Structural Integrity and Durability of High Voltage Composite (Non-Ceramic) Insulators

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Abstract: This paper deals with the structural integrity and durability of suspension composite (non-ceramic, polymer) insulators widely used in power transmission systems around the world. Under certain conditions, the insulators can fail in-service both electrically and mechanically resulting in the drop of energized transmission lines and power outages. In this work, predominantly mechanical failures of the insulators are discussed. In particular, the most important characteristics of a catastrophic failure process called brittle fracture are described. Subsequently, two examples of insulator failures by brittle fracture are shown and their causes explained. Finally, several recommendations on how to avoid brittle fracture as well as other mechanical and electrical failures of the insulators are presented.

Keyword: Composite (non-ceramic, polymer, polymeric) insulators, damage mechanisms, brittle fracture, structural integrity, durability, failure prevention.

1 Introduction

Composite suspension insulators (also referred to as either non-ceramic, polymer or polymeric insulators) are used worldwide in overhead transmission line applications with line voltages in the range of 69 kV to 735 kV. The first composite insulator was developed in the US by General Electric in the 50s. Then, over the years, the technology has been developed predominantly in Europe and in the US into the second and third generation of insulators supporting, in some cases, the most critical transmission lines in many places of the world. Despite the fact that this technology has been dramatically improved, the insulators have been sporadically failing in service, dropping energized transmission lines and causing line outages at various utilities [Owen, Harris, Noble (1986), Akhtar, Nadeau, Wang, Romily, and Taggart (1986), Kumosa, Shankara Narayan, Qiu, Bansal (1997), Burnham et al. (2002), Gubanski (2005), Kumosa, Kumosa, Armentrout (2005a), Liang and Dai (2006)].

The design of composite suspension insulators is rather straightforward. The insulators rely on unidirectional glass reinforced polymer (GRP) composite rods as the principle load-bearing component (see Fig. 1). The rods, usually 15 mm in diameter, are manufactured by pultrusion and the constituents are either polyester, vinyl ester, or epoxy resins reinforced with either E-glass or ECR-glass (also called boron-free E-glass) fibers. The surface of the GRP rod is covered with a rubber housing material with multiple weathersheds. The purpose of the housing is to protect the GRP rods against outside environments (predominantly moisture, pollution and corona discharges). The primary purpose of the weathersheds is to increase the leakage distance between the energized and ground ends of the insulators. Today, common housing materials are ethylene-propylene rubbers, different types of silicon rubbers and ethylene vinyl acetate-based elastomers [Gubanski (2005)]. Other composite insulators such as substation or line post insulators are based on the same design. However, they rely on large GRP rods up to 50 mm in diameter.

There are two metal end fittings attached to the GRP rods at both ends of the insulators. In modern composite insulators the fittings are usually attached to the rod by crimping [see for example: Bansal and Kumosa (1997), Kumosa, Han and Kumosa (2002), Kumosa, Armentrout, Kumosa,

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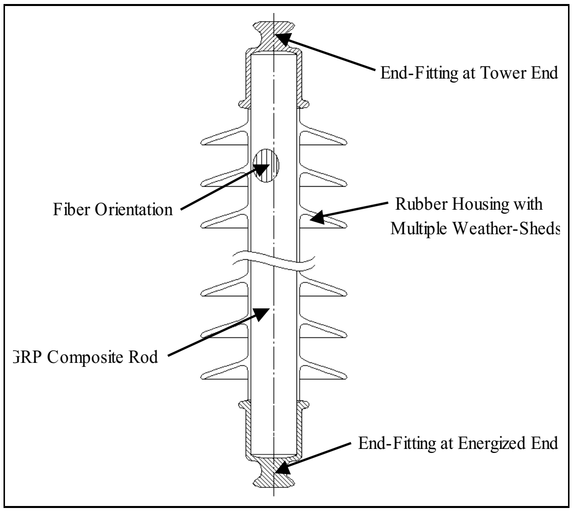

Figure 1: Schematic of a composite suspension insulator

Han and Carpenter (2002), Duriatti, Beakou and Levillain (2006), Prenleloup, Gmur, Botsis and Papaillou (2006)]. In the past, other joining techniques have been used. In some cases, metal wedges were inserted into the GRP rods creating a wedge type mechanical connection [Kumosa and Qiu (1996)]. Certain manufacturers have also glued the fittings to the rods with a liquid epoxy (the epoxy cone design [Kumosa, Shankara Narayan, Qiu and Bansal (1997)]. This design and potential problems with its application in-service will be further discussed in Section 3.2.1 of this work. Another characteristic feature of the insulators is the presence of grading rings near their end fittings. The grading rings are almost always placed near the energized ends (attached to transmission lines) on lines 100kV and higher. On lines 500 kV and higher, the rings are also placed near the ground end fittings. The purpose of the grading rings is to reduce electric field concentrations near the end fittings. This prevents corona discharges under dry conditions and internal discharges under wet conditions. The rings also prevent (or at least significantly reduce) aging of the rubber housing materials due to moisture, contamination and coronas [Gubanski (2005)]. A grading ring near the energized end fitting of a 500 kV insulator is shown in Fig. 2b as an example.

In spite of many benefits, which the insulators can offer in comparison with their porcelain counterparts (high mechanical strength-to-weight ratio, improved damage tolerance, flexibility, good impact resistance, ease of installation, improved resistance to vandalism, improved contamination performance, etc.), they can fail in service both electrically and mechanically. The most important mechanical failure modes of the insulators are electro-mechanical failures by a process called by the electric community as "brittle fracture", as shown in Fig. 2 [Akhtar, Nadeau, Wang, Romily, and Taggart (1986), Kumosa, Shankara Narayan, Qiu, Bansal (1997), Burnham et al. (2002), Gubanski (2005), Kumosa, Kumosa, Armentrout (2005a), Liang and Dai (2006)], purely mechanical rod fracture [Kumosa, Han and Kumosa (2002)], and mechanical failures of the end fitting attachments. Regarding purely electrical in-service failures, they include contamination flashovers and the failures of the rods due to internal discharges, between other less common failure modes [Gubanski (2005), Kumosa, Kumosa and Armentrout (2005a)]. In this paper we will concentrate predominantly on mechanical failures of suspension insulators caused either by brittle fracture or by simple rod fractures due to mechanical overloading either during manufacturing or in-service.

2 Characteristic Features of Brittle Fracture

Brittle fractures of composite suspension insulators are caused by the stress corrosion cracking (SCC) [see for example Hull, Kumosa and Price (1985), Qiu and Kumosa (1997), Ely and Kumosa (2000), Kumosa, Kumosa and Armentrout, (2003)] of their GRP rods. Since this failure mechanism is especially feared by electric utilities worldwide, several attempts have been made over the years to understand the process and provide potential means of avoiding it in-service [see for example Owen, Harris and Noble (1986), Ashtray, Nadeau, Wang, Romily, and Taggart (1986), Kumosa, Shankara Narayan, Qiu and Bansal (1997), Kuhl, (2001), de Tourreil, C, Pargamin, Thevenet and Prat (2000), Montesinos, Gorur, Mobasher and Kingsbury, (2002), Kumosa, Kumosa and Armentrout (2004a), Kumosa, Kumosa and Armentrout (2004b), Kumosa, Kumosa and Armentrout (2005b), Liang and Dai (2006)].

The reason why the brittle fracture problem has drawn so much attention is not because of the number of brittle fracture failures, which, apparently, has not been significant [Burnham et al. (2002)], but because of its characteristic features, which are:

- the failure is catastrophic leading to the drop of energized high voltage transmission lines and power outages,
- the failure is unpredictable; can occur after a few months or after a few years of being in service,
- there are no reliable monitoring techniques which could be used to monitor composite insulators in service for potential brittle fracture failures,
- the causes of failures, if one reads the available literature on this topic, are uncertain due to a number of confusing journal articles and conference presentations.

In brittle fracture, large cracks are formed inside the GRP rods and run perpendicular to the long axis of the insulators (Fig. 2). The cracks can be as large as 80% of the rod cross section, as reported by Kumosa, Shankara Narayan, Qiu and Bansal (1997) and Liang and Dai (2006). The failure process starts on the surfaces of the GRP rods by the initiation of stress corrosion C-type flows in individual E-glass fibers [Hull, Kumosa and Price (1985)] leading to their fractures (Fig. 3). Then, the failure process slowly accelerates causing more stress corrosion fiber failures. The final stage of the process is a catastrophic mechanical failure of the entire rod. The brittle fracture failure process is caused by a combined effect of electrical, mechanical and environmental fields [Kumosa, Kumosa and Armentrout (2004b)]. Due to the complexity of the problem, several different analyses are required as part of the failure investigation. Brittle fractures can only be determined

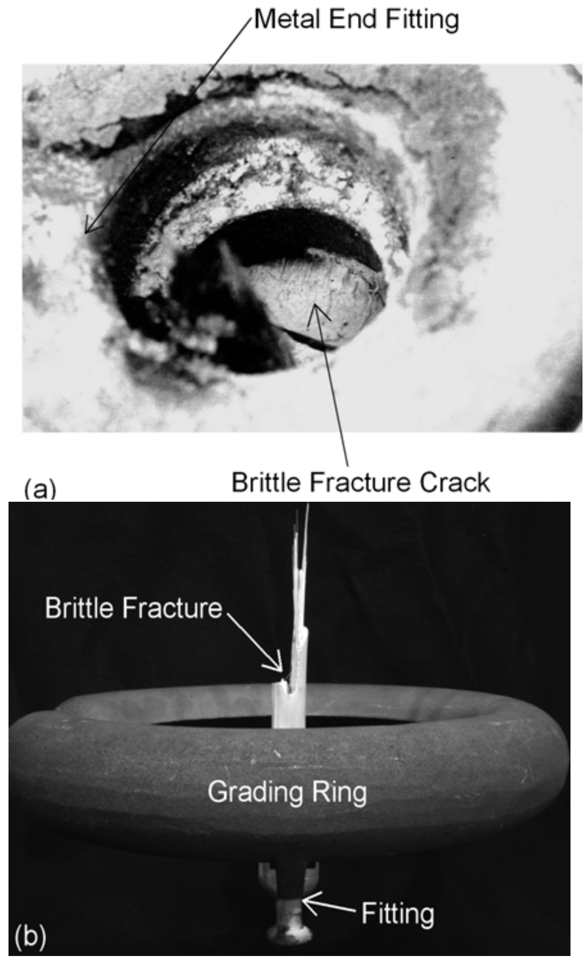

Figure 2: Examples of brittle fracture failures of 500kV suspension insulators; (a) failure inside the fitting and (b) failure above the hardware.

if the following three analyses of composite fracture surfaces are performed: macroscopic, microscopic and chemical. These fundamental analyses *must* all be performed to be absolutely sure that an insulator has failed by brittle fracture. It can be shown, however, that this combined type of failure analysis has not been usually performed in the past leading often to erroneous final conclusions regarding the actual causes of failure [Montesinos, Gorur, Mobasher and Kingsbury (2002)].

2.1 Macroscopic analysis

Brittle fracture can occur either inside (Fig. 2a) or just outside (Fig. 2b) of the energized end fittings [Kumosa, Shankara Narayan, Qiu and

Bansal (1997)]. A relationship has been observed between the location of failure and the position of the grading ring. When grading rings are present, the failures tend to occur just above the grading ring [Kumosa, Kumosa and Armentrout (2005a)]. Also, the location of failure seems to be related to the size of the grading rings. For higher line voltages with larger grading rings the location of failure was found to occur at larger distances from the end fitting [Kumosa, Kumosa and Armentrout (2005a]. In the absence of the grading rings the failure location was found to occur usually inside the fitting. In some sporadic cases the failure was a combination of transverse cracks in the composite rods inside and just outside the fittings linked by long axial splits along the rod.

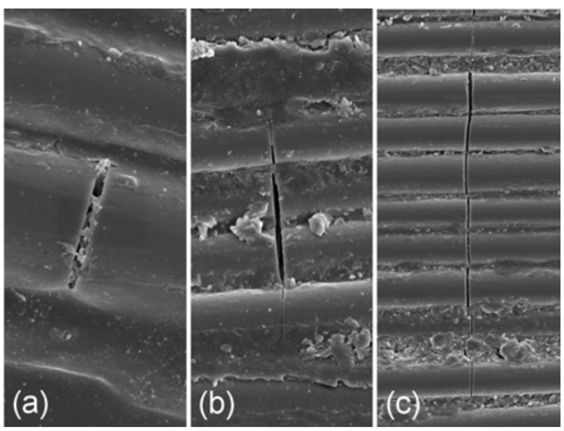

Figure 3: Initial stages of SCC and brittle fracture.

The fact that in brittle fracture transverse fracture surfaces form in the GRP rod and run perpendicular to the rod axis should not be immediately used as definite evidence of failure by this failure mode. According to Kumosa, Han and Kumosa (2002) a crimped composite insulator can fail mechanically in-service by rod fracture caused not by brittle fracture but overcrimping and excessive mechanical tensile loads. If crimped composite insulators are incorrectly designed and manufactured (excessive crimping deformations, incorrect design of the metal end fittings, excessive in-service mechanical loads, etc.) failure of the rod can also occur very close to the end fitting and the macroscopic fracture surface will be flat and almost perpendicular to the long axis of the rod (Fig. 4). In this case, the macro-fracture features will be almost indistinguishable from the fracture features caused by brittle fracture. This type of failure can occur at either end fitting. If crimping deformations are large, the loads at rod fracture can be quite low [Kumosa Armentrout, Kumosa, Han and Carpenter (2002)]. The only way to distinguish the purely mechanical failures by overcrimping from brittle fractures is by performing a detailed microscopic analysis of the rod's fracture surface.

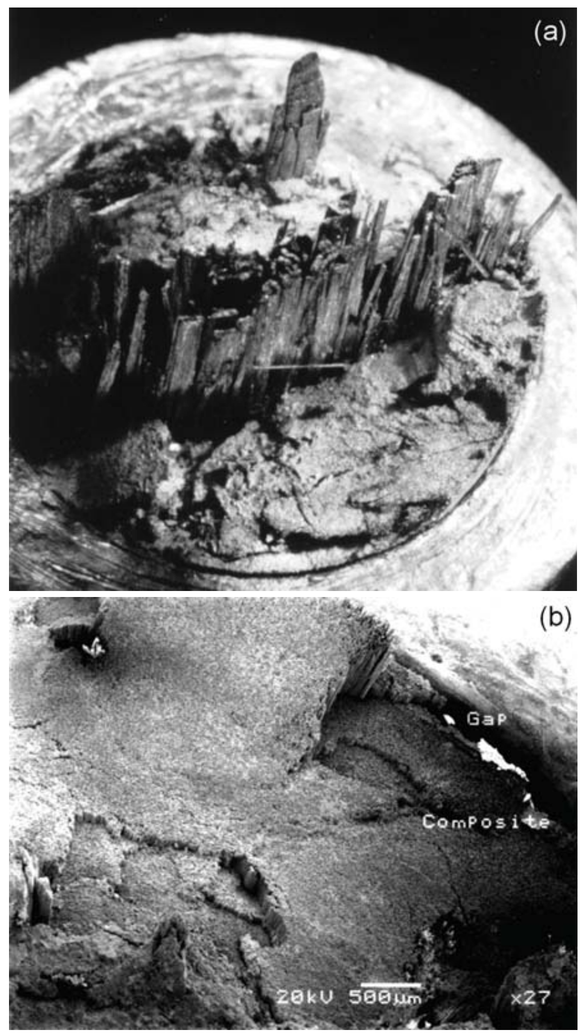

Figure 4: Failure characteristics of overcrimped 115kV insulator; (a) macro-damage zone and (b) composite fracture surface.

2.2 Microscopic analysis

The most characteristic feature of SCC of unidirectional E-glass/polymer composites and thus brittle fracture of non-ceramic insulators is the formation of the mirror, mist and hackle zones on the fracture surfaces of broken fibers, as shown in Fig. 5 [Hull, Kumosa and Price (1985)]. These three zones, however, are not observed on the fracture surfaces of glass fibers failed purely by mechanical loads (see Fig. 6) [Kumosa, Han and Kumosa (2002)]. The size of the mirror zones in the fibers failed by SCC does not depend on the chemical environment (usual misconception) but is related to the magnitude of the mechanical stresses [Hull, Kumosa and Price (1985)]. The fiber fracture under stress corrosion is caused by the ion exchange mechanism in which hydrogen ions from an acidic solution replace metal ions (Al, Ca, Fe, Mg) in the fibers. This weakens the fibers causing their fracture under low tensile stresses.

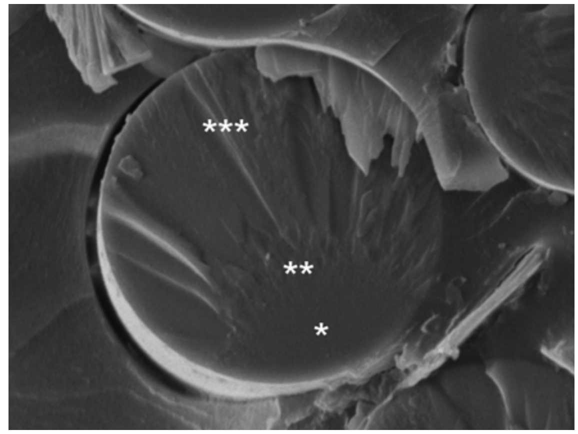

Figure 5: Mirror (*), mist (**) and hackle (***) zones on the fracture surface of E-glass fiber exposed to nitric acid.

According to the experimental observation presented by Marder and Fineberg (1996), cracks in brittle materials such as glasses suffer a dynamic instability, which makes them unable to accelerate up to high velocities predicted by classical theories of dynamic fracture. Thus, the transition from the mirror to hackle zone is related to a critical crack tip velocity above which the fracture process is highly unstable. Therefore, it can be shown that the size of the mirror zones depends primarily on the applied stress. The entire fracture process, after the formation of a ”C-type” flaw, is very fast but is not directly related to an acid attack on glass fibers [Ely and Kumosa (2000)]; an acid is only necessary to initiate a “C-type” flaw [Hull, Kumosa and Price (1985)]. If we consider the average crack tip velocity across a glass fiber to be about 200 m/s [Marder and Fineberg (1996)] then the time for fracture of an average fiber with a 14μm diameter is approximately 70 ns. From the moment of the flaw initiation until the final failure of the fiber, the process is dynamic not static (another usual misconception).

The zones shown in Fig. 5 are usually damaged during a corrosion process. This process is called post failure damage [Hull, Kumosa and Price (1985)], occurring after the fracture of individual fibers, and is caused by the chemical attack of a corrosive environment on the newly formed fiber fracture surface. In some cases, numerous surface cracks are formed in the mirror zones (Fig. 7) due to the leaching of aluminum, calcium and other metal components out of the glass fibers. The post failure damage is an important phenomenon very useful in the failure analysis. Its characteristics can be used to determine the cause of SCC for a composite structure. The amount of post failure damage is related to the acid type, its concentration and the time of exposure. For example, nitric acid of pH 1 will not develop post failure damage within a few weeks of exposure whereas other acids of the same concentration (sulfuric, hydrochloric, oxalic) will initite damage after a few hours or days [Qiu, Q. and Kumosa, M. (1997)]. In the case of oxalic acid the post failure damage can be so extensive (Fig. 7) that the entire fracture surface including the mirror, mist and hackle zones is essentially shattered.

Another very important micro-fracture feature is the presence of heavy deposits on the brittle fracture surfaces in composite insulators, in particular, when they were formed inside the fittings (see Fig. 8) [Kumosa, Shankara Narayan, Qiu and Bansal (1997), and Kumosa, Kumosa and Armentrout (2005a)]. Usually, the deposits are so thick that the fracture surfaces of individual broken fibers cannot be seen. Critical information about the causes of failure can be gained by chemically analyzing the deposits. For example, metal ions such as iron (Fe) and zinc (Zn) from the fittings can be traced along the insulators, which failed in-service, by brittle fracture. By tracing the metal ions, the extent of water/acid ingress inside the insulators can be established. Also, the presence of other contaminates such as sulfur, chlorine, sodium, potassium, etc., which could contribute to the failure process, can be established by chemically analyzing the deposits.

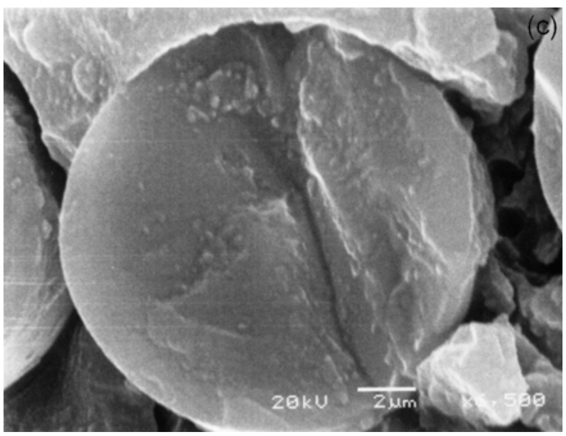

Figure 6: Typical example of fractured fiber caused purely by mechanical loads.

2.3 *Chemical analysis*

The definitive method of detection of brittle fracture consists of an elemental analysis of the relative depletion of calcium, aluminum and other metal ions in the glass fibers of a GRP core rod [Kumosa, Shankara Narayan, Qiu and Bansal (1997) and Burnham et al. (2002)]. Scanning electron microscope (SEM) and energy dispersive X-ray (EDX) analysis have been used in studying the corrosive morphological damage and elemental depletion analysis of fiberglass [Kumosa, Shankara Narayan, Qiu and Bansal (1997)]. Using these techniques, the decreases in calcium and aluminum relative to silicon can be determined in individual glass fibers and on composite fracture surfaces free from any major surface contamination. However, EDX and SEM could not be successfully used to determine the depletion in the field failed E-glass fibers on the brittle fracture surfaces. Since the chemical composition of the deposit shown in Fig. 8 consisted predominantly of Ca (with traces of Fe, Zn, S, Cl, etc.), the application of the two techniques could not determine the actual composition of the glass fibers on the composite surfaces. This could only be accomplished using Auger spectroscopy with depth profiling.

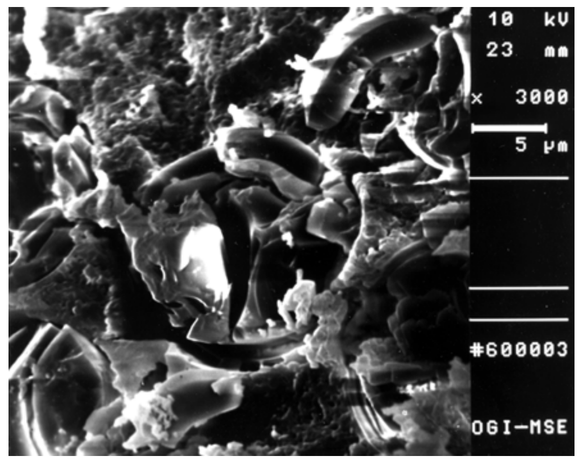

Figure 7: Post failure damage on the fracture surface of E-glass fiber exposed to oxalic acid.

It should also be very strongly emphasized that even if the depletion process in glass fibers in a field-failed insulator is determined, this will still not establish the actual cause of failure. In order to determine the actual composition of a chemical environment responsible for brittle fracture, a detailed surface analysis must be performed, not by using Auger, SEM and EDX, as often incorrectly recommended (Burnham et al. (2002), but by employing Fourier Transform Infrared (FTIR) spectroscopy which can detect nitrates [Chughtai, Smith and Kumosa, (1998) and Chughtai, Smith, Kumosa and Kumosa (2004)]. Using FTIR, nitrates were detected for the first time on the composite surface in the brittle fracture zones of several suspension insulators indicating that the failure was caused by nitric acid (see Fig. 9). It was also shown by Chughtai, Smith, Kumosa, and Kumosa (2004) that the highest concentration of nitric acid existed on the fracture surface on both sides of a separation caused by water ingress along the GRP rod/housing interface (Fig. 9, sites 2, 3 and 4). This finding supported the model of brittle fracture based on the water and acid movement along the rubber/rod interfaces into the high voltage field above the fitting the grading ring, if present [Kumosa, Kumosa and Armentrout (2005b)].

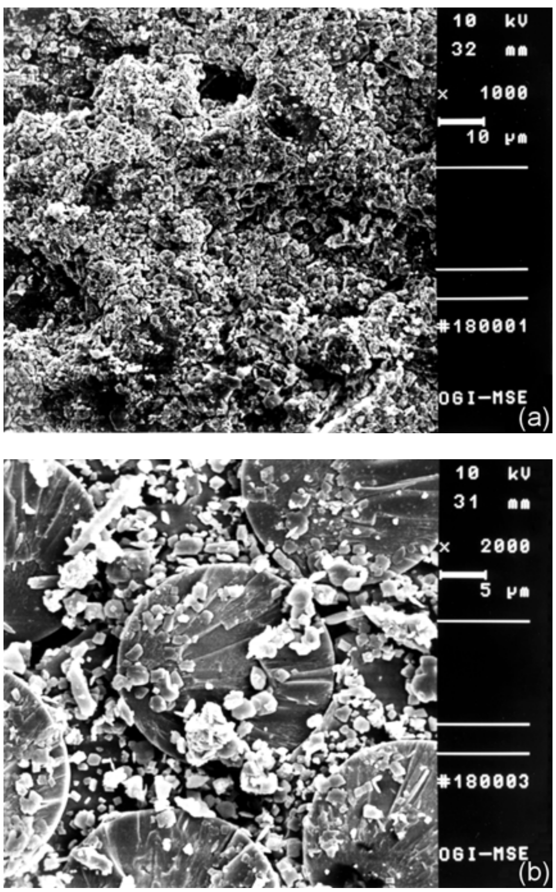

Figure 8: Examples of surface deposits on brittle fractures of composite insulators.

It should also be mentioned here that by using FTIR, nitrates and nitrides were detected by Liang and Dai (2006) on the brittle fracture surface of a 500kV insulator, which failed a few years ago in China. This is the first independent verification of the failure model proposed by us based on the formation of nitric acid in-service in the presence of moisture, air and corona discharges.

3 Examples of Failures by Brittle Fracture

3.1 Frequency of occurrence

It is impossible to find out how many insulators have actually failed by brittle fracture over the years. The fact is that many utilities will not admit that such failures have occurred on their transmission lines. It is also difficult to imagine that many cases of brittle fracture failures reported in the past were fully analyzed macroscopically, microscopically and chemically, as recommended in this work. Therefore, it can also be suspected that many in-service failures were incorrectly identified as brittle fracture instead of as overcrimped failures.

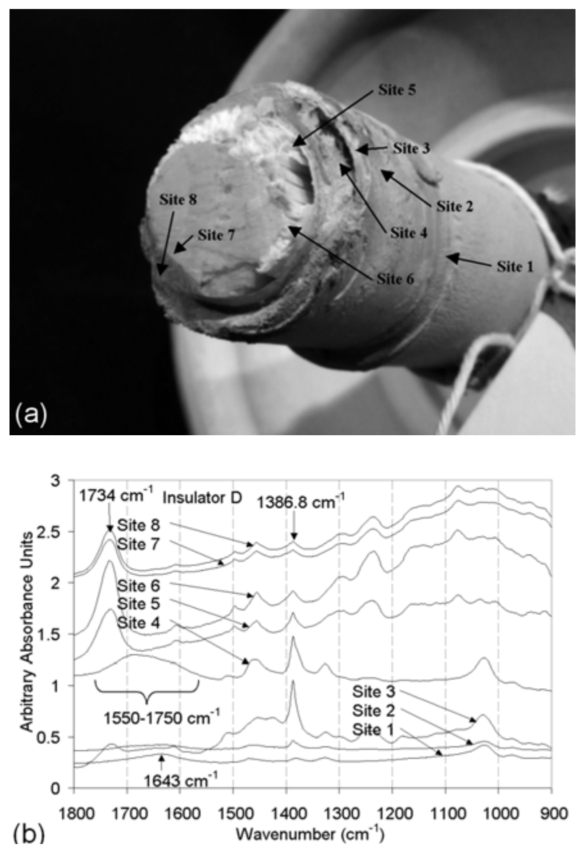

Figure 9: FTIR analysis of failed by brittle fracture suspension composite insulator; (a) failure morphology with site locations for FTIR and (b) FTIR spectra for the sites in Fig. 9a. Band at 1386.8cm^{-1} indicates presence of nitrates.

In our research we have identified approximately five 115 kV, twenty 345 kV and four 500 kV insulators, which failed by brittle fracture. This however, could only be a small portion of the total number of failures. The fact is that major brittle fracture failures have been reported in our research and in other sources (see for example Burnham et al. (2002)). The voltage levels of these failures ranged from 105kV to 500kV.

It has been stated by Burnham et al. (2002) that the probability of insulator failure by brittle fracture substantially increases with an increase in line voltage, which makes sense if the failure is partially caused by electric fields. Certainly, the higher field concentration will create an environment more suitable for the formation of nitric acid and the initiation of brittle fracture by SCC. Therefore, the only model of brittle fracture, which could explain these observations is a model which takes into consideration not only the presence of moisture and mechanical stresses but also the effect of the electric field [Kumosa, Kumosa and Armentrout (2004a), Kumosa, Kumosa and Armentrout (2004b), and Kumosa, Kumosa and Armentrout (2005b)]. However, even if our high voltage brittle fracture model is accepted, it cannot be used to predict these failures since all critical electrical, mechanical and chemical conditions for brittle fracture are unknown at present, and most likely, will never be known.

3.2 Examples and explanations of two major brittle fracture failures

Two examples of multiple insulator failures by brittle fracture on 345 kV and 500 kV lines are described in this section. They are of particular importance due to the sheer number of failures in the case of the 345 kV line and the voltage magnitude for the 500 kV failures. These two groups of failures received a large amount of attention in the 90s among electric utilities worldwide.

3.2.1 345 kV failures

The failures occurred in 1990/1991 on a 345 kV line. Fourteen brittle fracture failures occurred resulting in the drop of the conductor (see Fig. 10) within two years after the installation [Kumosa, Shankara Narayan, Qiu and Bansal (1997) and Kumosa, Kumosa and Armentrout (2005a)]. In addition almost 200 insulators were found to be severely damaged. We had full access to all the failed and damaged units removed from the line. The failure analysis of the damaged units (not the failed ones) was found to be particularly useful. The damage process was observed at different stages of its development in the damaged insulators.

In order to explain the 345 kV failures numerous experimental and numerical techniques were employed [Kumosa, Shankara Narayan, Qiu and Bansal (1997) and Kumosa, Kumosa and Armentrout (2005a)]. The field-failed units were examined using optical and scanning microscopes on the macro and micro-levels. Detailed chemical analyses of the fracture surfaces taken from the failed units were performed. Unique new experimental techniques were developed to simulate SCC under laboratory conditions with and without high voltage fields. All of the above proved that the failures were caused by brittle fracture. However, the exact causes of the failures were much more difficult to determine. Finally, after simulating numerically the mechanical performance of the insulators with the epoxy cone end fittings using non-linear finite element techniques (see Fig. 11), it was established that a manufacturer must have applied excessive mechanical loads during proof testing. The large loads applied to the insulators during proof testing crushed the epoxy cones inside the fittings, as acknowledged by Burnham et al. (2002), allowing easy access of water to the GRP rod of the insulators. In addition, water was also allowed to stay inside the fittings near the triple point shown in Fig. 11a,b. It was also established that all the units on the 345 kV line were not protected against moisture ingress into their end fittings. No silicone gel was applied at the fitting/rod interface to achieve the moisture seal. It would be difficult to find a more favorable set of conditions for the initiation of those failures. However, it must be added here that such insulators are no longer in service mostly due to the research performed in our laboratory and the overall improvement in the insulator technology over the last fifteen years.

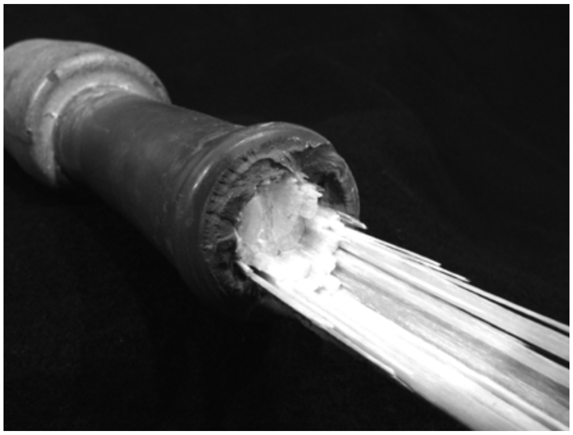

Figure 10: 345 kV suspension insulator failed in-service by brittle fracture.

3.2.2 500 kV failures

The 500 kV failures occurred on the West Coast of the US and were caused, as determined by Kumosa and Qiu (1996) and acknowledged by the electric community in Burnham et al. (2002) by spilt epoxy on the hardware during manufacturing (see Fig. 12). The spilt epoxy on the upper surface of the fitting allowed water to penetrate the fitting under the epoxy layer reaching finally the GRP rod. The research performed on the 500kV units showed three very important new effects. First of all, the amount of water responsible for brittle fracture must have been extremely small. All units from the line, including the failed ones, passed the dye penetration test, which is usually applied to composite insulators to determine the quality of their moisture absorption protection. Second, large amounts of water present on the surface of the GRP rods in the insulators did not lead immediately to brittle fracture. A couple of insulators from the line were found with the rubber housing near the hot end significantly damaged and the GRP rod completely exposed to moisture, without brittle fracture (Fig. 13) allowing easy access of water into the end fittings. It has also been shown that if water and partial discharges (PD) are present at the rod/housing interface above the hardware, cracks can be found in the rubber housing initiating at the interface and, then, propagating outwards across the rubber towards the external surface of a composite insulator (see Fig. 14). This could explain the origin of the damage to the housing presented in Fig. 13. It could also suggest that when such cracks are present, large amounts of water will penetrate the housing through those cracks, further accelerating the damage process in the housing. However, if a large quantity of water is present inside an insulator, nitric acid forming at the rubber housing interface will not be concentrated high enough. As a result, the critical chemical conditions for brittle fracture (acid concentration) will not be satisfied. It has been shown that the critical pH for SCC in nitric acid for a polyester type composite with E-glass fibers is somewhere between 3 and 3.5 and between 2.5 and 3 for an epoxy based composite [Kumosa, Kumosa and Armentrout (2004b)].

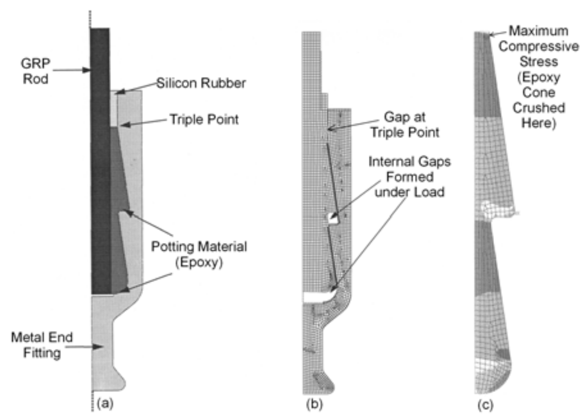

Figure 11: Finite element model of suspension insulator with the epoxy cone end fittings; (a) end fitting design (schematic) (b) deformed finite element mesh and (c) mechanical stress distributions in the cones.

4 Causes of Brittle Fracture

Obviously, if one knows the causes of brittle fracture one can also provide remedies. Therefore, a few different models of brittle fracture have been proposed over the years. The most important ones (Models I-III) are listed below.

Model I. According to Montesinos, Gorur, Mobasher and Kingsbury (2002) “the failure of in-service NCIs in the brittle fracture mode can occur under the influence of water and mechanical stresses, and the failure is more likely to happen with water than with acids."

Model II. According to de Tourreil, Pargamin, Thevenet and Prat (2000) and de Tourreil, Pargamin, Thevenet, Prat and Siampiringue (2001) "the brittle fracture of the FRP [Fiber Reinforced Polymer] rod of composite insulators is associated with an acid, derived from the hardener, lodged on the surface of the rod combined with the ingress of water at the same location and a mechanical tension load applied to the insulator."

Model III. Brittle fracture is caused by nitric acid being formed in service due to electrical discharge, ozone and moisture [see for example: Kumosa, Shankara Narayan, Qiu and Bansal, (1997), Kuhl (2001), Kumosa, Kumosa and Armentrout (2004a) and Kumosa, Kumosa and Armentrout (2004b)]. The acid can either be formed by water droplet coronas on the insulator surface near its energized end or by PD inside the insulator, close to its end. Recently, Model III has been proposed to the electric community in its final version [Kumosa, Kumosa and Armentrout (2005b)].

The only agreement between Models I - III is that brittle fracture is initiated by moisture ingress into a composite insulator. The issue of the chemical causes of brittle fracture has been discussed in Kumosa, Kumosa and Armentrout (2004a) and in Kumosa, Kumosa and Armentrout (2004b)]. In particular, the credibility of the models I-III has been evaluated. It was shown that the only model, which can explain all the aspects of brittle fracture, is Model III. This model also considers a strong effect of the electric field on the brittle fracture process. Using Model III the location of failure in the insulators, e.g. failure inside the fitting (Fig. 2a) or above the grading ring (Fig. 2b) can be explained [Kumosa, Kumosa and Armentrout (2005b)]. To support the model, electric field calculations were performed in order to demonstrate the possibility of PDs that are necessary to create nitric acid in service inside macroscopic delaminations and other large cracks that are always associated with the brittle fracture process. It has been shown that if the cracks are partially filled with water, the electric field concentration is high enough to initiate PD inside the transmission composite insulators near their energized ends, and to produce nitrogenous species (nitrates).

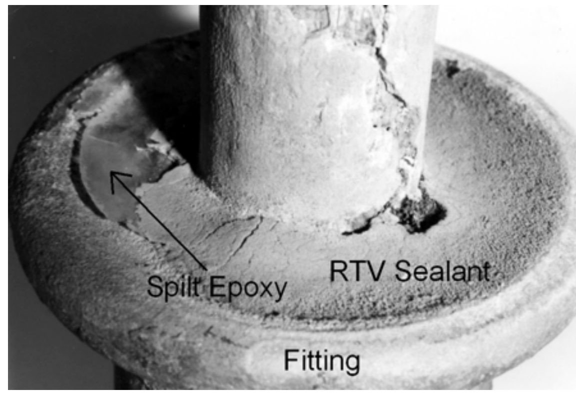

Figure 12: Spilt epoxy on the upper surface of the hardware of 500kV suspension composite insulator.

5 Manufacturing Prevention

5.1 Through proper insulator design

For the prevention of brittle fracture of composite insulators an excellent moisture seal and the use of the proper housing thickness are very important [Burnham et al. (2002]. In addition, a high quality sealant should always be used to protect the interface between the fitting and the rod/housing. Also, the grading ring is important since it will minimize corona cutting in the rubber housing. (Corona cuttings are cracks in the rubber housing in the vicinity of energized end fittings and are caused by aging of rubber housing materials due to corona, moisture, pollution, mechanical stress, etc.) However, none of the field-failed insulators investigated in our laboratory have shown any evidence of any damage to the rubber housing from the outside. Therefore, it is doubtful that grading rings will fully prevent brittle fracture if water ingress is allowed through the fitting. Since the failure above the hardware, which is the most common type, is associated with the movement of moisture along the rod near the rod/housing interface, the grading will only postpone the process, but do not prevent it [Kumosa, Kumosa and Armentrout (2005b)]. This can only be accomplished by keeping the housing thickness sufficiently large and not allowing any moisture ingress into the fittings. However, this might be impossible to achieve for long periods of time considering the harsh nature of the environment on high voltage transmission lines.

5.2 Through proper materials selection

If the GRP rods can fail by SCC when exposed to nitric acid and mechanical tensile loads, the easiest way to prevent this process from occurring in-service is by the chemical optimization of the rods making them immune to brittle fracture. Unidirectional glass/polymer composites, used in the GRP rods, can be designed for their very high resistance to SCC in nitric acid [see for example Armentrout, Kumosa and McQuarrie (2003), Kumosa, Kumosa and Armentrout (2003) and Kumosa, Kumosa and Armentrout (2005c)], high resistance to moisture absorption [Kumosa, Benedikt, Armentrout and Kumosa (2004)] and their resistance to the development of leakage currents [Armentrout, Kumosa and Kumosa (2004)]. Other recommendations regarding the resistance of insulator composites to damage by ozone, micro and macro-surface compression, sandblasting, etc. have also been given and are available in Kumosa (2001) and in Kumosa (2002). Below, the most important results, observations and conclusions are listed from our rod design research performed between 1993 and 2005. Such a comprehensive set of data of this type has never been reported by any other laboratory.

5.2.1 Resistance to SCC in nitric acid

The resistance to brittle fracture of insulator composites is strongly affected by such factors as fiber and resin type, surface fiber exposure, resin fracture toughness, moisture absorption, and interfacial strength [Kumosa, Kumosa, and Armentrout (2005c)]. Out of three E-glass/polymer composite systems (based on modified polyester, epoxy and vinyl ester resins and supplied by a single composite manufacturer), the resistance to the initiation of SCC in nitric acid of E-glass/modified polyester was found to be 10 times lower than for E-glass/epoxy, and approximately 200 times lower than for E-glass/vinyl ester. The ECR-glass/polymer composites exhibited vast improvement over the E-glass/polymer materials. The highest resistance to the initiation of SCC damage in the ECR glass-based composites was found for the low seed ECR-glass fibers embedded in either epoxy or vinyl ester resins. The ECR glass composites were shown to be equally resistant to the propagation of SCC even under highly accelerated testing conditions, which was not the case for the E-glass fiber based composites.

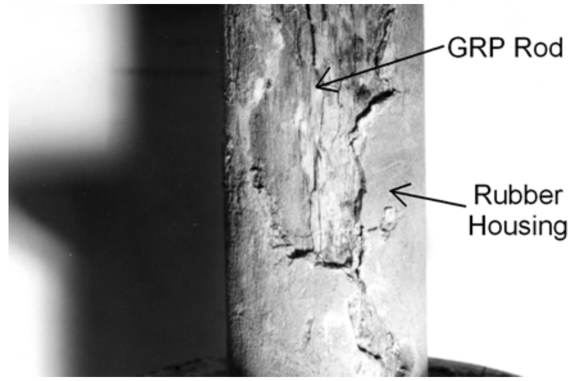

Figure 13: Damaged rubber housing in 500 kV composite insulator near its hot end.

According to our field experience, a vast majority of brittle fracture failures occurred in the insulators based on E-glass/polyester rods, as reported for example by Kumosa, Kumosa, and Armentrout (2004b). Some failures have also occurred in the insulators with E-glass/epoxy rods. No failures of E-glass/vinyl ester rods have been reported to the best knowledge of the author. It should also be mentioned at this point that insulators with boron free (ECR) fibers were introduced in 1983, and none of them has so far experienced any brittle fracture failures [Gubanski (2005)]. Therefore, it can be concluded that our field experience agrees very well with the observations made in our laboratory regarding the effect of fibers and polymers on the resistance of various composite systems to SCC in nitric acid and brittle fracture.

5.2.2 Resistance to moisture absorption and interfacial damage

The resistance to moisture absorption of insulator composites affects their insulation properties, resistance to SCC and brittle fracture, and their overall mechanical properties [see for example Kumosa, Kumosa and Armentrout (2005c)]. As shown by Kumosa, Benedikt, Armentrout and Kumosa (2004) the E-glass/modified polyester system exhibited by far the worst resistance to moisture absorption with a very high rate of moisture diffusion and high maximum moisture absorption in comparison with the other two E-glass based materials. They had very similar rates of moisture absorption, however the epoxy-based system did take more moisture than the vinyl ester-based material. A slight fiber effect was found to exist on the moisture absorption properties of the composites based on the three different resins. In general, composites based on the ECR (high seed)-glass fibers took smaller amounts of moisture than their E-glass and ECR-glass (low seed)-glass fiber-based composites.

Interfacial splitting along the glass/fiber interfaces accelerates brittle fracture and therefore should be minimized [Kumosa, Kumosa and Armentrout (2005b)]. The resistance of the interfaces to failure caused by shear in dry E-glass/polymer composites was found to be the lowest in E-glass/modified polyester followed by E-glass epoxy (approximately 50% higher) and E-glass/vinyl ester (approximately 4% higher) than for the epoxy based composite) [Kumosa, Kumosa and Armentrout (2005c)]. Immediately after full saturation with distilled water at 50^{o}C the resistance to interfacial splitting was only slightly reduced. The quality of the interfaces of the ECR-glass fiber composites has not been investigated. It can be assumed however that their resistance to interfacial splitting would be similar to the E-glass/polymer systems.

5.2.3 Resistance to leakage currents

The resistance to leakage currents of insulator composites [Armentrout, Kumosa and Kumosa (2004)] could be more important for their insulation properties than for their resistance to brittle fracture. The fact is however that the electric field plays a critical role in brittle fracture. Therefore, high leakage currents could accelerate the nitric acid formation process inside the insulators. After boiling in deioniozed water with 0.1% (by weight) of NaCl for four days, E-glass/modified polyester developed significantly higher leakage current that the E-glass/epoxy and E-glass/vinyl ester systems, caused by its high water absorption [Armentrout, Kumosa and Kumosa (2004)]. For the same amounts of absorbed moisture by their resins, the ECR (high seed)-glass fiber composites developed several hundred times higher leakage currents than their E-glass counterparts. The leakage currents in the composites with recently developed ECR (low seed)-glass fibers were similar to the E-glass-based systems. The high leak-

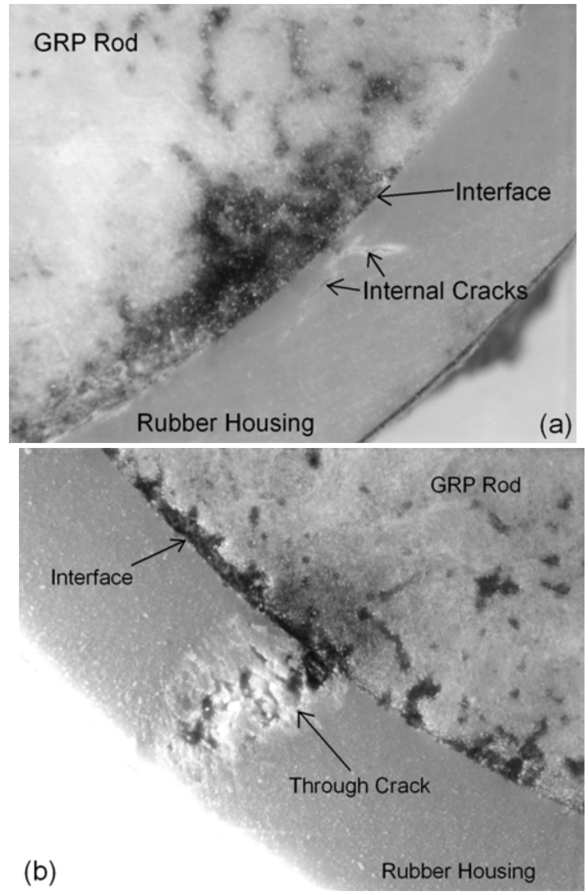

Figure 14: Cracks in rubber housing at different stages of their formation; (a) partial crack and (b) through crack.

age current for high seed ECR-glass fiber composites subjected to moisture is one of the major reasons why most manufacturers have not used these materials until now. The seeds, which are gaseous voids left inside the fibers during manufacturing, significantly increase leakage currents in the composites in the presence of moisture.

5.2.4 *Ranking of composites for resistance to brittle fracture*

We have not yet identified all critical material related factors affecting brittle fracture. In addition, such known factors as the resistance of insulator polymers and their interfaces with glass fibers to the decomposition by discharge, acids, electric wind, etc., has not been systematically investigated. Also, no systematic studies of the resistance to moisture movement along E-glass and ECR-glass composites have been performed. Considering however the thoroughly examined material properties of several different composite systems for high voltage insulation applications and taking into consideration our field experience, E-glass/modified polyester exhibits by far the lowest resistance to brittle fracture with the ECR (low seed)- glass/vinyl ester being the best. The ECR (low seed)/epoxy and E-glass/vinyl ester must also be ranked very high.

5.3 *Through proper process control*

The GRP rods should always be free from large voids, cracks or any other type of macroscopic damage to minimize the probability of brittle fracture [Burnham et al. (2002)]. Such material imperfections could create problems caused by the development of PD especially in the presence of moisture. However, such imperfections can easily develop in-service if water is allowed into the insulators. The fact that voids and cracks are not present in the rods during manufacturing does not mean that these imperfections will not develop in service causing problems. Therefore, composite materials with high resistance to moisture absorption [Kumosa, Benedikt, Armentrout and Kumosa (2004)] and damage initiation caused by moisture should be used.

Some insulator manufacturers occasionally performed sandblasting of their composite rods to increase adhesion between the rods and the rubber housing (see Fig. 15) [Kumosa, Armentrout and Kumosa (2002)]. During sandblasting the surface of the rods can be severely damaged. This damage is usually created in the glass fibers left on the composite surface. The initial assumption made by us was that sandblasting could have an extremely negative effect on the resistance of the GRP rods to brittle fracture. It was found however that low/medium sandblasting could actually improve slightly the resistance of the composites to SCC in nitric acid. This was attributed to the relaxation of mechanical residual stresses on the surface of the composites due to sandblasting. This clearly indicates that not all types of damage to the composites can negatively affect their resistance to brittle fracture.

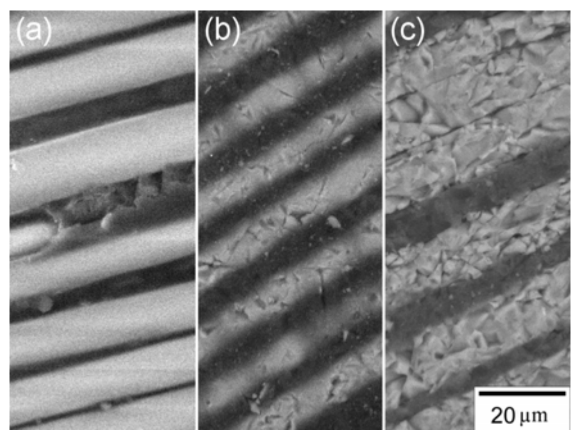

Figure 15: Surface damage in E-glass fibers caused by sandblasting; (a) as supplied, (b) after low sandblasting and (c) after medium sandblasting

It has been suggested by Burnham et al. (2002) that over-stressing the GRP rod due to crimping can lead to brittle fracture. This is certainly an important issue related to the insulator design and its manufacturing. The fact is that extensive damage to the GRP rods can be created by insulator manufacturers by applying excessive crimping [Kumosa, Han and Kumosa (2002)]. However, not a single insulator failure by brittle fracture initiated by overcrimping has ever been documented.

Certainly, excessive and badly distributed crimping deformations on the rod surface inside the fittings in combination with high mechanical loads will significantly increase the tensile axial stresses in the rods just outside the fittings. Then, if nitric acid is present on the surface of the rod in this location, the probability of failure by brittle fracture could increase due to the higher mechanical stresses.

The cracks caused by overcrimping [Burnham et al. (2002)], depending on their location, size and orientation could reduce the resistance of the insulators to brittle fracture. However, the critical mechanical flaw size and type, and the loading conditions for the initiation of SCC are unknown at present. Therefore, we can also speculate which composite system (see the Materials part of this section) will have the highest resistance to brittle fracture if initiated by overcrimping. It can be safely assumed, however, that the vinyl ester based composites will have the highest resistance to brittle fracture due to its high fracture toughness [Kumosa, Armentrout and Kumosa (2002)]. Without doubt more research is still required to understand the effect of overcrimping on the initiation of brittle fracture

6 User Prevention

Composite insulators should not be mechanically damaged at any stage; manufacturing, transportation, installation. Certainly, damage caused by mishandling "may result in a brittle fracture or some other type of failure" as stated by Burnham et al. (2002). However, the evaluation of the effect of mechanical damage (of various types) on the electrical and mechanical in-service performance of composite insulators is not a straightforward problem. Numerous different types of failure caused by mishandling can exist in nonceramic insulators. At the same time, we still do not know what is acceptable and what is not regarding the mechanical damage and its effect on the short- and long- term properties of the insulators and, in particular, on brittle fracture.

The critical type of damage for the initiation of brittle fracture in composite insulators subjected to the combined effect of mechanical, electrical, and environmental stresses is an issue which most likely is never going to be correctly addressed. The best example of the complexity of this problem is gun shot damage. In certain areas, the insulators can be severely damaged by gunshots [Burnham and Waidelich, (1997)]. When damaged by gunshots the insulators are entirely open to moisture ingress. In addition, huge amounts of mechanical damage are created to the GRP rods. It would be difficult to imagine any worse type of mishandling of the insulators in-service than by gunshots. Yet, not a single composite insulator has been reported to fail by brittle fracture initiated by gunshots. Therefore, the only credible recommendation, which can be provided on how to avoid brittle fracture due to mishandling, is related to the moisture sealing conditions, which should never be compromised during manufacturing, transportation and installation.

7 Conclusions

It has been shown in this research that despite major improvements in the insulator technology over the years, composite insulators can fail in-service either mechanically or electrically causing severe interruptions in power supply. Various types of failure can occur especially in the insulators supporting high voltage transmission lines. Under in-service conditions the insulators can develop various forms of mechanical damage in their GRP rods, rubber housing, and in their fittings. In particular, the brittle fracture process can be devastating to an electric utility. The most important characteristics of this highly feared failure process have been described in this work. Several recommendations on how to avoid this type of failure have also been given here. However, there are still several critical issues which need to be correctly addressed in the future in order to fully understand this failure process and, in particular, to be able to prevent it from occurring in-service.

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