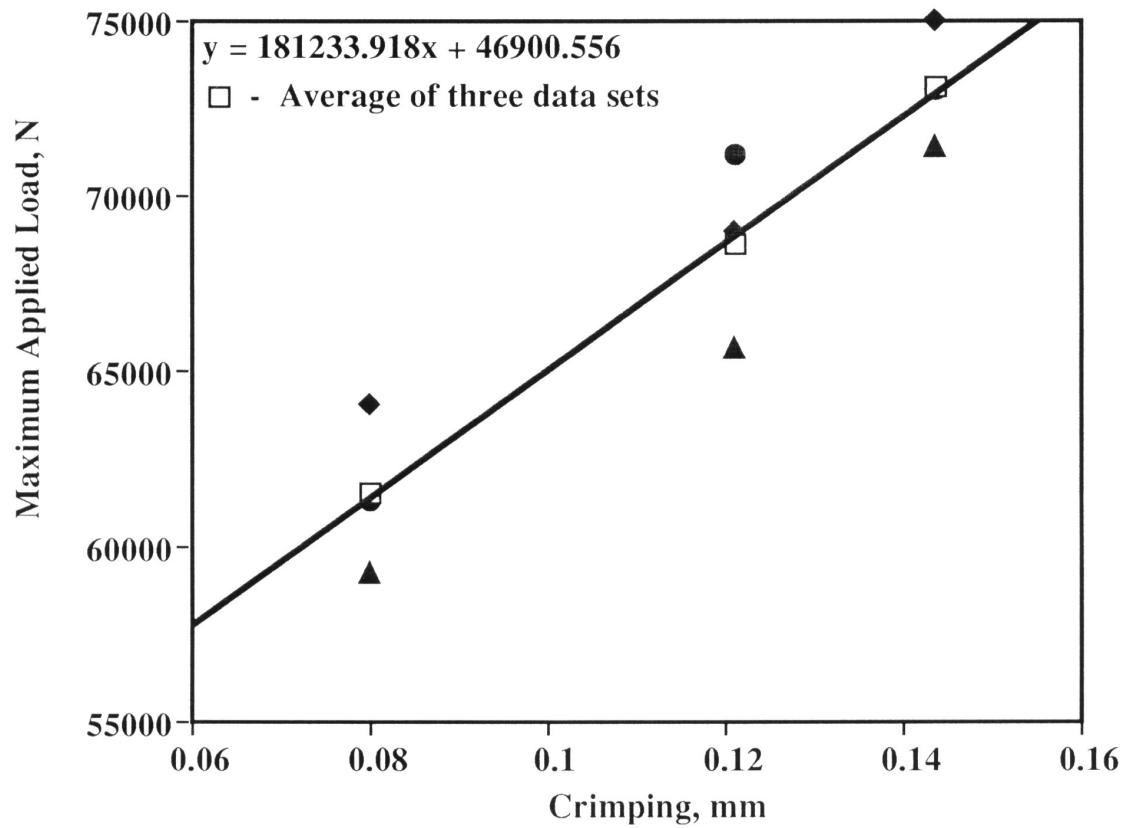


Figure11: Relationship between the maximum load from the pull-out tests and the magnitude of the radial compression for the insulators examined

B

COMPLETE LIST OF PUBLICATIONS, DISSERTATIONS AND MAJOR REPORTS BASED ON THE EPRI PROJECT

Publications:

1. A. Bansal, A. Schubert, M. V. Balakrishnan and M. Kumosa, Finite Element Analysis of Composite Substation Insulators, Composite Science and Technology, Vol. 55 (1995) pp. 375-389.
2. M. Kumosa, Mechanical Aspects of Non-Ceramic Insulators, Symposium on Non-Ceramic Insulator Technology (Worldwide Experience & Technology), June 12-14, 1996, Singapore.
3. M. Kumosa, H. Shankara Narayan, Q. Qiu and A. Bansal, Brittle Fracture of Non-Ceramic Suspension Insulators with Epoxy Cone End-Fittings, Composites Science and Technology, Vol. 57 (1997) pp. 739-751.
4. Q. Qiu and M. Kumosa, Corrosion of E-Glass Fibers in Acidic Environments, Composites Science and Technology, Vol. 57 (1997) pp. 497-507.
5. A. Bansal and M. Kumosa, Mechanical Evaluation of Axially Loaded Composite Insulators with Crimped End-Fittings, J. Composite Materials, Vol. 31 (1997) pp. 2074 - 2104.
6. Interview with Maciej Kumosa of the University of Denver, Research of Brittle Fractures in Composite Insulators, Insulator News & Market Report, (July/August 1997) pp. 46-51
7. A. Chughtai, D. Smith and M. Kumosa, Chemical Analysis of a Failed Composite Suspension Insulator, Composites Science and Technology, Vol. 58 (1998) pp. 1641-1647.
8. T. Ely and M. Kumosa, The Stress Corrosion Experiments on an E-Glass/Epoxy Unidirectional Composite, Journal of Composite Materials, Vol. 34, No. 10 (2000) pp. 841-878.
9. S. H. Carpenter and M. Kumosa, An Investigation of Brittle Fracture of Composite Insulator Rods in an Acid Environment with Either Static or Cyclic Loading, J. Materials Science, Vol. 35, Issue 17 (2000) pp. 4465-4476.

Dissertations:

1. Q. Qiu, Brittle Fracture Mechanisms of Glass-Fiber Reinforced Polymer Insulators, Ph.D. Thesis, Oregon Graduate Institute of Science & Technology, October 1995.
2. A. Bansal, Finite Element Simulation and Mechanical Characterization of Composite Insulators, Ph.D. Thesis, Oregon Graduate Institute of Science & Technology, January 1996.
3. M. V. Balakrishnan, Application of the Biaxial Test Fixture for the Mechanical Characterization of Unidirectional Composites, MS Thesis, Oregon Graduate Institute of Science & Technology, September 1995.
4. Y. Zhao, An Electrical Study of the Brittle Fracture Failure of Composite Insulators, MS Thesis, Department of Engineering, University of Denver, Denver, November 1997.
5. Y. Han, Finite Element Analyses of Advanced Composite Structures, MS Thesis, Department of Engineering, University of Denver, Denver, November 1997.

Major Reports:

1. M. Kumosa et al., Fracture Analysis of Composite Insulators, Annual Progress Report to EPRI, Oregon Graduate Institute of Science & Technology, July 1995.
2. M. Kumosa et al., Fracture Analysis of Composite Insulators, Annual Progress Report to EPRI, Oregon Graduate Institute of Science & Technology, July 1996.
3. M. Kumosa et al., Fracture Analysis of Composite Insulators, Annual Progress Report, University of Denver, July 1997.
4. M. Kumosa, S. H. Carpenter and D. Armentrout, An Investigation of Mechanical Strength Properties of a Crimped Composite Suspension Insulator, Composites Science and Technology (October 1997) in press.
5. D. L. Armentrout, S. H. Carpenter and M. Kumosa, Stress Corrosion Experiments in Flat Composite Coupons, Internal Report, 1998 (in preparation for publication).
6. M. Kumosa et al., Fracture Analysis of Composite Insulators, Final Report to EPRI, Department of Engineering, University of Denver, Denver, Colorado, February 1998.

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