Composite Materials for Electrical Transmission Mast Structures

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“If somebody offers you an amazing opportunity but you are not sure you can do it, say yes – then learn how to do it later!”

— Richard Branson
Preface and acknowledgement

This thesis is submitted in partial fulfilment of requirements for PhD degree in Technical University of Denmark (DTU). The work is related to a larger project on development of a new composite power pylon concept, which is a collaboration between DTU, Aalborg University and industrial partners. The main part of this work has been carried out in the Lightweight Structures Group within the Solid mechanics section at the department of Mechanical engineering and High Voltage Lab in the Electrical engineering department of DTU. This work has been accomplished between June 2014 and January 2019 under the supervision of Associate Professor Christian Berggreen and Professor Joachim Holbøll; without their support and guidance it would have not be possible to perform these tasks.

The effect of combined mechanical-electrical stresses during fatigue on glass fiber composite materials has been investigated throughout this work, on small and large-scale specimens. The core of this study is based on experimental works and multi-environment aging of similar type of materials.

This PhD was funded by the Innovation Fund Denmark under the name ‘Power Pylons of Future’, and their support is highly appreciated.

During this project, I had the opportunity to take advantage of laboratories and workshops at DTU Mechanical, Electrical and Physics departments, and I would like to thank all my colleagues and the personals at these facilities. I would also like to thank my colleagues in the Energy Technology department of Aalborg University for their contribution to this project. I would like to thanks all of my colleagues at Lightweight Structures Group and DTU mechanical department, especially Vishnu Saseendran and Mathias Kliem for their support in writing this thesis.

It is because of the support from my family through all these years, that I have been able to achieve my goals. They are in my deepest thoughts and have my greatest appreciation. Finally, I would like to thank my dearest friend and partner Pernille Møller for her patience and support, which helped me accomplish this task.

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Kgs. Lyngby, Denmark

February 2019
Resumé


Den overordnede ramme for denne afhandling er fokuseret på multimiljømæssige aldring (mekanisk og elektrisk) af GFRP (Glass Fiber Reinforced Polymer) materialer. Forsøgene er blevet gennemført på prøver i en lille skala (kupon-størrelse) og i store skala (arm i fuld længde), hvor de på samme tid udsættes for træthed mekaniske og elektriske belastninger. Materialegevalget er baseret på de konventionelle strukturharpikser med fortsatte glasfiberforstærkninger.

Den første del af arbejdet i denne afhandling er relateret til beregningen af forskellige typer belastninger, som anvendes på strukturen hovedsageligt af vind, is eller kombinationen heraf. Disse beregninger er baseret på de europæiske standarder for strukturdesign af luftledninger.

Den anden del fokuserer på at udvikle en eksperimentel opsætning til udmattelsestest af kuponprøver, der er i stand til at anvende mekaniske og elektriske belastninger på samme tid. Et S/N (stress/number of cycles to fail) kurvediagram blev udviklet for at sammenligne trætningslevetiden for enkelriktede GFRP-prøver, mens de blev udsat for rene mekaniske og kombinerede mekaniske-elektriske belastninger.

Den tredje del omhandler undersøgelsen af effekten af forskellige layoutkonfigurationer og fremstillingsfejl (præ-de laminering og hulrum) i for materialet og træthedbestandigheden under samtidig mekanisk og elektrisk spænding.

I den afsluttende del af denne afhandling er der udviklet en eksperimentel opsætning til storskalaoprøvning af kraftpylonen med en fuldlængdesarm, mens den udsættes for kombineret mekanisk og højspændingsbelastning. I slutningen er resultaterne fra træthedforsøg sammenlignet med de endelige element-simuleringer.
Abstract

The Large energy demand in the global market, a total estimate of 14050 million tons of oil equivalent in 2017 [1], and especially the electrical power consumption has increased the necessity of expanding power grids for transmission and distribution. Although underground transmission lines seem to be the primary choice with respect to the visual impacts, due to high costs and technical difficulties, overhead lines are still the preferred tools for this matter. However, mainly because of public resistance towards installation of overhead line structures and their negative impact on the landscape, designers have been motivated to come up with new concepts to overcome this issue. One of these concepts developed by BYSTRUP, an architecture company in Denmark, is known as ‘The Composite Pylon’. Using non-conductive materials for the structure of this pylon results in the omission of conventional insulators since the overhead transmission lines may be rigidly and directly mounted to the power pylon structure; this lowers the electrical clearances and the size of the power pylon structures may be reduced considerably. Other advantages of this concept are a lighter structure, broader public acceptance and simpler installations.

The overall framework of this thesis is focused on the multi-environment (mechanical and electrical) ageing of GFRP (Glass Fiber Reinforced Polymer) materials. The experiments have been carried out small-scale (coupon size) and large-scale (full-length arm) specimens, while subjected to fatigue mechanical and electrical loads simultaneously. The material selection is based on the conventional structural resins with continues glass fiber reinforcements.

The first part of the work in this thesis is related to the calculation of different types of loads, which are applied on the structure mainly by wind, ice or their combination. These calculations are based on the procedures suggested by Euro code standards for overhead line structure designs.

The second part is focuses on developing an experimental setup for fatigue testing of coupon specimens, capable of applying simultaneous mechanical and electrical loads. An S/N (stress/number of cycles to fail) curve diagram has been developed in order to compare the fatigue life of unidirectional GFRP specimens, while subjected to pure mechanical and combined mechanical-electrical loads.

The third part is related to investigating the effect of different layup configuration and manufacturing defects (pre-delamination and voids) within the material, on the fatigue resistance while subjected to mechanical and electrical stresses simultaneously.

In the final part of this thesis, an experimental setup has been developed for large scale testing of a full-length arm of the power pylon while subjected to combined mechanical and high voltage electrical loads. At the end, the results from the fatigue experiments were compared to the finite element simulations.
Symbols and abbreviations

DTU  Technical University of Denmark
GFRP  Glass fiber reinforced polymer
S/N  Stress versus number of cycles to fail
UV  Ultraviolet
EMC  Electromagnetic compatibility
IEC  International Electrotechnical Commission
MoP  Manuals of Practice
NINAs  National Normative Aspects
ASTM  American Society for Testing and Materials
SCC  Stress corrosion cracking
FEM  Finite element method
DIC  Digital Image Correlation
UD  Unidirectional
$S, F$  Scale factor
Cp  Capacitance of the dielectric
Cv  Void representative capacitance
Cs  Remaining capacitance of the dielectric in series with the void
Rs  Resistance of the dielectric in series with the void
E  Elastic modulus
ρ  Density
$\sigma_f$  Failure strength
$E_{el}$  Magnitude of electric field
V  Applied voltage
$V_f$  Fiber volume
$V_s$  Sample volume
$\rho_f$  Density of the fibers
$\rho_r$  Density of the resin
$W_f$  Relative weight of the fibers
l  Distance between toroids
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1 Introduction

The global energy demand has increased by 2.1% in 2017 compared to 0.9% in 2016, and has reached a total estimate of 14050 million tonnes of oil equivalent; this growth is more than twice compared to 2016 [1]. The share of the power sector from global energy market is by far the largest with over 40% with an increase of 2.8% in 2017, close to its 10-year average [2]. Renewable power generation plays a significant role on the net addition to global power generation capacity by an estimate of 70% in 2017 [3]. The growth in world power generation and consumption requires expanding the current grid systems for transmission, both locally and in trading between supply and demand on international scales. The generated power is transmitted either by overhead lines or by underground cables. Each of these methods have their own advantages and disadvantages. Underground installations have the advantage of reduced exposure to electromagnetism and improvement of aesthetics but suffer from higher installation costs and difficulties in assessing equipment for repair. On the other hand, overhead installations have faster service installation, higher operating temperatures but are negatively affected by storm and wildlife [4], vandalism and other extreme environmental conditions. The Danish Energy Agency has established some guidelines regarding the expansion of transmission grids considering secure supply, technology and economy, and aiming to use underground installation for 400 kV power lines; however this approach is currently technically and economically too expensive [5]. Therefore, overhead power transmission lines are still the primary choice for extra high voltage levels (300-700 kV) around the globe, providing lower electrical losses and security of supply [6]. However, there is an increasing public resistance in Denmark against overhead transmission lines due to environmental and visual impacts [7]. The Electricity Infrastructure Committee report on “the future expansion and undergrounding of the electricity transmission grid”, points out the improvement of the visual appearance of the existing 400 kV overhead line network, by replacing the existing towers with lower towers with new design [8].

The visual impact issue has motivated many designers to come up with new and innovative designs. Some of these ideas are illustrated in Fig. 1.1.

![Innovative Designs for Overhead Transmission Lines](image-url)
1.1 Composite in overhead Transmission line structures

Since the introduction of composite insulators in the 1950’s in the USA [9], the use of composite materials has been increased widely, not only in insulators, but also as the main load carrying structure such as composite poles. The composite insulators are yet the main target in this market whereas the composite poles are becoming more popular especially at lower voltages.

Composite insulators are less sensitive to impact loads and weigh less compared to conventional insulators. Conventional insulators could contribute up to 20% of the total vertical load on the tower, and using the composite insulators could save up to 90% of this weight [9].

Some aspects of utilizing composite materials in overhead line structures are briefly described here.

1.1.1 Composite poles

The use of composite poles for overhead electric power lines dates back to the 1960s in Hawaii. These poles served for almost 50 years before they were replaced due to fiber blooming caused by ultraviolet (UV) light exposure. Since they lacked any protection against ultraviolet. Modern UV inhibitors or surface veils could protect against this phenomena up to 80 years. Fiber blooming not only affects the surfaces exposed to UV rays aesthetically, but it could also compromise the non-conductivity of FRP (Fiber Reinforced Polymer) material [10]. Composite utility poles could be manufactured with constant cross section or tapered tubular, Fig. 1.2. These poles are usually manufactured by pultrusion or filament winding techniques [11].

![Composite poles, left) Constant cross section (11), right) Tapered (65).](image)

1.1.2 Insulators

Papailiou and Schmuck [9], mention that, even though the composite insulators were first developed in the 1950’s, it was not until the 1970’s that they found their place in the market for insulators. This was due to major advances in manufacturing FRP materials used as the core and polymers which form the housing of these insulators.

The main components of an insulator with a composite core are shown in Fig. 1.3. The GFRP core is either solid or with a hollow core, manufactured potentially by pultrusion or filament winding.

The role of different parts in composite insulator could be summarized as [9]:

- Composite rod: Mechanical load carrying part.
- Housing: shed-like design, which increases creepage distance (shortest distance between two conductive parts along the surface) and electrical insulation (the housing is made of Silicon).
- Metal end fitting: for transmitting mechanical loads.

![Fig. 1.3: Main components of a composite insulator.](image)

**Composite long rod insulators**

Composite long rod insulators are primarily subjected to tensile loads and are used in suspension strings in straight-line supports and tension strings in anchor and dead-end towers [9].

![Fig. 1.4: Tension string (left) and floating dead-end (right) [9].](image)

**Composite post insulators**

Contrary to long rod insulators, composite post insulators are fully clamped at one end, and therefore they are capable of carrying compression or bending loads.

![Fig. 1.5: 230 KV composite post insulator (left), 132 KV line with trident cross-arms (right) [9].](image)
Compact lines

Papailiou and Schmuck [9], explain that these configurations are more suitable for situations where right of the way, and visual impact are of importance. Additionally, they provide higher power transfer and lower electromagnetic compatibility (EMC). They started to become popular in 1990s, after the composite insulators became widespread, Fig. 1.6.

1.1.3 The composite power pylon

The composite power pylon concept was developed by a Danish architecture company, Bystrup, with the intention to integrate the insulators within the structure itself since the composite structure is non-conductive and alone can be used as an insulator, Fig. 1.7. The suggested design was developed for 400 kV overhead lines and is capable of carrying 2*400 kV lines, one at each arm. The pylon structure material is made of glass fiber reinforced polymer (GFRP), which reduces the height of the tower to 22.5 meters and uses a monopole foundation.

This design is beneficial to both, transmission system operator (TSO) and a broader public acceptance in different ways:

- Less visual impact due to a smaller and more compact structure.
- Reduction of installation cost due to the lightweight design of the structure, both in terms of smaller structure and foundation.
- Reducing magnetic fields and corona noise due to use of nonconductive materials.
1.2 Partial discharges

Partial discharge breakdown occurs due to sparks within the voids and gaps of the material, causing damage and degradation of the void walls and progressive deterioration [12]. Manufacturing faults could result in small voids in composite materials, for example due to air leakage during infusion or larger voids because of lack of resin (pre-delamination). Voids could also be formed due to non-uniform contraction or slow chemical reaction during curing of thermosets [12]. These pre-defects in the material, combined with damage propagation due to fatigue, creates an ideal situation which in the presence of high voltage, can excite partial discharges and further deterioration of the material and structure.

Two main theories describing the discharge activity in a void known as, Townsend, and Streamer model, are explained briefly here.

**Townsend discharges**

The theory was developed by Townsend concerning the electrical breakdown in gases while subjected to an electric field [13]. Dissado and Fothergill [12], explain that this theory is based on the avalanches caused by electrons, propagating inside the void in the direction of applied electric field. An electron injected from the cathode side of the void causes the initial avalanche. If the electric field is high enough and the mean path in the direction of the field is long enough, this electron may gain kinetic energy and by colliding with other molecules ionises them and generate more free electrons. This is known as secondary avalanche. This act could be continued and result in self-sustaining avalanche. There is a voltage below which breakdown will not occur, known as inception voltage. This voltage depends on the nature of the void and surrounding material. The shape, size, temperature and pressure of gas are important factors for the level of inception voltage.

The schematic of initial and secondary avalanches in Townsend discharges are show in Fig. 1.8

![Schematic of Townsend discharges](image)

**Streamer discharges**

Holbøll [13] mentions that, streamer discharges can be seen as the follow-up of Townsend discharges. Once a space charge is generated as a result of ionisation from the Townsend discharges, and if the resultant field reaches the same order of magnitude of the applied field, photoionization may occur, due to the photons emitted from the ionised molecules, and start new avalanches. This may generate a discharge channel across the whole gap and form a streamer like discharges and the channel could be observed as a plasma.
An important difference between Townsend and Streamer discharges is the dependency of the magnitude of Streamer discharges to the size of the gap as opposed to magnitude of Townsend discharges, which are independent from the size of the gap and only depend on the overvoltage [14]. Streamer dischargers have much larger magnitude compared to Townsend discharges which make them more damaging [12].

**Partial discharge degradation in polymers**

According to Dissado and Fothergill [12], partial discharges could result in degradation of polymers by different mechanisms:

- Chemical reaction: either between excited molecules (particularly oxygen) and the void surface or between metastable molecules such as ozone, and the void surface.
- Heat: localized heating due to formation of high-energy gas.
- Ion bombardments: bombardment of the surface of the void by high-energy ions. However due to the relatively low energy of each individual ion, it is unlikely that this mechanism could cause any significant damage, though it can worsen the exiting damages such as cracks caused by chemical attack or mechanical strains.
- Electrical tree initiation: electrical tree is a degradation mechanism that occurs in high voltage polymeric insulation. Partial discharge activities results in hollow channels of degradation in the propagation stage [15].

**Partial discharge measurement**

Holbøll [13] explains that, in order to quantify the actual discharge displacement in the voids and cavities, a relationship between measurable quantities, commonly voltage in electrical installations or current under laboratory conditions, and actual discharge displacement needs to be constructed. Apart from the magnitude of measurable quantities, the time of occurrence of partial discharges with respect to the phase of applied voltage can be detected.

Two models that establish these relationships are, the ABC model presented by Whitehead [16], and Pedersen theory [17]. Due to the simplicity and wide use of the ABC model, only this model will be explained here.

The ABC model, describes the relationship between the discharge in a void in a dielectric and measurable voltage variation between the two electrodes [13]. This is a rather simple model that is widely used to demonstrate this relationship. The physical representation and the equivalent electrical circuit are shown in Fig. 1.9.

**Fig. 1.9: Physical representation and equivalent electrical circuit of PD in a void.**

Following explanation of partial discharge measurement, by using the ABC model, is presented by Dissado and Fothergill [12]:
$C_v, C_s, R_s$ and $C_p$, serve as void representative capacitance, capacitance of the dielectric in series with the void, resistance of the dielectric in series with the void and capacitance of the rest of the dielectric, respectively. This model is only an approximation, since in reality the capacitive impedances will be distributed. The void voltage can be shown as:

$$V_V = V_A \frac{C_v}{C_v + C_s}$$

(1.1)

Typically, $C_p \gg C_v \gg C_s$ and the charging time, $C_v R_s$, due to high leakage resistance of the insulation $R_s$, is in order of seconds. When the void voltage exceeds the inception voltage (the voltage which below that, the break down does not happen in a gas filled cavity [18]), it is likely that the discharge happens in the void that reduces the voltage to a level less than inception voltage. This happens in the order of microseconds.

The model could be extended by taking into consideration the possible voids or gaps in the interfaces of the electrodes, and the dielectric as well.

### 1.3 Fiber reinforced composites materials and their aging

According to Mazumdar [19], composite materials are a combination of two or more materials with unique final properties that is a combination of constituent materials properties. This definition is general and can include metal alloys, minerals and plastic co-polymers. The category of composite material which is of particularly interested is known as fiber reinforced composites. Fiber reinforced composites have existed in nature long before being fabricated by human, such as woods. Today these materials are usually made of short or continues fibers in a matrix resin. Introduction of polymer-based composites in the 1960s attracted industries attention towards these type of materials.

The type of reinforced composite material, which will be addressed in this work, consists of continuous fibers with polymeric thermoset matrices (resin) as shown in Fig. 1.10.

![Fig. 1.10: Formation of Fiber Reinforced Composite with Continues Fibers [19].](image)

Today, typical fibers in engineering applications are glass and carbon and the matrix is in the form of polymers such as Vinyl ester, epoxy or Polyethylene that are either thermoset or thermoplastics. The most attractive properties of fiber reinforced-materials are their high specific modulus and strength ($E/\rho, \sigma_f/\rho$), which makes them suitable for structural applications.
Aging and fatigue of composite materials

The history of fatigue can be traced back to 1837 by Albert, who studied the fatigue life of conveyer chains [20]. Since then, many studies have been carried out to characterize the fatigue behaviour of homogenous and isotropic materials. Reifsnider [21] points out that, most materials are subjected to change in form and functionality in respond to their environment during time. These changes could be the result of one or more external influences such as, mechanical, chemical and thermal. Composite material are not an exception in this regard. Composite materials contain many internal boundaries between their constituents and the constituents respond differently to long-term application of external influences. This makes the fatigue phenomena in composite material, more complicated compared to some other types of materials. Most composite materials are anisotropic, and properties such as strength and stiffness is in the form of tensor and arrays. Each component within these tensors could change differently with regard to fatigue, during time.

Together with the challenges that Refsnider points out, manufacturing methods and errors have also a large influence on the aging and fatigue life of the composite materials. These issues has made it difficult for the researchers to come up with a comprehensive fatigue model for composite materials.

Aging and failure of composite insulators

Composite insulators on overhead lines have to face mild to extreme weather and environmental conditions, which affects their lifetime. Overhead lines are rather expensive infrastructures, which should last for a few decades while keeping their integrity to provide safe and secure power transmission. Wind, humidity, ice, UV radiation, temperature variation from very cold to hot, are some of the environmental challenges that these structures have to endure.

Tourreil et al [22] states that, one of the aging failure mechanisms that occurs in composite insulators in service is known as “brittle fracture”. Although the number of failures of this type in composite insulators are not high, they have a significant influence on reliability of power transmission lines. This phenomenon was first observed during the 1970’s when some composite insulators that have been in service, failed mechanically short after installation even though they were subjected to loads that were much lower than their load carrying capacity.

Since then, many researchers have investigate this type of failure and tried to understand the underlying mechanisms [22-25]. Kumosa et al. [25], describes brittle fracture as a stress corrosion cracking (SCC) process in load carrying GFRP insulator rods. He has summarized the cause of brittle fracture into three models; each model is based on different mechanisms, as they are described below:

- Model I: failure due to presence of water and mechanical stresses. The failure mode is more likely due to presence of water than acids. [One source of the acid (carboxylic acid) in composite insulators is the presence of the acid particles, which are formed during the manufacturing of the composite rods [22]].
- Model II: the failure is due to presence of acid combined with water and mechanical stresses.
- Model III: the failure is caused by nitric acid formed by corona discharges, ozone and moisture (with the presence of mechanical stresses).

Based on the location of brittle fracture on the composite insulators, Kumosa et al. [25], concluded that the only model that could explain all aspects of brittle fracture in composite insulators is of the third type (Model III).
1.4 Experimental test reviews and standards

The experimental investigations regarding failure of composite insulators, have been mainly focused on the study of the insulators which have been in service and failed due to brittle fracture. Some of these studies have already been mentioned in previous section (aging and failure of composite insulators). Other investigators have focused on the material, rather than the insulator itself, and many of them are regarding the presence of a void in polymeric samples and the resultant partial discharge (PD) activities. Few experiments have been carried out to study the simultaneous effect of mechanical stresses on GFRP specimens while subjected to electrical loads. However, the mechanical stresses applied in these experiments were by static loads. The objective of these experiments, were mainly focused on how the mechanical stresses affect and change the electrical properties and development of partial discharges, rather than the effect of electrical stresses on the mechanical strength of the material. Kutil and Frohlich [26] have described a multi-stress test procedure for qualifications of composite insulation materials in GIS (Gas-insulated switchgear). They have carried out experiments on tube samples with different material configurations, epoxy/glass fiber, epoxy/polyester and thermoplastic with short multidirectional glass fibers. The mechanical load was applied by four-point bending, which has been applied to the samples in steps to achieve multiple strain levels while subjected to 12 kV/mm AC voltage and monitored the PD pattern and its magnitude throughout the tests. To avoid surface discharges the specimens have been tested under 600 [kPa] SF6 pressure. In these experiments, they also compared the PD activities of a pure epoxy tube with a 4 mm diameter void. They have observed two PD modes, named low and high modes with respect to the PD magnitude that occurred without any mechanical loading. However, their results show the correlation between increasing mechanical stress and switching from low to high modes in PD pattern. They also observed, that at the PD impulse frequency was significantly lower at the end of each mechanical stress period compared to the beginning. They argue, since switching between low and high modes (without mechanical load) did not happen in pure epoxy tube with void, switching is only due to composite structure and the imperfections between fiber and matrix. Kutil (1998) [27] mentioned on a similar topic, that the effect of mechanical stress on the behaviour of PD is related to the change of mechanical stresses rather than absolute value of mechanical stress. He suggested a model to describe the steps towards electrical breakdown, which is illustrated in Fig. 1.12.
The contribution of mechanical stresses to enhance these steps are mainly [27]:

- Increasing the PD amplitude and/or number of discharges per half wave, which in some cases considerable PD activates was only triggered by mechanical stresses, during low magnitude (LM) PD activities.
- Accelerating changes in PD activities (development of sinusoidal shape and decrease of PD frequency), after switching to high magnitude (HM).

Burgener and Frohlich (1999). [28], have studied the impact of mechanical stress on the dielectric behaviour of fiber-reinforced insulation materials by testing polyester fabric-reinforced tubes. Three of the samples have been loaded mechanically in tension up to maximum 8% elongation whilst the failure strain was about 10%. Two other samples were not loaded mechanically for comparison. Then the samples were stressed electrically by increasing the voltage stepwise while monitoring the PD activities. Results show no measurable PD inception before flashover for the two specimen which have not been mechanically loaded, as opposed to samples which have been mechanically stressed and all showed measurable PD before the breakdown. They also suggested a model which could relate the crack length to the filed strength required for PD initiation.

IEC (International Electrotechnical Commission) provides many standards, both in term of material selection and tests regarding the composite insulators in their full size. Some of these standards are similar to conventional insulators, while some are focused on composite insulators. Major part of these standards are related to verification of electrical properties of insulators and some are focused on their mechanical strength. Some of these standard and guidelines are mentioned below:

- IEC TR 62039:2007 (Selection guide for polymeric materials for outdoor use under HV stress) [29].
- IEC 61109:2008 (Insulators for overhead lines - Composite suspension and tension insulators for A.C. systems with a nominal voltage greater than 1 000 V - Definitions, test methods and acceptance criteria) [30].
- IEC 61952:2008 (Insulators for overhead lines - Composite line post insulators for A.C. systems with a nominal voltage greater than 1 000 V - Definitions, test methods and acceptance criteria) [31].
- IEC 61462:2007 (Composite hollow insulators - Pressurized and unpressurized insulators for use in electrical equipment with rated voltage greater than 1 000 V - Definitions, test methods, acceptance criteria and design recommendations) [32].
- IEC 62217:2012 (Polymeric HV insulators for indoor and outdoor use - General definitions, test methods and acceptance criteria) [33].

With respect to the available standards and the researches which have been carried out, to the knowledge of the author, no attempts have been made to investigate the possible effect of simultaneous fatigue mechanical and electrical stresses on the lifetime of the GFRP materials. This has formed the basis of motivation for the work presented in this thesis.
1.5 Scope and limitations

Within the scope of this project, the possible aging effect of high voltage electric field combined with mechanical loads have been investigated. These experiments have been carried out on two scales. The first series of the tests were focused on material level, by developing an experimental setup to apply mechanical fatigue loads together with high voltage electrical loads on coupon size specimens. The second series of experiments were conducted on a full-scale composite power pylon arm with combined mechanical and electrical loads.

Fatigue experiments on their own, are rather time consuming; adding to this issue, tight safety regulations with regard to the safety of high voltage experiments, stretched the experiments to a much longer time span compared to what was initially planned. Other issue which affected this project largely in terms of time schedule, resources and results, was related to the quality and delivery of some of the specimens and the full-scale arm. Mismatch between delivered composite panels for material characterization and material configuration in the full-length arm, made it difficult to relate the properties appropriately. Full scale experiments could only be conducted on repaired arms due to lack of resources and the poor quality of the repairs resulted in pre-mature failure. These led to incomplete results and the loss of considerable amount of time.

1.6 Thesis outline

A short summary of the different chapters in this thesis are presented below:

Chapter 2: Design loads on composite power pylon structure.

In this chapter different type of loads (wind, Ice, their combination and weight of the cables) acting on the structure of the power pylon were calculated based on the Euro code standard guidelines.

Chapter 3: Combined mechanical-electrical fatigue of GFRP specimens in fiber direction.

An experimental setup with a specific load introduction unit was developed to be able to apply mechanical and electrical loads in fatigue. Series of experiments were conducted on GFRP coupon specimens with unidirectional laminas, loaded in fiber direction. Partial discharge and temperature measurements were used together with developing an S/N curve to investigate the effect of partial discharges on degradation of these materials.

Chapter 4: Combined mechanical-electrical fatigue of GFRP specimens with off axis layups and manufacturing defects.

Similar experiments as in chapter 3 were carried out on the GFRP specimens with artificial voids, pre-delamination and [90/0]s layups. Two different resin system were used for each type of specimens namely, epoxy and vinyl ester.

Chapter 5: Combined mechanical-electrical fatigue experiments of full-scale composite arm.

In this part of the project, an experimental setup was developed for fatigue testing of a full-scale composite arm while subjected to simultaneous mechanical and electrical loads. Series of tests were conducted on the full-scale arms and the results are discussed in this chapter.

Chapter 6: Conclusion.

This chapter includes conclusion and remarks with respect to the work carried out in this project. At the end, Suggestions for future works are presented in this chapter.
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2 Design loads of composite power pylon structure

The design of high voltage overhead power line structures are mainly dependent on the magnitude of the voltage, and environmental parameters. The allowable distance between each phase and minimum distance between the cables and the ground is affected by the voltage magnitude. These distances will get larger when the voltage magnitude becomes higher. Environmental factors such as wind and ice are local parameters that depend on the surrounding terrain and climate conditions. The overall geometry of the composite power pylon in this project was designed based on electrical allowances and architectural considerations by other partners (Bystrup and Department of Energy Technology of Aalborg University). Once the outer geometry was designed, the mechanical loads induced by environmental factors had to be taken into account, and the subsequent steps in designing the structure, such as strength, durability and stiffness could be carried out.

Different standards and MoP (Manuals of Practice) provide guidelines to calculate the loads imposed on the structure by various environmental factors. Among them IEC 60826 (Design criteria of overhead transmission lines) [34] and Eurocode standard DS/EN 50431-1 (Elektriske luftledinger, der overstiger 1 kV AC – Del 1: Generelle krav – Fælles specifikationer) [35], which is the Danish version of EN 50341-1 (Overhead electrical lines exceeding AC 1 kV – Part 1: General requirements – Common specifications) [36].

DS/EN 50431-1 provides general requirements and common specifications for the design of conventional overhead structures such as lattice towers. The parameters and correction factors highly depend on the terrain specifications and therefore each European country has its own National Normative Aspects (NINAs), which need to be taken into account. Since the geometry of composite power pylons, are not quite similar to the traditional lattice towers, these guidelines have been manipulated to accommodate such differences.

DS/EN 50431-1 standard provides details for calculating nominal and extreme loads from wind and ice on the structure. These loads are split into two main sources. 1) Wind and ice loads affecting the structure directly based on its own geometry, and 2) the loads imposed on the structure from the conductors due to wind and ice loads and the weight of the conductors. The basic input for these calculation starts with basic wind load velocity, basic ice load, terrain category, geometry of the structure and the height of the conductors from the ground. Multiple correction factors are used to calculate different subsequent parameters such as extreme wind and ice loads or the combinations of both. These factors also take into account other parameters such as wind direction and reliability levels such as 50, 150 and 500 years theoretical return period of climate actions. The dynamic effect are also corrected through correction factors in these guidelines. Some of the basic inputs used in this project to calculate wind and loads are presented below.

- Basic wind velocity. This parameter is defined as annual probability exceeding 0.02, which is equivalent to mean return period of 50 years (DS/EN 50431-1, section 4.3.1). (24 m/s, most of Denmark).
- Terrain category. Five different terrain categories are defend in this standard. (DS/EN 50431-1, Table 4.1). (Category II has been used here which corresponds to areas with low vegetation and isolated obstacles).
- Characteristic ice load (On the conductor), is calculated based on the conductor diameter. (Danish NNA. 4.2.3.2)
- Weight of the conductors. (Based on the weight/m of the suggested conductors for this design).

The simplified scheme to calculate the wind load on structures is shown in Fig. 2.1.
Three different load scenarios have been calculated for this structure namely, extreme wind, extreme ice and combined wind and ice in two major directions, perpendicular and parallel to the conductors. Fig. 2.2 shows an example of wind load in the direction perpendicular to the conductors (similar loads on each arm are not shown).
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3 Combined mechanical-electrical fatigue of GFRP specimens in fiber direction

3.1 Objective

As it was mentioned in the introduction, the concept of mechanical-electrical loading on GFRP materials in fatigue has not been investigated thoroughly yet. The lack of experiments on this matter has been the motivation for this study in order to find the possible coupling effects of simultaneous mechanical and electrical degradation of this type of materials. The finding from these experiments will be necessary to design the composite power pylon, which is the main objective of the overall project. The focus of the work at this phase was first to develop an experimental setup that could make it possible to apply mechanical fatigue load on specimens at coupon size level, while simultaneously loaded with high voltage electricity. Multiple measuring techniques have been used to monitor the change in material status during time such as surface temperature, partial discharge activities and visual damages. The results from the combined mechanical-electrical experiments were compared to pure mechanical experiments in order to evaluate if the applied electrical field has any effect on the life expectancy of GFRP materials. This comparison was carried out by developing a semi S/N curve for each type of loading conditions.

3.2 Experimental setup

To speed up the experiments, different servo hydraulic universal tensile machines were used, based on the test loads. The hydraulic machines and their capacity are listed below:

- Instron 8502, 100 [kN]. Load cell capacity of 100 [kN] with Instron 8800 controller.
- MTS 312, 100 [kN]. Load cell capacity (Two different load cells with 100 and 5 [kN]) with MTS FlexTest 100 controller.
- MTS 810, 100 [kN]. Load cell capacity of 20000 [LBS] with MTS FlexTest 100 controller.
- MTS 858, 25 [kN]. Load cell capacity of 25 [kN] with MTS FlexTest 100 controller.
  (These machines have been used for pure mechanical experiments)
- Instron 8516, 100 [kN]. Load cell capacity of 50 [kN] with Instron 8500+ controller. (This machine has been used primarily for combined mechanical-electrical tests).

The strain measurements for static tests have been carried out by either strain gauge, extensometers or DIC methods or a combination of them, depending on the desired outcome. The specification of these measuring tools are listed below:

- 3 and 6 [mm] strain gauges (Depending on the gauge length of the specimens) with 120 [Ω]. Used for alignment check for different setups based on the respective test standards.
- Instron extensometer with 12.5 [mm] gauge length. To measure the stiffness.
- DIC (digital Image Correlation) system with 12 M cameras with Aramis software from GOM for strain filed measurements.

All measuring equipment such as load cells, extensometers and DIC system were calibrated prior to the experiments. Additionally, two different Infrared cameras from Optris GmbH and FLIR, one Olympus optical camera and a PD measuring device from ICMsystem have been used to monitor different outputs of the experiments.
In order to apply an electric field to the specimen, the specimen should have been isolated electrically from the machine. To do so, a special load configuration was developed, to isolate the specimen electrically from the rest of the setup, in order to be able to apply mechanical and electrical loads simultaneously. In this configuration, the specimen would be placed between one of the machine’s grips (lower grip) and a mechanical clamp. A flat insulator bar made of GFRP, with larger dimensions compared to the specimens, was placed between the mechanical clamp and the upper grip. The high voltage input was through the mechanical clamp, named here as “middle clamp”, and the lower grip was grounded. The schematic of this setup is shown in Fig. 3.1.

![Combined Mechanical-Electrical Setup for Coupon Specimen](image)

**Fig. 3.1: Combined Mechanical-Electrical Setup for Coupon Specimen.**

The physical geometry of the machine was the limiting factor of the specimen size due to electrical concerns. In order to avoid flashover from the middle clamp to the columns or other part of the machine, the distance between the middle clamp and grounding point (D1 in the Fig. 3.1) was set three times less than the distance between middle clamp and the surroundings. This would assure that in case of any flashover, it would be confined within the gauge length, D1. With this limiting factor and size of the middle clamp, which had to be able to withstand the mechanical fatigue loads and accommodate for the tests specimen and the insulator bar, the gauge length of the specimen was set to 35 [mm]. This gauge length is shorter than the recommendations for tensile testing of composite specimens, based on ASTM standard [37], and therefore, the uniformity of the strain field in the specimen had to be verified first. This verification is explained in more details in section 3.4 (specimen geometry justification). The middle clamp consists of two sets of wedges, which were placed in a hub and tightened with two bolts Fig. 3.2. This setup, made it possible to apply sufficient gripping forces on the specimen and the insulator rod, which would increase in correspondent with the applied force to the specimen and avoid any slip. However, the wedges needed to be preloaded before the test; otherwise, the specimen would slip out right at the beginning of applying the tensile load. To preload the wedges in this setup, a flat rectangular spacer was placed between the upper and lower wedges, which by tightening the bolts, would apply force on the wedges (same as common manual mechanical grips) and consequently the tab area of the specimen. This configuration led to an easy mounting and alignment of the specimen in the setup, whilst acting as part of the electrical circuit. Other consideration regarding the middle clamp, involved uniformity of the electrical field on the specimen and avoiding sharp corners, to reduce electrical stress concentration. The uniformity of the electric field was verified by finite element simulation, as it is described in the following section.
3.3 Electrical field simulation on coupon specimens

The uniformity of the electric field on the coupon specimens was verified by a finite element model in Ansys® mechanical 15 by APDL coding, Fig. 3.3; however a 3D model was first built in SolidWorks 2014, and was imported to Ansys® using Parasolid format. Ansys® SOLID122 element type was used for this simulation. The element is a 3D charged-based electric element, with 20 nods and has only one degree of freedom, voltage, at each node. This element is applicable to 3-D electrostatic electric fields and suitable for modelling curved boundaries [38]. In this simulation, the lower grip of the hydraulic machine, the specimen and the middle clamp were modelled and were all surrounded with 800*800*800 [mm³] air cube. Applied boundary conditions were: grounding of the faces of the surrounding air, grounding of the parts in the lower grip including the wedges and 20 [kV] voltage on the middle clamp. The material properties used in this model are:

- Metallic parts relative conductivity: 100000 (since the metal parts are conductive, a large number has been chosen for this parameter).
- Relative permittivity of the laminate: 3.2 (based on experimental value for 2 mm thick laminate carried on by Qian Wang at Aalborg university) [39].
- Relative permittivity of the air: 1.

As it can be seen from Fig. 3.3, the electric field on the specimen is uniform. The magnitude of the electric field, \( E_{el} \), is also comparable to a simple analytic calculation.

\[
E_{el} = \frac{V}{D1} = \frac{20000}{35} = 571 \ [V/mm] \ or \ 0.571 \ [kV/mm]
\]  \hspace{1cm} (3.1)

Where \( D1 \), is the closest distance between two electrodes and \( V \), is the applied voltage.
FIG. 3.3: ELECTRIC FIELD SIMULATION ON THE COUPON SPECIMENS.
The insulator bar made of glass fiber/epoxy with 65% of the fibers in 0 degree and 35% in ± 45 degree fiber directions, had a gauge length of 180 [mm] and 30*6 [mm²] cross section area, which was sufficient to avoid flashover to the upper grip.

3.4 Specimen geometry justification

As it was mentioned earlier, the gauge length of the combined mechanical-electrical specimens were shorter than the recommended gauge length of standard specimens for tensile tests which is appx 140 [mm] (standard test method for tensile properties of polymer matrix composite materials D3039/D3039M-08 table 2) [37]. Therefore, the strain field of the specimens in tension, was monitored by using DIC method, in order to verify its uniformity. Prior to manufacturing composite panels with final layup and material which was going to be used in this part of the experiments, two dummy specimen with UD fabric with 0° angle were tested in static and the strain field was monitored. The nominal dimensions of the dummy specimens were 15*35*2 and 20*35*2 [mm³], similar to the nominal dimensions of the final combined mechanical-electrical specimens. The principal strain direction of these two specimens are shown in Fig. 3.4 which are uniform and aligned in the direction of the applied load.

![Image](image_url)

**Fig. 3.4: Principal strain directions on dummy specimens with a) 25, b) 20 mm width and c) load direction.**

The material and layup configuration of the combined mechanical-electrical specimens will be discussed in more detail in the section related to material characterization (3.6.1); However, it should be mentioned that the specimens are composed of 2 UD laminates and have been loaded in fiber direction Fig. 3.4, (c). The major strain direction on the combined specimens at representative load level is shown in Fig. 3.5 (left). The pattern that was repeated along the gauge length seemed rather unusual and wavy and different from major strain pattern on the dummy specimens. As an initial attempt to understand this difference, the strain filed on the standard length specimens were also monitored by the same method (DIC) Fig. 3.5 (right). The same pattern was observed on the specimen with standard gauge length and same width, thickness and layup. Therefore, it was concluded that this behaviour should be from the configuration of the fiber bundles in each layer. To investigate this issue a micro CT scan of a similar specimen was used to visualize the configuration of the fiber bundles, see Fig. 3.6. The fiber bundles were not straight and showed the same wavy pattern as major strain direction, shown in Fig. 3.5. The possible source of this pattern could be due to the manufacturing error or the type of stitching pattern of the fabric as is shown in Fig. 3.6 (left).
Fig. 3.5: Major strain direction on combined (left) vs standard (right) length specimens.

Fig. 3.6: Stitching pattern (left), Fiber bundles (right).
3.5 Electrical setup

The electric setup consists of two parallel circuits. The first circuit provides high voltage electricity input and the second circuit is used to measure partial discharges Fig. 3.8. The circuit providing the high voltage consists of two transformers. The first transformer, provided low voltage as an input for the second transformer (high voltage). The equipment used in these circuits were: a variable transformer (low voltage side) with capacity of 250 volts, a secondary transformer with total output of 10 [kVA] (high voltage side), a 10 [MO] current limiting resistor, a high voltage surge resistor of series P500 and a voltage divider probe. The circuit for measuring PD consists of a coupling capacitor with 0.001 [µF] and 50 [kV] capacity, a digital oscilloscope and a PD measuring device from ICMsystem (Fig. 3.7). The simplified PD measuring circuit is shown in Fig. 3.8 With Cs and Cp representing the specimen equivalent capacitance and the coupling capacitor, respectively. A more detailed of equivalent capacitance and resistance of the specimen is shown in Fig. 1.9

Prior to PD measurement, PD magnitude and its phase with respect to the phase angle of the input voltage were calibrated, using a standard negative corona discharge and a charge generator respectively, Fig. 3.9.

In order to maximize the electrical stress on the material, the input voltage was increased as close as possible to the flashover voltage. Flashover would occur between the middle clamp and the lower grip that was grounded. However, when the flashover would happen, it would disturb the signals from the measuring devices to the controller, causing failure of the controller and abrupt the test. Multiple attempts were carried out to bypass this issue and to secure the measuring units such as load cell. These attempts are listed below:

- Grounding multiple points on the setup.
- Isolation transformer (to isolate the power source from the devices)
- Aluminium foil as insulator around the cables.
- Limiting diodes (not applicable to the units which uses AC voltages such as LVDT)
- Safety fuse, which could terminate the voltage, as soon as the flashover would occur. (Finding appropriate size of the filament was rather a trial and error and very time consuming. The commercial fuses used in housing circuits were tested but the response time was too long. In the later stage of the experiments in which a different transformer was used, it was equipped with internal switch for protection against over current; this issue was solved to a great extent. The current was cut down as soon as the flashover would happen. However, in some instances, even this fuse was not fast enough and before it would cut down the voltage, the controller would experience disturbances).

Nonetheless, in order to avoid disturbances and damage to the controller due to flashover, the controller was shut down and all the cables were unplugged, prior to the flashover test. The experiments were then conducted by dropping the voltage 8% below flashover voltage to make sure the measuring units were safe. This procedure was successful in the majority of the tests. However in some cases, after approx. 10-15 minutes after the tests were started, flashover would still happen and therefore the voltage was decreased even more. In addition, the procedure of finding the voltage level where the flashover would occur was repeated multiple times (since this value was not quite the same in each trial), and the appropriate voltage was then selected to run the tests.
3.6 Results

3.6.1 Material characterization

The laminates used to fabricate specimens in this part of the project were manufactured by Saertex in Germany through the industrial partner, TUCO. The laminates consisted of 2 layers of UD glass fiber and CRYSTIC (polyester resin) resin type, with nominal thickness of 1.8 [mm]. The fabrication of the specimens were carried out at DTU Structural Lab by N.B. Israelsen as part of his Bachelor thesis whom also carried out most of material characterization tests.

Series of standard test procedures were conducted both in static and fatigue, to achieve common in-plane properties of the material. The specimen dimensions were chosen based on the recommendations from ASTM standards, mentioned below, and the type of fixtures used for these tests. Three different type of tests, tensile, compression and shear, were used for material characterization in fiber and transvers directions. In addition, tensile tests were also carried on for non-standard specimens, only in fiber direction, which were used for combined mechanical-electrical tests. The nominal dimension of each type of specimens are shown in Fig. 3.11.

![Fig. 3.11: Schematic of the specimens. A) shear, B) tensile, C) compression and D) combined mechanical-electrical.](image)

The ASTM standards used as guidelines for these tests are:


The configuration for each type of these tests are shown in Fig. 3.12.

![Fig. 3.12: Test setup for material characterization. From left to right: tensile, compression, shear and tensile test on combined mechanical-electrical specimens.](image)
Strain measurements on standard specimens have been carried out by Digital Image Correlation (DIC) method, Fig. 3.13. In case of the combined mechanical-electrical specimens, an Instron extensometer was used to measure the stiffness.

According to ASTM standards [37, 40, 41], poor system alignment in tensile, twisting of the specimen during shear loading and buckling during compression tests could result in premature failure during tests, thereby not yielding accurate elastic module measurements. Therefore, it is suggested to use back to back strain gauges at least on one of the specimens to verify any issue regarding alignment of the test setup. These measurements have been also carried out for each type of tests to insure the mentioned issues do not affect the results, Fig. 3.14.

Pictures of the specimens after failure for each type of tests are shown in Fig. 3.15.
Summary of these material characterization tests are shown in Table 3-1.

<table>
<thead>
<tr>
<th>Fiber direction</th>
<th>Max load [kN]</th>
<th>Failure stress [MPa]</th>
<th>Modulus of elasticity [GPa]</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>Average</td>
<td>28,27</td>
<td>773,39</td>
<td>37,94</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>28,75</td>
<td>783,01</td>
<td>38,41</td>
</tr>
<tr>
<td>transvers</td>
<td>Average</td>
<td>1,53</td>
<td>41,18</td>
<td>10,54</td>
</tr>
<tr>
<td>direction</td>
<td>Median</td>
<td>1,53</td>
<td>41,76</td>
<td>10,47</td>
</tr>
<tr>
<td>Shear</td>
<td>Fiber direction</td>
<td>Average</td>
<td>1,91</td>
<td>34,25</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>1,91</td>
<td>34,37</td>
<td>2,55</td>
</tr>
<tr>
<td>transvers</td>
<td>Fiber direction</td>
<td>Average</td>
<td>2,90</td>
<td>49,38</td>
</tr>
<tr>
<td>direction</td>
<td>Median</td>
<td>2,90</td>
<td>49,38</td>
<td>3,11</td>
</tr>
<tr>
<td>Compression</td>
<td>Fiber direction</td>
<td>Average</td>
<td>10,07</td>
<td>343,48</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>9,90</td>
<td>327,69</td>
<td>36,73</td>
</tr>
<tr>
<td>transvers</td>
<td>Fiber direction</td>
<td>Average</td>
<td>2,58</td>
<td>90,63</td>
</tr>
<tr>
<td>direction</td>
<td>Median</td>
<td>2,64</td>
<td>91,83</td>
<td>9,10</td>
</tr>
</tbody>
</table>

Table 3-1: Material property characterisation.

In the case of combined specimen, two specimens with middle clamp and three with standard grips were tested. The average failure stress of the combined specimens was approximately 12% higher than the standard tensile specimens but the elastic modulus differed by 2.2% only. Composite materials show similar strength characteristics as of brittle ceramics, which is known to show reduction in their strength when the volume is increased for a uniform state of stress [42], therefore, such a reduction in the strength of the specimens with longer gauge length is expected.

**Fiber volume content**

To calculate the fiber volume content of the specimens, a method of burning off the matrix is widely used and was adopted here. ASTM D3171-15 (Constituent Content of Composite Materials) [43], describes two methods to calculate the fiber volume content. In both methods, the density of the specimen needs to be known based on the volume of the samples. Since the volume of the samples were not measured prior to burning off, the density of the glass fiber and the resin from the datasheets were used to calculate the fiber volume instead:

\[
\frac{V_f}{V_s} = \frac{1}{1 + \left( \frac{1}{\rho_f} \right) \left( \frac{W_f}{\rho_r} \right)}
\]  

(3.2)

Which, \(V_f\), \(V_s\), \(W_f\), \(\rho_f\) and \(\rho_r\), represent, fiber volume, sample volume, relative weight of the fibers, density of the fiber and density of the resin, respectively.

Three samples were weighted prior to applying the heat. These samples were then placed in ceramic cups, which were exposed to direct flames at 762° [C] for 10 minutes; this procedure would burn the main part of the matrix and afterward they were placed in an oven with 650° degrees of Celsius for three hours, to completely burn of remaining of the matrix. The samples were weighted afterwards. The datasheets values for fiber and resin density used in this work were, 2.5 and 1.1 [gr/cm³], respectively. Table 3-2, shows the calculated fiber volume based on these data.
TABLE 3-2: FIBER VOLUME FRACTION.

<table>
<thead>
<tr>
<th># Sample</th>
<th>Relative weight of fibers</th>
<th>Fiber volume</th>
<th>Average value</th>
<th>Sample size [mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,741</td>
<td>0,557</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0,699</td>
<td>0,506</td>
<td>0,538</td>
<td>35*20</td>
</tr>
<tr>
<td>3</td>
<td>0,736</td>
<td>0,551</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In addition, two series of tension-tension fatigue tests with the ratio of 0.1 (max stress/min stress) and frequency of 5 [Hz] have been carried on in fiber direction and transvers direction on standard specimens. The S/N curves from these experiments are shown in Fig. 3.16 and Fig. 3.17.

**Fig. 3.16: S/N curve in fiber direction. Tension-Tension.**

**Fig. 3.17: S/N curve transvers to fiber direction. Tension-Tension.**
3.6.2 Assessment of the performance of the middle clamp in fatigue

The effects of clamping, gripping methods and tabs on the static and fatigue properties of composite specimens have been investigated by different researchers [44, 45, 46]. Therefore, in order to investigate the possible effect of the middle clamp and the load train on the fatigue life of the specimens, series of tests with conventional load train (specimen gripped directly between the two hydraulic grips) and combined mechanical-electrical configuration (Fig. 3.1) was carried out. The results from these tests are shown in Fig. 3.18. As it can be seen, no significant effect of the configuration with middle clamp on the fatigue life of the specimens compared to conventional clamping type is noticeable.

![Graph showing effect of different clamping types on the fatigue life of the specimens.](image)

**Fig. 3.18: Effect of two different clamping types on the fatigue life of the specimens.**

To compare the effect of size on the lifetime of the specimens in fatigue, the data from figures and Fig. 3.18 are shown together in Fig. 3.19. As shown in the figure, the S/N curve from standard length specimens has steeper slope compared to the short length specimens (combined mechanical-electrical), approximately 60% higher. This is most likely due to the same reason which was explained to justify the higher strength in short specimens compared to standard length specimens when the failure stress of these two types were compared in static tests; Meaning the shorter the gauge length, less imperfections and impurities in the material volume, which results in higher strength and resistance to fatigue.
Figure 3.19: Size effect comparison between standard and combined mechanical-electrical specimens.
3.6.3 Temperature measurements

The energy released by partial discharges results in raise in temperature. To quantify this effect for the material of the test specimens, an infrared camera was used to monitor the surface temperature of the specimens as will be described here. The measurements have been carried out on two of the specimens, namely SC#24 and SC#41. During these measurements, the specimen was clamped in the test machine with no mechanical load on it. Afterwards, the voltage was increased in steps until reaching the maximum voltage level before flashover and the surface temperature was continually monitored Fig. 3.20 and Fig. 3.21. This procedure was extended over 8 minutes, however in case of the specimens SC#41; the measuring time was increased from 8 to 15 minutes while the voltage was kept at max voltage to see if a steady state will be reached. Surface temperature of this specimen was monitored once more, after 96800 cycles that corresponds to approximately 5 hours and 20 minutes. At this point, the specimen was unloaded both mechanically and electrically and rest for 8 minutes to dissipate the generated heat. The temperature monitoring procedure was followed once more within 8 minutes, as it was described before Fig. 3.22. These initial and final temperature for these specimens are shown in table Table 3-3.

<table>
<thead>
<tr>
<th>Change in temperature [°C]</th>
<th>SC#24</th>
<th>SC#41</th>
<th>SC341 (96800)</th>
<th>Electric field [kV/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>3,36</td>
<td>3,8</td>
<td>1,6</td>
<td>0,68</td>
</tr>
<tr>
<td>Maximum</td>
<td>4,92</td>
<td>4,4</td>
<td>1,9</td>
<td>0,57</td>
</tr>
</tbody>
</table>

Table 3-3: Surface temperature change due to the applied voltage.

Comparison between temperature change in specimen CS#41 before initiating the test and after 96800 cycles show that this change has reduced more than half. This could be because the surface of the specimens are not quite free of any contamination and these contaminations are burned off after applying voltage for a longer period.

![Figure 3.20: Surface temperature vs applied voltage, SC#24.](image)

Furthermore, surface temperature of few specimens were monitored throughout the fatigue cycling, to see the correlation between damage evolution in the specimens and if there are any influence on the temperature of the specimen from PD activities. These measurements for two of the specimens, namely SC#24 (with combined mechanical-electrical load) and SC#27 (only with mechanical load) with maximum stress value of 183.45 [MPa] are shown together with correspondence optical images in Fig. 3.23 and Fig. 3.25.
Both specimens have been tested at maximum stress value of 183.45 [MPa]. Specimen SC#24 has lasted 272986 cycles while specimen SC#27 failed at 658500 cycles. The surface temperature pattern in both specimens shows a good correlation with the damage zone on the specimen in both cases. At the final stages of the failure, the maximum temperature raised to up to 64 and 72° [C], which are 42° and 45° [C] increase from the initial temperature for specimen SC#27 and SC#24, The specimen SC#24 has been tested in two runs, with few hours gap in between. As it can be seen from Fig. 3.24, the temperature of the specimen has been drop due to this interfere, however, the temperature raised to the same level as it was at the end of the first run very quickly. Part of this dramatic raise could also come from the fact that at this stage, due to extensive damage, some internal part of the material will be exposed and the heat can scrape out from these regions and add to the sudden increase of temperature. The raise in the temperature in this specimen mainly occurs toward the end of the test and the dramatic increase in the temperature only happens within few numbers of cycles before failure. Reifsnider and Williams [47], have investigated temperature raise on boron/epoxy and boron/aluminium specimens for different fatigue frequencies. They have monitored the surface temperature throughout the fatigue cycling in these experiments. They mention two types of heat generation mechanisms during
fatigue cycling, rate-dependent (linear) and rate-independent (non-linear) mechanisms. The rate-dependent mechanism is directly proportional to stress, strain amplitudes and specific-loss coefficient of the material. In the rate-independent mechanism, mechanical damage is the common source of heat dissipation, such as cracks and local plasticity. DAO [48], has shown the temperature raise during fatigue testing of talc-filled polypropylene copolymer and homopolymer. He has investigated the effect of test frequency on the generated heat and cycle to failure of these materials. Apart from the fact that the materials tested with higher frequency had a shorter fatigue lifetime, the shape of the temperature-cycles to failure graphs also changes based on the frequency. At lower frequencies, these curves stay more or less flat until close to the failure that the temperature starts to raise sharply but more or less linear; at higher frequencies the temperature raise starts much earlier with a slope that changes smoothly, the flat part of the curves also becomes much shorter. The final temperature at the failure that he reports are 28° [C] at 1 [Hz] for both material types and 53° and 60° [C] at 10 [Hz] for each material. The initial temperature in his experiments is about 22° [C]. The experiments that has been carried out in and discussed in this section, have been run at 5 [Hz]. The higher temperature raise in the experiments that are shown in this section, apart from the difference in material configuration and the type of constituents, is possibly due to the small gauge section, 35*20 [mm²], which results in the damage distribution in a small volume and hence higher temperature at the failure.

Figure 3.23: Surface temperature monitoring of specimen CS#27 during pure mechanical fatigue cycling. a) 16200, b) 601966 and c) 658500 cycles.
**Fig. 3.24**: Increase in temperature during fatigue, specimen SC#24.

**Fig. 3.25**: Surface temperature monitoring of specimen CS#24 during combined fatigue cycling. A) 7050, B) 225044, C) 243044 and D) 271786 cycles.
3.6.4 Partial discharge measurements

Partial discharge measurements play an important role in the combined mechanical-electrical experiments that were carried out in this work; as they can indicate the change in the material status while exposing to mechanical stresses. The measurements have been carried out in different stages of the experiments. Typically at the before initiating the mechanical loading of the specimens, partial discharges were monitored until they would have reached a steady-state condition which afterwards mechanical loading would have been started and partial discharge activities were monitored continuously throughout the experiment. In the case of specimen CS#41, partial discharges were also monitored in the initial stage (before mechanical loading), which the surface temperature of the specimen was monitored by applying voltage in multiple steps. The applied voltage and surface temperature are provided in Fig. 3.21.

Different stages of PD development of this pre-test together with their related phase distribution figures are described below.

1- In the first 2 minutes, V<4 [kV] or E<0.065 [kV/mm], no PD activities are apparent and the surface temperature does not increase noticeably.

2- At 4 kV, the PD activities start to appear with a low magnitude.

3- By increasing the voltage from 4 to 16 [kV] (E≤0.52 [kV/mm]), the PD activities were spread along the negative phase angle of the input voltage but their magnitude stays more or less the same. During this phase, the temperature on the surface of the specimen starts to increase gradually.

4- Increasing the voltage from 16 to 18 [kV] (E≤0.58 [kV/mm]), had a significant effect on the Partial discharges both in terms of magnitude and the pattern. The magnitude of partial discharges increases up to three orders of magnitude compared to previous step (The peak of the PD magnitudes are not clear in Fig. 3.26 due to gain adjustment and saturation). Partial discharges also become apparent in the positive phase angle with respect to the input voltage. The temperature increases slightly at this stage and remains constant.

5- While the level of voltage has been kept constant at 18 [kV], after approximately 13 minutes since the start of this test, partial discharge activities drops dramatically. The temperature of the specimen’s surface however, remains constant until the end of this test.

![Fig. 3.26: PD pattern development during increasing voltage.](image-url)
The fact that the temperature on the specimen did not drop when the partial discharge activities were reduced in stage five, could indicate that apart from partial discharges, some current leakage might also take place. Applying voltage to insulators causes some current leakage, which results in electric power dissipation and increase in temperature. If the thermal break down (from electrical perspective) does not occur, a steady state will be reached [12].

Partial discharge measurements were carried on continuously throughout the fatigue tests to find any correlation between these measurements and damage propagation in the specimen. In total, five specimens have been tests with combined mechanical-electrical loading, which in the first test, specimen SC#20, PD measurements were not logged. The test on specimen SC#41 was terminated after approximately 1750000 cycles. All measurements, more or less show the same PD pattern, with an exception of one of the specimens, SC#24 as it will be shown here later. The general PD development observed in these experiments are described below:

1- Specimens show a rather high PD activities which could last for few minutes before they are mechanically stress. This is mainly due to surface contamination, which are decease after a while. Partial discharges drop and becomes stable.
2- After applying mechanical loads on the specimen, the PD activities start to raise in terms of magnitude and number of detected PDs for a period of time. This raise in PD activities are usually spontaneous with sharp raise and fallings.
3- As the test progresses, high PD activities would cease and PD level would drop quite dramatically. This period usually lasts much longer than previous stage.
4- Stage 2 and 3 of might repeat multiple times.
5- Towards the end of the test, that specimen would get close to failure; the magnitude of the PD would increase more gradually compared to stage 3, until the failure.

The level of magnitude of partial discharges in stage 3 is usually of the first order, whilst in stage 2 and 4 it would raise 2 or 3 order of magnitudes. However, the increase in magnitude in level 4 is not necessarily higher than what is observed in stage 2.

These general behaviours are shown for two of the specimens, SC#32 and SC#24, are shown in Fig. 3.27 and Fig. 3.28 respectively. The phase and temporal windows shown in these figures are not proportional to the time period and are only representative of the overall pattern observed during the tests. Specimen SC#24, showed a rather different PD activities; as it can be seen from the phase diagrams of this specimen, only positive PD activities are observed with no elevated PD magnitude for approximately the last 6000 cycles before the failure. However, it should be mentioned that in the case of specimen CS#41 which was a run out, similar high PD activities to the one from SC#24 in in Fig. 3.28 (between 876 and 899 minutes), was observed during some periods, but with opposite 180 degrees phase shift and negative sign (some minor PD activities were also present with positive sign), as it is shown in Fig. 3.29.

Other three specimens, SC#20 (only temporal PD activities were monitored and measurements were not logged), 21 and 32, follow more or less the same pattern. In specimen CS#32, the high PD activity prior to mechanical load did not ceased and therefore mechanical loading started after 20 minutes. The PD pattern evolution of specimens SC#21 and 32, before final failure, are shown in more detail in Fig. 3.30 and Fig. 3.31.
**Fig. 3.27:** Partial discharge measurements during fatigue, Specimen SC#32.
**Fig. 3.28:** Partial discharge measurements during fatigue, Specimen SC#24.

**Fig. 3.29:** PD activities in specimen CS#41.
Fig. 3.30: Partial discharge measurements before final failure, Specimen SC#21.
99843 - 102243 cycles
8 min.

102243 - 104643 cycles
8 min.

104643 - 107043 cycles
8 min.

Fig. 3.31: Partial discharge measurements before final failure, Specimen SC#32.
3.6.5 Fatigue results

In total, 21 specimens were tested with pure mechanical fatigue loading 5 specimens with combined mechanical-electrical loads to achieve an S/N curve (Fig. 3.32), and the results from these two load scenarios were compared. All tests have been carried out with 5 [Hz] and a max/min stress ratio of 0.1. To define the 95% confidence band, ASTM E739-10 standard [49] procedure has been followed. Only the specimens with pure mechanical loading have been used for defining confidence band. Even though a slight shift towards the lower limit of the confidence band of the in the specimen with combined loading could be noted, based on these results and scatter in the data no significant effect of combined loading on the fatigue life of these specimens could be concluded. Table 3-1, lists the electrical and mechanical parameters of the specimens with combined loading. The electric field strength is calculated based on the applied voltage and closest distance between the middle clamp and lower grip D1, Fig. 3.1.

![S/N curve: Mechanical vs Combined Mechanical-Electrical Loading](image)

**Table 3-4: Electric and Mechanical Parameters of Combined Mechanical-Electrical Testing.**

<table>
<thead>
<tr>
<th></th>
<th>Flash over voltage [kV]</th>
<th>Test voltage [kV]</th>
<th>Gauge distance (D1) [mm]</th>
<th>Electric field strength [kV/mm]</th>
<th>Max stress [MPa]</th>
<th># cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC#20</td>
<td>22.5</td>
<td>21.00</td>
<td>Not measured&lt;35</td>
<td>&gt; 0.6</td>
<td>211.57</td>
<td>56823</td>
</tr>
<tr>
<td>SC#21</td>
<td>19.00</td>
<td>17.50</td>
<td>32.10</td>
<td>0.55</td>
<td>154.47</td>
<td>509170</td>
</tr>
<tr>
<td>SC#24</td>
<td>24.60</td>
<td>22.60</td>
<td>33.03</td>
<td>0.68</td>
<td>183.45</td>
<td>272986</td>
</tr>
<tr>
<td>SC#32</td>
<td>25.00</td>
<td>23.00</td>
<td>35.50</td>
<td>0.65</td>
<td>202.06</td>
<td>107043</td>
</tr>
<tr>
<td>SC#41</td>
<td>19.40</td>
<td>17.80</td>
<td>31.00</td>
<td>0.57</td>
<td>153.81</td>
<td>1756829</td>
</tr>
</tbody>
</table>

(Run out)
3.6.6 Damage initiation mechanisms

Failure mechanisms in fiber-reinforced composites in static and fatigue are, and have been the subject of many research studies. Possibly one of the largest attempt to investigate failure mechanisms and correlating experiments to different models is World Wide Failure Exercise (WWFE). From manipulation of internal state variables [50], to statistical approaches in assessment of fatigue reliability [51], multiple strategies have been used to come with an appropriate models and failure mechanism explanations, especially in fatigue. The focus of this section however, is not concern with principle failure mechanisms such as matrix cracking, delamination and fiber breaking; but rather it is to distinguish the secondary parameters which influence damage initiation, meaning the effect of sewing threads and backing fibers, using optical methods and visual inspections. Effect of these parameters in the damage initiation and progression have been investigated by other researchers which some of them could be found in [52, 53].

An optical camera has been used for sequential photography of the specimens, while they were illuminated from behind with a cold light. The damage initiation and propagation in specimen SC #23, which has been tested with pure mechanical load at maximum 200 [MPa] with a total life cycle of 110255, is shown and discussed below.

![Fig. 3.33: Damage initiation and propagation in specimen SC#23. A) Initial stage, B) 48000 cycles, C) 81000 cycles and D) 107500 cycles.](image)

1- Damage along the longitudinal sewing threads.
   This type of damage occurred along the longitudinal sewing threads, highlighted by “*”.

2- Damage initiation on the off-axis sewing threads.
   Two type of damage mechanisms on the off-axis sewing threads could be distinguished in these specimens. The first type are sharp cracks which are in a slight angle with regard to the longitudinal axis of the specimen and are highlighted with “x”; The second type which appear as delamination regions, are marked with “+” in these images. Both of these damage types on off-axis sewing threads, seems to be influenced by the transverse backing fibers that cross path the sewing threads however in case of delamination type “+” the intersection of longitudinal and off-axis sewing threads has also a high influence on damage initiation.
**Damage due to electrical stresses**

Specimens with combined mechanical-electrical loading were also monitored by an optical camera to follow the damage status during the fatigue cycling. Only in one of the specimens, SC_41, a visual damage was observed on its surface, which will be explained here. In this specimen approximately after 334000 cycles, a small horizontal damage appears on the surface of the specimen. Initial damage appeared in less than 500 cycles (sequential setting of the image recording); however, it grew very slowly towards the end of the test. The evolution of this damage is shown in Fig. 3.34. To further study this damage, the surface of the specimen was scanned 3D optical microscope from “Alicona”.

![Damage evolution in specimen CS#41](image1)

**Fig. 3.34: Damage evolution in specimen CS#41. A) Initial status, B) 334000 cycles, C) 334500 cycles and D) 1725000 cycles.**

As it can be seen from Fig. 3.35, the damage seems to be due to burning which is the result of partial discharge activities. Similar damage was also observed on the side of the specimen as it is shown in Fig. 3.36.

![Damage on the surface of specimen CS#41](image2)

**Fig. 3.35: Damage on the surface of specimen CS#41.**
Partial discharge activities on this specimen after approximately 1460000 cycles is shown in Fig. 3.37 together with optical image of the specimen in Fig. 3.38. The magnitude of these partial discharges is low but the number of PD’s in period of 8 minutes is quite high. Multiple PD activities can be distinguished in this figure which can be related to multiple damages on the specimen even though they are overlapped.
3.7 Discussions

The scope of this study was to investigate the possible effect of simultaneous mechanical and electrical stresses on the fatigue lifetime of glass fiber reinforced material with polymeric resin. The mechanical fatigue load was applied on the specimens in tension-tension for different stress levels, while applying electrical stresses. An experimental setup was designed and developed which was able to achieve this goal. The specimen layup consists of two UD layup, which were tested along the fiber direction. Different challenges had to be overcome in terms of avoiding flashover and safety regulations in design and conducting these experiments. Multiple measuring techniques such as partial discharge measurements, infrared thermal and optical photography were used to study the damage propagation in the specimens during their fatigue life.

The surface temperature study of the specimens that were loaded only electrically showed approximately 4° [C] increase initially which dropped to 2° [C] after some period, as shown for one of the specimens. This increase in temperature was shown to be related to the partial discharge activities, however as it was discussed before, electrical losses might also be responsible for part of this increase. Temperature measurements during the fatigue of the specimens with and without electrical loading did not show noticeable difference, and it was concluded that mechanical damages were mainly responsible for it. The temperature field pattern showed a good correlation with regard to the damage status on the material (Fig. 3.23 and Fig. 3.25).

Partial discharge activities monitored during fatigue tests were quite dynamic, with raise and fall in terms of repetition, magnitude and the phase shape. With exception of one specimen (SC#24), increase on partial discharges was obvious towards the final failure of the specimens. Multiple damage initiation and propagation on the specimens results in overlap of partial discharge patterns, which makes it difficult to distinguish them from each other. However change in partial discharge amplitude and phase pattern during the fatigue of the specimens show the correlation to the state of the damage in the material. Partial discharges, specially the one with high magnitude appear periodically and vanish but they are tempted to increase in terms of frequency of their occurrence towards the end of the tests. This shows that partial discharges are somewhat self-healing, which is most likely due to increase in the conductivity of the damage are and void surfaces after a while. Damage areas in composite specimens in fatigue could appear in multiple regions. After some periods, the growth in each of these regions might slow down and a different zone becomes activated until some of them are merged towards the end of the specimen’s lifetime and cause final failure. From this, one could conclude that, partial discharge activities (specialy the one with higher magnitudes) are more sensitive to the generation and propagation of damages; as a steady damage regions seems to heal (with respect to partial discharges) after a period of time.

Comparison between the lifetime (S/N curves) of the specimens with pure mechanical load vs specimens that were loaded both mechanically and electrically, show no significant effect of electrical stresses in the cyclic regime these tests were carried out. In addition the fatigue lifetime is governed by mechanical stresses rather than combined mechanical-electrical stresses. It should also be noted that the electric field intensity on these specimens was rather quite low, and unable to have a significant effect in material degradation. In general, PD aging takes a much longer time than these experiments were carried out.
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4 Combined mechanical-electrical fatigue of GFRP specimens with off-axis layups and manufacturing defects

4.1 Objective

One of the major benefits of composite laminates compared to conventional materials such as metals is that by changing the stacking configuration of each lamina and aligning the fibers in different angles, one can achieve different properties such as stiffness and strength in different directions. This allows using the material in a smarter way. Having fibers aligned in only one direction is not uncommon such as manufacturing profiles by pultrusion method; however, in most applications, a laminate consists of different laminas (mainly unidirectional), in which the fibers are aligned in various directions. The change in the fiber direction in a laminate in each layer results in different failure mechanisms. In the experiments that were presented in previous chapter, the laminate consisted of two layers of unidirectional laminas (0)\(_2\), that were both aligned with the load direction. Therefore, in this chapter, the possible effect of different failure mechanism in a laminate with off-axis fiber direction with respect to 0 degree direction, subjected to pure mechanical and combined mechanical-electrical loads will be investigated.

Defects and voids are also a part of manufacturing process in composite laminates which need a precise manufacturing process in order to avoid them. Defects in composite materials can be grouped into three categories: matrix, fiber and interface defects. Matrix defects include voids and incomplete curing; Fiber defects comprise of misalignments, broken fibers and waviness; Unbonded regions between fiber and resin, and between layers are categorized as interface defects [19]. To investigate the effect of defects in the lifetime of GFRP materials while being simultaneously stressed with mechanical and electrical loads, the most common type of these defects namely, voids and pre-delamination were investigated and are presented in this chapter.

The experimental setup is similar to what was presented in the previous chapter for combined mechanical-electrical experiments.
### 4.2 Specimen manufacturing

Four types of specimens were manufactured with various layups and artificial defects. Two types of resin, epoxy and vinyl ester were used, as they are some of the most commonly used thermoset resin systems.

The four specimen types manufactured, can be briefly summarized as:

1. **Type Z**: Unidirectional laminate (0)\textdegree with artificial voids.
2. **Type Y**: Unidirectional laminate (0)\textdegree without artificial voids.
3. **Type X**: Biaxial layup [90/0]s.
4. **Type W**: Biaxial layup [90/0]s with pre-delamination.

The [0\textdegree] and [90/0]s, layup configurations are illustrated in Fig. 4.1.

The fabric consisted of more than 90% of 0° fibers, which was a mix of 2400 and 1200 Tex (appendix A). The epoxy resin system consisted of PRIME™ 20 LV, which was mixed with PRIME™ 20 slow hardener with 100 to 26 weight ratio. The vinyl ester resin was of type Polives™ 702 with PEROXAN ME-50 LA hardener that were mixed with weight ratio of 100 to 2.

To manufacture these laminates, vacuum infusion method was used. An infusion unit from Vacmobile was employed. The module consisted of a single pump and a trap chamber.

Apart from specimen type “Z” with artificial voids, prior to infusion, the resin was degassed, using the same infusion unit. After the infusion the inlet for the resin was closed and pump kept running for approximately 20 hours for curing before disconnected. The laminate was later removed from the mould. Afterwards the epoxy resin laminates were post cured at 80° [C] for 8 hours. Post curing for vinyl ester laminates was carried on at 80° [C] for 3 hours.

The fabrication procedure were as follows:

1. Fabrics were first cut into 570*390 [mm\textsuperscript{2}] pieces.
2. The surface of the glass was cleaned with acetone.
3. The surface of the glass was then polished by release agent.
4. The fabrics were stack up in the desired layup.
5. A layer of peel ply was stacked on top of the laminates.
6. A layer of mesh was then added on top of the peel ply.
7. Spiral tubes were emplaced.
8. The whole setup was then covered with vacuum bag and sealed with sealing tapes.

Stacking sequence of vacuum infusion parts and Infusion setup are illustrated in Fig. 4.2 and Fig. 4.3, respectively.
The source of voids in infused composite panels are either leakage, insufficient vacuum pressure or the curing process and avoiding degassing procedure before infusion. Avoiding degassing before infusion results only small size voids; to enhance the effect of voids with respect to partial discharges, larger voids were needed in case of type “Z” specimens. To do this, an artificial leakage was used to add voids in the laminates of this type. In case of specimens with epoxy resin matrix, since the viscosity of epoxy is low, it was sufficient to remove the intake from the resin container out and let the air to be sucked in; however, the distribution of the voids would not be homogenous in the laminate alone the length of the panel. To solve this problem to some extend an extra tube was added in the position mark with “*” (see Fig. 4.3) equipped with a manual valve which was opened at same time the resin inlet tube was pulled out of the resin container. This would solve the problem of uneven spreading of voids across the laminate in length direction but not along the width, between inlet and outlet. Therefore, the specimens collected for the experiment were selected from the same region to have approximately the same distribution pattern. Same procedure was used in the case of vinyl ester resin laminates with an exception that since the viscosity of vinyl ester resin is much higher than epoxy resin, exposing the inlets to atmospheric pressure was not sufficient to infuse enough voids in the panels. Therefore, an air pressure gun was used to force the air in the laminate. This procedure of infusing voids is rather subjective and is not possible to control the size and quality of the voids precisely. The specimens which were cut from these panels, were inspected visually to make sure they have more or less same void distribution globally. As it can be seen from Fig. 4.4, the voids were elongated in the direction of infusion along the stiches. Further more, micro CT-Scan inspection, revealed that the voids are mainly distributed in the two top layer of the laminate with respect to the glass side of the mould, Fig. 4.5. This resulted in an uneven void distribution in the thickness of the specimens.
For specimen type “W” (with pre-delamination), a thin layer of nylon with thickness of 12.7 [$\mu$m] was placed between the 0 degree layers before the infusion. This type of specimen had a width of 25 [mm], were as other types had the same nominal dimension as combined mechanical-electrical specimens used in previous chapter, Fig. 3.11 (d), with average thickness of approximately 2.28 and 2.12 [mm] for specimens with epoxy and vinyl ester resin were, respectively.

Specimen type “W” and its nominal dimension is shown in Fig. 4.6.
Same procedure that was carried on for specimens presented in the previous chapter (equation 3.2), was conducted here to assess the fiber volume fraction of different specimen types with epoxy resin matrix. The method is not precise especially for the specimens with artificial void, but gives a reasonable approximation, which was the intention here. The epoxy resin density used in these calculation was 0.936 [gr/cm$^3$]. These results are shown in Table 4-2.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Average fiber volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>0.41</td>
</tr>
<tr>
<td>X</td>
<td>0.42</td>
</tr>
<tr>
<td>W</td>
<td>0.42</td>
</tr>
<tr>
<td>Z</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 4-1: Fiber volume fraction for different specimen types.
4.3 Results

Same format as previous chapter has been utilized to present the results here: The temperature raise of the specimens surface prior to the fatigue experiments by increasing the voltage in steps. PD activities during the fatigue tests and fatigue strength of the material with and without electrical stresses.

4.3.1 Thermal measurements

Thermal measurements have been only carried on specimens with epoxy resin matrix as are shown in figure Fig. 4.7. The increase in temperature these specimens varies between 1.1-2.3° [C] with specimen type “W” the lowest and specimen type “Z” showing the highest raise in temperature. During testing of the specimen type “Z”, while increasing the voltage, flashover occurred which its effect on the temperature is highlighted in Fig. 4.7, b.

![Fig. 4.7](image)

**Fig. 4.7: Surface temperature vs applied voltage for specimens with epoxy resin matrix. a) Type “Y”, b) Type “Z”, c) Type “W” and d) Type “X”**.
4.3.2 Partial discharge measurements

Partial discharge measurements were carried out on specimens with epoxy resin matrix throughout fatigue tests. These measurements on specimens with void (type “Z”) have been only carried out on one of the specimens up to 9000 cycles, due to accessibility of PD measuring device. The representative partial discharge pattern which has been dominant throughout the testing of each of these specimens are shown in Fig. 4.8.

![Partial discharge measurements](image)

**Fig. 4.8: Partial discharge pattern for different type of type of specimens with epoxy resin matrix.**

A) Type “Y”, B) Type “Z”, C and D) Type “W” and E) Type “X”.

Specimen type “Y” and “X” (Fig. 4.8, a and e) show only small magnitude partial discharges which were spread through the half cycle of the with respect to the input voltage phase. The pattern looks similar but having 180 degrees phase shift. In specimen type “Z” (Fig. 4.8, b), which the partial discharges were only monitored for the first half an hour (9000 cycles), high partial discharges which are less spread in the phase axis but more extended in the magnitude are visible. Fig. 4.8 c and d, show the PD pattern for specimen type “W” (specimen with pre-delamination), the pattern in (c), occurred initially which lasted about 30 minutes (9000 cycles). This pattern indicates that the partial discharges are focused in a small region, which could be due to the edge of the pre-delamination on this type of specimen. After this
period, only small magnitude partial discharges as it is shown in (d), were present. It should be noted that detection of partial discharges when the magnitude varies a lot depends on the gain adjustment of the PD measuring device and the pattern in d has possibly existed from the beginning in this test. In which the specimen lasted for ~120000 cycles. However, measurements on another specimen of similar type (W_3), showed quite different pattern as shown in Fig. 4.9. The pattern in (a), was only detected for a period of approximately 20 minutes after 24000 cycles and (b), is the PD pattern before final failure which occurred within only in few seconds. This specimen lasted for 64000 cycles. Both of these specimens had a similar failure pattern.

![PD Pattern in Specimen W_3](image)

**FIG. 4.9: PD PATTERN IN SPECIMEN W_3.**

Furthermore, apart from specimen W_3, no significant partial discharge activities was observed in any of the specimens of different types, towards the final failure.
4.3.3 Static and fatigue results

Three specimens of each type were tested in static. The results for maximum stress and stiffness are listed in Table 4-2.

<table>
<thead>
<tr>
<th>Resin</th>
<th>Specimen type</th>
<th>Max Stress [MPa] (average)</th>
<th>Max Stress [MPa] (median)</th>
<th>Stiffness [GPa] (average)</th>
<th>Stiffness [GPa] (median)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>Y</td>
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<td>747.15</td>
<td>32.52</td>
<td>33.32</td>
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<tr>
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<td></td>
<td>Z</td>
<td>805.71</td>
<td>804.07</td>
<td>32.36</td>
<td>31.73</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>417.00</td>
<td>418.77</td>
<td>22.53</td>
<td>22.92</td>
</tr>
<tr>
<td>Vinyl ester</td>
<td>Y</td>
<td>855.01</td>
<td>859.86</td>
<td>35.44</td>
<td>35.56</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>442.15</td>
<td>426.09</td>
<td>25.05</td>
<td>24.49</td>
</tr>
<tr>
<td></td>
<td>Z</td>
<td>827.78</td>
<td>824.03</td>
<td>34.20</td>
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</tr>
<tr>
<td></td>
<td>W</td>
<td>432.75</td>
<td>433.03</td>
<td>23.02</td>
<td>23.30</td>
</tr>
</tbody>
</table>

TABLE 4-2: STATIC RESULTS FOR DIFFERENT TYPE OF SPECIMENS.

Similar to the experiments which were carried on in previous chapter, number of specimens from each configuration were tested in fatigue, with and without electrical stresses to investigate the possible influence of combined loading on the lifetime of the material. For specimens with epoxy resin matrix, it was decided to limit the combined tests to 100000-500000 cycles to failure. To do this, primary mechanical fatigue experiments were carried on to find the appropriate stress levels that could result in these numbers of cycles to failure. In terms of specimens with Vinyl ester resin matrix, the combined test fatigue points were distributed along the fatigue cycles which the pure mechanical tests were conducted. All tests were carried on at 5 [Hz] with fatigue stress ratio (max stress/min stress) of 0.1.

Epoxy resin specimens

Fatigue results from these experiments are presented here for each individual specimen type. Different failure modes in specimen are marked separately in an attempt to explain the large scatter which was observed in these data. In the case of specimen type “Y”, only one specimen was tested with a combined mechanical-electrical loading. For these type of specimens, “Y”, two specimens, one with pure mechanical and the other with combined mechanical-electrical load were tested at 330 [MPa]; the specimen with pure mechanical load last for approximately 258000 cycles and the one with combined mechanical-electrical load last for 416000 cycles. Since the specimen loaded with combined load configuration lasted much longer than the one with pure mechanical and no significant effect of combined loading on the lifetime of the specimens with similar layup, which were tested in the previous chapter, was observed, no further experiments were carried on these type of specimens.

- Type “X”:
  Two failure modes in this type of specimen are shown in Fig. 4.10. These specimens either failed at the vicinity of the tab or in the gauge zone.
Fig. 4.11 illustrates the fatigue lifetime of these specimens for both mechanical and combined mechanical-electrical loading. In terms of scatter in the data in stress magnitudes below 160 [MPa] for specimens with combined load configuration, it appears that the specimens which have failed in the vicinity of the tab have a shorter lifetime compared to failed specimens at the gauge zone; however, this is not the case for specimen with pure mechanical load. This indicates that the scatter in the lifetime of these specimens are not considerably affected by the two mentioned failure mods. A slight shift towards shorter lifetime for specimens with combined loading compared to mechanical loaded ones might be visible; however, the large scatter of these data does not help to support this claim.

![Graph showing fatigue data for specimen type “W” with epoxy resin.]

- **Type “W”:**  
  Similar to type “X”, these specimens either failed in the gauge zone in the vicinity of the pre-delamination or at the tab as it is shown in Fig. 4.12.

![Image showing failure modes in specimens type “W” with epoxy resin matrix.]

The fatigue data for this type of specimens is shown in Fig. 4.13. Since the fatigue life of specimens with combined loading at lower stress levels, surpass the one with pure mechanical loads, the tests were considered as run out. As it can be seen from this figure, the fatigue life of the specimens that have been mechanically loaded and failed in the vicinity of the tab is slightly shorter than one which failed in the gauge section with the similar type load. These data show a lower lifetime for combined loaded specimen compared to pure mechanically loaded specimens at higher stress level, however in low stress level, 135 [MPA], this pattern is reversed. Since the aging effect of partial discharges cannot
have a positive effect on the fatigue life of the specimens, the pattern seen from this figure should be related to the scatter in the data.

- **Type “Z”**:  
  The only failure mode for this type of specimen is shown in Fig. 4.14.

![](image1.png)  
**Fig. 4.14: Failure modes in specimens type “Z” with epoxy resin matrix.**

Fatigue results for this type of specimens shows a large scatter below 240 [MPa], as seen in Fig. 4.15. From these results it does not seem that there is any effect of combined loading on the fatigue life of the specimens with this configuration.

Large scatter in fatigue data of composite materials especially in high cycles is not uncommon and therefore many researchers have tried to use statistical approaches to determine the fatigue life prediction for composites [54, 55, 56]. Regarding the results for the experiments which was carried on here, it was tried to find a correlation between different failure types (failure in the gauge section or vicinity of the tabs) and the fatigue life to explain the large scatter in the data. However, as it can be seen from Fig. 4.11, the specimens with pure mechanical load that failed in the vicinity of the tab, did not necessarily had a shorter fatigue life compared to the ones that failed in the gauge section. In case of specimen type “W”, the effect of failure in the vicinity of the tab on the fatigue life of specimen with only mechanical loading could be observed, but the general scatter in the data with respect to both mechanical and combined loaded specimens could not be explained in this way. These scatter in data are more pronoun when it comes to the type “Z” specimens. A part of the reason for such a large scatter could be the fact that the void distribution in all specimens might not have been quite homogenous and the same. Such a large scatter in specimens with artificial voids could also be found in the work done by Dill et al [57], where the fatigue data for approximately the same stress level vary between a few thousands to a few hundred thousand cycles.
FIG. 4.15: FATIGUE DATA FOR SPECIMEN TYPE “Z” WITH EPOXY RESIN MATRIX.
**Vinyl ester resin specimens**

The fatigue data points for specimens with combined mechanical-electrical loading were distributed throughout the S/N curve which was constructed based on the data from specimens that were tested with pure mechanical load. The results showed much significantly less scatter compared to the specimens with epoxy resin matrix. Nonetheless, no reduction in lifetime of the specimens with combined loading configuration was observed compared to pure mechanical loaded specimens. Fatigue results from these experiments together with failure modes of specimen type “W” and “X”, are shown in Fig. 4.16. No experiments were conducted on specimen type “Y” with vinyl ester resin matrix.

![Fatigue results graphs](image-url)

**Fig. 4.16:** Fatigue results for specimens with vinyl ester resin. a) Type “Z”, b) Type “X” and d) Type “W”. e) The failure mode of specimen type “W” and f) Type “X”.

Fig. 4.17 shows failed specimens of type “Z”. The specimens with a combined load, except one specimen (R_06), exhibited a different failure pattern than the ones which were loaded only mechanically. Specimen R_06, also showed
a slight shorter fatigue life compared to the other three specimens with combined load configuration as it is marked in Fig. 4.16. Whether or not this type of failure is the result of electrical load or just a random failure pattern will require more experiments to ascertain.

![Figure 4.17: Failure modes of specimen type “Z” with vinyl ester resin.](image)

### 4.4 Discussion

To investigate the effect of layup configuration, resin and defects on the fatigue life of GFRP material, series of test with a similar setup as experiments in previous chapter were carried out. Thermal and partial discharge measurements were only conducted on specimens with epoxy resin and mechanical and combined mechanical-electrical fatigue experiments for both epoxy and vinyl ester resin based specimens.

Surface temperature measurement on epoxy/glass specimens showed a lower raise compared to specimens with CRYSTIC resin, which were analysed in the previous chapter (1.1-2.3° [C] in epoxy/glass and approximately 4° [C] in CRYSTIC/glass specimens).

Partial discharge measurements for each specimen type was carried on during the fatigue tests. Specimen type “Y” and “X” showed a similar PD pattern, but the types “W” and “Z” had a distinct pattern as shown in Fig. 4.8. Compared to the specimens with CRYSTIC resin which were described in the previous chapter, epoxy resin specimens did not show any raise in PD activities towards the end of their fatigue life and not even as high PD activity as was observed in each of them before their failure.

The electric field intensity on different type of specimens (for both resin systems) varied between 0.7-1 [kV/mm]. This electric intensity value is higher than the specimens that were tested in the previous chapter (0.55-0.68 [kV/mm]).

Large scatter and limited number of fatigue tests in specimens with epoxy resin, made it difficult to conclude any effect of combined mechanical-electrical load on the lifetime of these specimens. However, in specimens with vinyl ester resin, ineffectiveness of combined loading compared to pure mechanical loading on the fatigue life of the specimens is clear (within the cyclic regime that these experiments were carried out).
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5 Combined mechanical-electrical fatigue experiments of full-scale composite arm

5.1 Objective

In the previous chapters, the effect of combined mechanical-electrical stresses on the fatigue life of composite material was investigated on coupon size specimens.

Zweben [58], points out the significance of the size effect, and the lack of inconclusive experimental evidence for tensile and compressive loadings. Wisnom [59], studied the significant size effect on the strength of composite materials and discussed different sources such as: defects, free edge effects, stress gradient, specimen manufacturing and material microstructure.

Especially, manufacturing defects have a great influence on the strength of composite materials since it is sometimes hard to detect them. These effects are enhanced when the structures are scaled. Both in terms of layup configuration due to manufacturing limits, such as ply drop, draping or manufacturing errors like, fiber waviness, misalignments or voids and defects induced during fabrication and curing process.

The scaling issue and sceptical point of view regarding capability of the final product to keep its integrity based on the design criteria established by small scale testing, makes it necessary to conduct full-scale experiments. In the line of work related to this project, full-scale testing makes it easier to convince TSOs, which are the end line users of overhead power pylon, to adopt this new design in their grid network.

The definition of full scale however needs to be stablished first. Concerning this project, the final product in terms of structural design, consists of a pole, two arms and a conjunction part, see Fig. 2.2. What is described as full-scale testing here, is the load carried section of an arm of the pylon with final length and dimeter.

To get reliable results from these experiments, number of tests should be carried out on multiple arms. However due to lack of time and resources in this project, the following presented work may be viewed as a demonstration case, to show the possibility of combined mechanical-electrical fatigue loading of a large-scale insulator arm.
Multiple experiments were carried out, and to avoid ambiguity, the assigned name and titles for each one of them are mentioned below:

1. Dummy arm. For electrical setup validation.
2. ARM 1. Arm with initial configuration.
3. Arm 2-1. Arm with modified geometry and repaired gauge section.
4. Arm 2-2. Similar to Arm 2-1 with modified joint section.

5.2 Electrical setup validation

In the first stage, a dummy arm was used with the same geometry of the middle section of the designed arm, in which the electrical loading was intended to be applied. Since the objective of this part of the experiments was to validate the electrical setup, the material and the layup in the dummy arm, was not relevant and the emphasis was on the right outer geometry of this section of the arm. To be able to stress the material, electrically, two corona toroids, needed to be placed parallel to each other on the arm. One would be the input for applying high voltage, while the other ring would be grounded. The appropriate size of these toroids, was calculated by finite element simulation in Department of Energy Technology at Aalborg University, by Tohid Jahangiri, Fig. 5.1. The results from these simulations suggested a section diameter of 100 [mm].

Since the final position of the toroid and the distance between them had to be flexible so they could be adjusted on the arm, a simple locking mechanism was added to each of the toroid, which made it easy to fix them on the arm with the desired distance and location Fig. 5.2. The configuration of the voltage input toroid was modified in the experiment due to the fact that the sharp edges on the fixing mechanism would have increased the possibility of the flashover and limit the magnitude of the applied voltage. To overcome this issue in the test’s setup, an extra toroid was placed on the outside of the electrical gauge zone, which would cover the fixing linkage between these two toroids.

Finding the exact size of these customized toroids was not easy. Taking into account the diameter of the ring, which had to be large enough to be mounted on the arm. Therefore, four 90° elbows for each toroid, were put together to get the right dimensions for both section and the full ring diameter as close as possible to FEM simulation results. The material for these toroids were aluminium with thin wall thickness to reduce the weight. The final dimension of the manufactured toroids are mentioned below:

- Section diameter: 4”.
- Radius of the full ring: 18”
- Wall thickness: 0.12”

FIG. 5.1: FEM SIMULATION OF THE ELECTRIC FIELD ON THE ARM.
The final electrical setup consisted of a dummy arm, three toroids, a transformer with maximum nominal capacity of 200 [kV], a variable transformer, digital oscilloscope, and an ultrasonic detector. This experiment was conducted at high voltage lab, at the electrical department of DTU. This experimental setup is shown in figure Fig. 5.3.

After increasing the voltage, large PD activities was observed between the two voltage input toroids marked with “*” (using ultrasonic detector), which indicated the distance between the two input toroids was larger than it should have been. In order to reduce and avoiding flashover in this region, this section was covered by thin aluminium foil.
5.3 Electrical setup on the arm

The electrical setup for the test was the same as was used on the dummy arm (section 5.2). When dealing with high voltage, one of the main concerns is related to safety. Therefore, proper grounding and an isolated test area are necessary for these kinds of tests, especially when they are combined with hydraulic units. The distance between the safety cage and the test units was set to approximately two meters and it was fully closed in all directions. The entrance to the isolated zone was possible through two safety doors that were connected to a safety switch, and if they were to be opened accidentally, the high voltage would be cut off immediately. The distance between the two rings was 270 [mm]. Flashover in ARM 2-1 occurred at 125 [kV]. Therefore, initially the voltage in the test was set to 95 [kV] to avoid flashover during the test. However, after few cycles, flashover accrued and therefore the voltage was further reduced to 80 kV. With a simple calculation, the magnitude of the electric field in the gauge length between toroids were:

\[ E_{et} = \frac{V}{l} = \frac{80000}{270} = 296 \ [V/mm] \ or \ 0.3 \ [kV/mm] \]

In which \( l \) was the distance between two toroids.

This electrical field strength is lower than the tests that were carried on coupon specimens (0.55-0.68 kV/mm), however, when compared to the electrical configuration of the real arm, approximately 0.13 [kV/mm], it was about twice more.

In the experiments carried on ARM 2-2, the maximum voltage before flashover was 135 [kV] which was approximately 10 [kV] higher compared to flashover voltage in ARM 2-1. This difference is mainly due to the change in temperature and humidity in the interval in which these tests have been carried out and possible assembly differences of toroids in each setup. Therefore, the applied voltage on ARM 2-2 was set to 100 [kV], which resulted in 0.37 [kV/mm] electrical field strength.

5.4 Mechanical setup

The experiments on the arm were carried out at the DTU structural lab, which was equipped with a vertical strong floor, making it possible to mount large structures such as the ARM. The mechanical setup consisted of a hydraulic actuator with 50 [kN] load capacity with 20 inches stroke length and a MTS 50 [kN] load cell which were all calibrated prior to the experiments. A swivel joint was used at the end connection of the actuator and load cell module to remove forces applied by lateral movements, on the actuator and the load cell. The load introduction point was through two metal slab plates, which were mounted on both the inner and outer side of the arm’s walls thickness at section “E” Fig. 5.6. The thickness of the wall at this section was increased, to avoid premature failure at the load introduction point. The root section of the arm, section A, was first mounted on a coupling plate through bushings manufactured by Fiberline Composites, with 24 “M20” bolts. These bushes are common in wind turbine industry, used to connect the blade to the rotor hub, see Fig. 5.4. These bolts were pretensioned by applying 375 [N.m] torque. Thereafter the coupling plate was fixed on the strong wall with six “MFT50” Bolts. A MTS test star II control unit was used for the experiment that was equipped by MTS series 793 software. The test procedure was implemented with the MTS® MPT software which is preinstalled on this type of controllers. In order to monitor the strains on the gauge zone of the arm, a 12M DIC system from “GOM” with ARAMIS software was positioned approximately two meters above the arm, using a mobile hydraulic arm. The output of the load signal was input to DIC system to match the strains readings to the respected load values. The entire test setup is shown in Fig. 5.5.
**FIG. 5.4:** BUSHINGS CONFIGURATION ON THE ARM.

**FIG. 5.5:** COMBINED MECHANICAL-ELECTRICAL SETUP OF THE ARM.
5.5 ARM 1

The geometry of ARM 1 is illustrated in Fig. 5.6. In order to force the failure in the gauge zone of the arm, section B, the thickness of the walls was reduced compared to the rest of the arm. The structural design of this arm has been carried out separately by Jacob Paamand Waldbjørn, at DTU lightweight structures group.

Upon receiving the arm, it was noticed that multiple regions on the structure were not properly infused. These regions were repaired onsite by the manufacturer of the arm, TUCO, before conducting the test, see Fig. 5.7. The layup of the laminate throughout arm regarding the length of the arm in the design was [0/20/-20/0] with varying thickness in different sections.

Failure mode

During the first static ramp of the ARM 1, before the load level reaching the final value, 45 [kN], the specimen failed due to local buckling on the compression side approximately 3300 [mm] from the root end Fig. 5.8. Since the initial loading of the arm was to adjust different setup parameters, no data were logged. However, the observed failure load was approximately 40 [kN].
5.6 ARM 2

Based on the failure mode of ARM 1 (will be discussed later in this chapter), and further consideration of confining the mechanical gauge length to match the electrical gauge length, a new section, “AB”, was added within the section “B”. The new section “AB” had a length of 340 [mm]. The wall thickness of the gauge zone, “AB” was increased from 4 to 6 [mm] on the tension side and from 6 to 10 [mm] in the compression side. The configuration of the modified and repaired arm is shown in Fig. 5.9.

To manufacture this arm, the damaged section of ARM 1 was removed and new section was replaced using sleeve joints as shown in Fig. 5.10.
5.7 Fatigue procedure and PID control mode

To measure the strain in the gauge zone during fatigue, a repeated block consisting of constant load amplitude sine-wave, followed by a ramp and a dwell was used, see Fig. 5.11.

The number of cycles in this block before the ramp, for ARM 2-1 and ARM 2-2 were 150 and 500, respectively. In ARM 2-1, the duration of the dwell was 5 seconds and while the Load was kept constant during dwell, the DIC system would capture one image and the procedure was repeated. Due to the noise in the strain reading from the DIC measurement of ARM 2-1, the dwell duration in ARM 2-2 was increased to 6 seconds, and three DIC images were captured instead. The strain measurements were carried on the tension side of the section “AB” using a virtual extensometer of length 200 [mm].

This procedure was implemented in the MPT software in the controller and would repeat the procedure automatically. One of the main issues in running fatigue test on specimens which induce large noise in the load signal due to complexity of the specimen, setup or for example tests which deal with crack propagation, is that controller is not capable of following the input command and often the tests will become unstable. To deal with this issue, MTS controller offers two solutions that are more or less of the same nature but different in complexity. The more advance method is called cascade control. This control mode consists of two control loops; the output of the secondary control loop is used as an input for the primary loop [60]. Both primary and secondary loops PID can be adjusted separately. This control mode is not pre-installed in all MTS control software and needs to be further configured. The second method is known as dual compensation control modes. This method is slightly different from the cascade control, as the secondary feedback is used as a compensation command for the primary loop [60]. However, no PID adjustment is possible on the secondary loop. In either of these control methods, the primary loop engages the more stable feedback, which is usually of displacement nature and secondary feedback comes from the load signal.
5.8 Results

5.8.1 ARM 2-1

The fatigue test was carried out in two steps. Initially the arm was loaded up to maximum 25.2 [kN] with fatigue ratio of 0.1 (max load/min load). The frequency of the test was set to 0.5 [Hz]. The specimen was subjected to 378450 cycles. The strain measurements with DIC in the gauge zone showed strain magnitude of approximately 1500 [μmm/mm] which did not change significantly throughout the test. After these number of cycles, a static test was carried on by loading the specimen up to 45 [kN]. The load-displacement (based on the reading from LVDT) and Load-strain (based on virtual extensometer) are shown in figure Fig. 5.12. The overall stiffness of the arm based on the load-displacement response was 0.155 [kN/mm]. The strain field in longitudinal direction on the arm at 45 [kN] is shown in Fig. 5.13.

![Graphs showing load-displacement and load-strain](image_url)

**Fig. 5.12: Static ramp results for arm 2-1. a) Load-Displacement, b) Load-strain.**

![Image showing strain field](image_url)

**Fig. 5.13: Strain field in longitudinal direction (x) of ARM2-1.**
After the static test, fatigue load level was increased to 43 [kN] and the specimen was tested for another 21850 cycles before it failed. The strain monitoring of the gauge zone by DIC showed strain magnitude of approximately 2200 [$\mu$mm/mm] which remained more or less constant before final failure of the arm. The failure of the specimen however was not expected. The specimen failed at the sleeve joint closer to the tip of the arm. Adhesive failure mode was obvious, and the two pieces of the arm sections were pulled out. Fig. 5.14, demonstrate the failure of the arm. On the instance of the joint failure, the root section of the arm was also damaged on the tension side, approximately 500 [mm] from the root end which was the end tip of the bushings in the arm.

![Image](image_url)

**Fig. 5.14: Failure mode of ARM 2-1.**

The overall stiffness of the arm, based on the readings of the load and displacement of the actuator, did not shows any significant drop until the end of the test where the failure in the sleeve joint has accrued, see Fig. 5.15.

![Graph](graph_url)

**Fig. 5.15: Change in stiffness. ARM 2-1.**
5.8.2 ARM 2-2

ARM 2-1 was repaired once more by using a different type of adhesive (epoxy) in the sleeve joints. Initially the arm was loaded statically in force-displacement (using dual compensation) control mode up to 43 [kN] to check the stiffness of the arm. Load-displacement (LVDT readings) and load-strain (tension side of section “AB”) are shown in Fig. 5.16. The overall stiffness of the arm after was similar to the previous test (ARM 2-1), 0.156 vs 0.155 [kN/mm] respectively. The stiffness in section “AB” however, was 140.26 [kN/mm/mm] which was lower than in the previous test, 173.59 [kN/mm/mm], since no repair has been carried on this section of the arm, this deviation is possibly due to error in DIC measurements.

Afterwards the fatigue experiments were conducted with similar load level and frequency as previous experiment. This arm failed once again in a similar way as the previous experiment after 11850 cycles, meaning the failure of sleeve joint in the outer section of the arm (closer to the tip of the arm), see Fig. 5.18. The strain filed (along the longitudinal axis) and direction of major strains are shown in Fig. 5.17.

**Fig. 5.16:** Static ramp results for arm 2-2. a) Load-Displacement, b) Load-strain.

**Fig. 5.17:** a) Strain field in longitudinal direction (X) and b) Major strain direction.

**Fig. 5.18:** Sleeve joint failure, second run. a) Before failure, b) After failure.
5.9 Finite element simulation of the arm

A simple finite element simulation of the arm was developed and modified throughout the project based on the change in the design and manufacturing considerations. These simulations have been carried out by ANSYS® numerical tool. The FEM model was constructed with shell elements. Shell elements are used in thin structures where the ratio of one dimension to the other dimensions are small. SHELL181 element type, which was used in these simulations, is suitable for modelling composite structures and applications with linear or large non-linear strains [61]. The load introduction point was distributed over a circular area with diameter of 350 [mm]. Boundary conditions at the root section were fully constraint through a master node coupled with all the nodes at the root section. Material properties input in these simulations are based on the experiments which was carried on in earlier chapter (Combined mechanical-electrical fatigue of GFRP specimens in fiber direction) and assuming same properties in out of plane direction, see Table 5-1.

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</tbody>
</table>

The objective of these simulations were to find a stress level on the tension side of the gauge zone, “AB”, which corresponded to approximately 600,000 cycles until failure, based on the experimental fatigue results in section 3.6.1, see Fig. 3.16. The tensile stress value corresponding to this amount of cycles is approximately 150 [MPa]. The linear FEM analysis of the first arm, showed that in order to achieve this stress level, the applied load should be approximately 43 [kN]. As it was mentioned in section 5.5, ARM 1 failed due to local buckling below this load level. In the initial design an eigenvalue buckling analysis was carried on which predicted buckling load of 61 [kN]. This value was much higher than the load that this arm failed due to local buckling, therefore, a non-linear buckling analysis was carried on later and it revealed that the correct buckling load was approximately 38.8 [kN], which would cover a zone starting from 1.8 to 6.8 [m] from the root wit maximum deformation at 2.36 [m], Fig. 5.19. These results are closer to failure load and its position from the experiment, ~40 [kN] and 3.3 [m] from the root.

![Fig. 5.19: Buckling mode of ARM 1.](image-url)
Results from FEM simulation of Arm 2-1 at 45 [kN] load, are shown in Fig. 5.20. These results estimate the maximum displacement of 246 [mm], at the load introduction point. The maximum strain value at the gauge section, disregard of the peak stresses due to laminate drop at boundries of this section, shows approximaetly 3366[µmm/mm] corresponding to at 118 [MPa]. Since the model is linear, the corresponding values with 43 [kN] load (experimental input load) can be calculated with scale factor, based on the input load:

\[
S.F = \frac{\text{Load } 1}{\text{Load } 2} = \frac{43}{45} = 0.956
\]

Therefore:

- Maximum displacement= 0.956*246= 235 [mm]
- Stress value in gauge zone= 0.956*118= 112.81 [MPa]
- Strain value in gauge zone= 0.956*3366= 3218 [µ mm/mm]

Nonlinear buckling analysis of this arm showed no indication of local buckling up to 100 [kN] force.
Fig. 5.20: FEM analysis of Arm 2 at 45 [kN].
5.10 Comparison of FEM model and experimental results

The displacement (measured by LVDT), and strain measurements of the gauge section by DIC are compared to FEM model at 45 [kN] load. The FEM analysis shows maximum displacement of 246 [mm] vs displacement reading of 291 [mm] from LVDT in ARM 2-1. The global stiffness of the arm based on these displacement values and the applied load were, 0.183 and 0.155 [kN/mm], for the FEM model and the experiment, respectively. Meaning that the compliance of the arm was more than what estimated by the FEM analysis. This could be due to various reasons such as imperfection in the geometry, laminate layup and thicknesses and applied boundary condition. The strain comparison between FEM model and experiment at 45 [kN], in the gauge zone showed average strain (ignoring the peak values close to boundaries of section “AB”) of 3366 [μmm/mm] and 2600 [μmm/mm] (extracted from Fig. 5.12) respectively.

The strain analysis of the arm from the fatigue test however, showed approximately 1500 and 2200 [μmm/mm] for 22.5 and 43 [kN] load magnitude, respectively. These values in FEM simulation, are 1683 and 3218 [μmm/mm]. The experimental strain values at 22.5 [kN] is closer to the FEM analysis than at 43 [kN] load. The comparison of the strain ratio with respect to the applied load from static and fatigue tests are shown below:

Static:

\[
\text{Load ratio} = \frac{22.5}{43} = 0.523
\]

\[
\text{Strain Ratio} = \frac{1323 \text{ (strain at 22.5 kN)}}{2504 \text{ (strain at 43 kN)}} = 0.528 \quad (\text{Extracted from Fig. 5.12})
\]

Fatigue:

\[
\text{Strain Ratio} = \frac{1500 \text{ (strain at 22.5 kN)}}{2200 \text{ (strain at 43 kN)}} = 0.68
\]

The strain ratio from static test matches quite well with the load ratio, however this ratio in fatigue measurements, is not quite the same. Since the strain value in the gauge zone remained more or less constant during fatigue and no visual damage was observed in this zone, deviation of strain ratio is possibly related to the accuracy of strain measurements in fatigue.

The strain measurements on ARM 2-2, shows a maximum strain of 2977 [μ mm/mm] at 43 [kN] in fatigue which is much closer to the FEM simulation compared to measurements of ARM 2-1 in fatigue.
5.11 Discussion

A large-scale experimental setup to test a full-length insulator arm was described in this chapter. Issues related to the design, manufacturing issues and their significant effect on conducting a valid experiment was shown and discussed.

The importance of non-linear buckling analysis compared to an eigenvalue buckling analysis was apparent. The eigenvalue buckling analysis is computationally less expensive. However, the accuracy of the result was not sufficient in this design. A good correlation between non-linear buckling analysis and experimental results was shown in this work.

Few uncertainties in terms of matching the design and the final product existed, however, the FEM simulation showed a reasonable correlation to the experimental results in terms of overall stiffness and strains.

Apart from ARM 1, which the pre-mature failure was the result of a non-conservative design, In Arm 2-1 and 2-2, the failure of the sleeve joint after repairs was the primary reason of the failure. These repairs were carried on based on the manufacturer’s hand on experiences rather than analysing and testing the joint; and no experiments were carried out with regard to fatigue resistance of the joint. Therefore, in order to save time, reduce the costs and having reliable test results, the quality of the test specimen should improve.

No trace of the electrical ageing was observed in these experiments. The magnitude of the electrical field applied to the arms, were lower compared to the experiments on the coupon specimens. However, the magnitude of the electric field in these experiments, were more than twice of the electric field on the designed pylon.

Apart from the pre-mature failures of the specimens, the setup was adequate to conduct full-scale fatigue experiments with combined mechanical-electrical loads. Keeping in mind that high safety precautions need to be taken into account when dealing with high voltage.
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6 Conclusion

The work carried out in this thesis, was related to a new design of overhead power line structures (composite power pylon). Composite power pylon concept, benefits from non-conductivity of GFRP material, which would redundant the necessity of traditional insulators and results in reducing the size of the pylon. In this project, the effect of combined mechanical-electrical loads on the fatigue life of GFRP material was investigated experimentally.

Few design load scenarios were investigated initially, to have a basis for developing this structure. Wind, ice, combination of both and the weight of the conductors were considered to calculate the external loads on the structure. The calculations were based on the DS/EN 50341-1 standard recommendations.

In the next stage, an experimental setup was developed, which was capable of applying mechanical fatigue loads and high voltage electricity on coupon size specimens, simultaneously. Due to limitations regarding safety and avoiding flashover to the different parts of the hydraulic test machine, the length of the specimens were designed shorter than the standard specimens used in tensile tests of composite material. Therefore, static and fatigue tests were carried out to study the size effect. The static experiments showed that the failure stress of these specimens were approximately 12% higher than the specimens with similar configuration, but with standard gauge length. The elastic modulus however was only 2.2% higher in these specimens. The strain field measurements with DIC, revealed a wavy pattern in the direction of major strains on the specimen which was rather unusual. This wavy pattern was possibly due to the stitching pattern of the fabric. The fatigue life comparison of the combined mechanical-electrical specimens and standard size specimens showed that the S/N curve of standard specimens decayed faster than combined specimens, Fig. 3.19. A special type of clamps (named “middle clamp”) were used in combined setup to isolate the electric field on the specimen. To investigate the effect of this clamp in fatigue of the specimens, fatigue experiments were carried on with and without middle clamp on combined specimens which did not show any considerable effect, Fig. 3.18. before conducting combined tests on each specimens the temperature change on the surface of the specimens were monitored by and infrared camera while the voltage was increased in steps. The results show an in crease of approximately 4° [C] of Celsius increase. The raise in the temperature matched with increased PD activities, however it was pointed out that current leakage might be also responsibly for part of temperature raise. The temperature monitoring during fatigue tests, showed a good correlation between the damage zones and the temperature field pattern. The increase in the temperature was rather dramatic towards the end final failure of the specimens, approximately 42-45° [C]. However, the major temperature raise was monitored only in the few last cycles, see Fig. 3.24. Partial discharge activities were monitored during the fatigue tests. The overall pattern showed a reasonable correlation with damage status in the specimens, with a clear raise of PD activities towards the failure. Fatigue comparison of the specimens with pure mechanical and combined mechanical-electrical load, did not show any considerable difference, see Fig. 3.32. Only in one of the specimens, visual damage due to electrical load was observed which progressed during fatigue as presented in Fig. 3.34-36.

The second series of experiments were conducted on the specimens with two different types of resin (epoxy and vinyl ester). Four different types of specimens for each resin system were manufactured to investigate the effect of off axis layups and common manufacturing defects, voids and pre-delamination. These four types were:

1- (0)4 layup (only one specimen of this type with epoxy resin was tested in fatigue, with and without electrical load).
2- [90/0]s layup.
3- (0)4 layup with artificial voids.
4- [90/0]s layup with pre-delamination.

During fatigue tests, the specimens with epoxy resin were monitored in terms of temperature change with only electrical load and partial discharges. These specimens showed an increase between 1.1-2.3° [C]. In comparison with previous
specimens with CRYSIC resin, the temperature had raised less than twice. The PD measurements in specimens with (04), and [90/0] showed a similar pattern with 180 degrees phase shift. These PD patterns in specimens with voids and pre-delamination are different, as it is shown in Fig. 4.8. The fatigue results of the specimens with epoxy resin were scattered and made it difficult to conclude any effect of combined loading on their lifetime. In the specimens with vinyl ester resin, no aging effect due to combined loading was observed, Fig. 4.16.

In the final stage of this project, a full-scale experimental setup was developed to be able to apply simultaneous mechanical and electrical loads on the arm. The arm was fixed at the root as a cantilever beam and subjected to transvers load. The electric field was applied through toroid which were mounted on the arm approximately 27 cm apart. The gauge section between the toroid had a smaller wall thickness to enforce the failure in this region. After the first trial on the initial arm which failed due to buckling before reaching the maximum design load, a non-linear buckling analysis was carried out which showed that the previous eigenvalue buckling calculation was not sufficient and was the reason of pre-mature failure. The damaged section of the arm was then replaced with a new section and the wall thickness was increased to avoid buckling failure. The gauge section with reduced wall thickness was confined between the toroid with only thickness reduction on the tension side. The new section was then connected to the rest of the arm by sleeve joints. However, after running the fatigue experiments on this arm, the sleeve joint failed and terminated the test. By looking at the failed joint surfaces, it was apparent that the failure was adhesive failure type. The arm was once again repaired, and an epoxy resin was used in the joint section since this adhesive is compatible with most type of reins used in the laminates (the specification of the adhesive joint used in the first repair was not clearly disclosed by the manufacturer). Similar failure occurred on this version of the arm and no further experiments were conducted. The gauge zone on the specimen which the electrical loads were applied, did not show any trace of electrical aging after approximately 200 Hrs in total.

6.1 Future work recommendations

- Partial discharge aging in dielectric materials is a slow process. In order to enhance this aging effect, either the applied voltage or number of fatigue cycles needs to be increased. The applied voltage in these experiments was limited by the flashover threshold on the surface of the specimen and in the air. To increase this threshold, a medium with high dielectric strength such as SF6 could be beneficial.
- Applying electric field in the thickness direction of the specimens needs to be investigated. This also allows increasing the intensity of the applied electric field, since the thickness dimension is much smaller than the gauge length of the specimens.
- Partial discharges appear with different magnitudes throughout the experiments. To capture different PD patterns at different magnitudes which could coexist, a multi-channel PD measurements would be beneficial.
- To avoid time consuming tests regarding justification of small gauge length specimens, a test machine with larger dimensions which could give more clearance distances with regard to high voltage concerns is recommended.
- Large scatter in fatigue data requires more experiments to have a statistically valid results and justify any conclusion on the aging process.
- The damage mechanism in composite materials is rather complicated and multiple damage mechanism coexist together. In order to distinguish the effect of these mechanisms, it is better to carry on the experiments on more basic laminates. For example, laminates with only one layup, to eliminate the effect of delamination when monitoring partial discharges.
- The manufacturing technique in producing the full-length arm could be improved by using filament-winding method, which seem more appropriate with respect to the geometry of the arm.
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References


[38] SOLID122 Element Description, ANSYS, Release 15.0.


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Appendix A.

Fabric specification used in specimen manufacturing in chapter 4.
The overall framework of this thesis is focused on the multi-environment (mechanical and electrical) ageing of GFRP (Glass Fiber Reinforced Polymer) materials. The experiments have been carried out small-scale (coupon size) and large-scale (full-length arm) specimens, while subjected to fatigue mechanical and electrical loads simultaneously. The material selection is based on the conventional structural resins with continues glass fiber reinforcements.

The first part of the work in this thesis is related to the calculation of different types of loads, which are applied on the structure mainly by wind, ice or their combination. These calculations are based on the procedures suggested by Euro code standards for overhead line structure designs.

The second part is focuses on developing an experimental setup for fatigue testing of coupon specimens, capable of applying simultaneous mechanical and electrical loads. An S/N (stress/number of cycles to fail) curve diagram has been developed in order to compare the fatigue life of unidirectional GFRP specimens, while subjected to pure mechanical and combined mechanical-electrical loads.

The third part is related to investigating the effect of different layup configuration and manufacturing defects (pre-delamination and voids) within the material, on the fatigue resistance while subjected to mechanical and electrical stresses simultaneously.

In the final part of this thesis, an experimental setup has been developed for large scale testing of a full-length arm of the power pylon while subjected to combined mechanical and high voltage electrical loads. At the end, the results from the fatigue experiments were compared to the finite element simulations.