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AALBORG UNIVERSITY
DENMARK

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Preface

This thesis has been submitted to the Faculty of Engineering and Science at Aalborg University in partial fulfilment of the requirements for the Ph.D. degree in Mechanical Engineering. The underlying work has been carried out at the Department of Mechanical and Manufacturing Engineering, Aalborg University in the period from November 2009 to December 2012. The work presented here is part of the project “Reliability-based analysis applied for reduction of cost of energy for offshore wind turbines” supported by the Danish Council for Strategic Research, grant no. 09-065195. The financial support is greatly appreciated.

I would like to thank my supervisors Professor Erik Lund, Professor Ole Thybo Thomsen and Professor John Dalsgaard Sørensen for their advice and support and showing me the confidence to direct this project.

I would also like to thank Associate Professor Theodore P. Philippidis and his staff specially Iordanis T. Masmanidis at the University of Patras for hosting me during a month visit at their department in the summer of 2012.

I am glad to have been a part of the Department of Mechanical and Manufacturing Engineering. It has been a great place to work which most certainly is due to the pleasant atmosphere brought about by nice colleagues. I would express my sincere appreciation to my colleagues and friends at the department for all their support and good time we had together.

Finally I would like to thank my family, girlfriend and friends for their love and support throughout the period of this work and for giving me the courage to face problems.

Amin Kimiaeifar
Aalborg, January 2015

ENGLISH SUMMARY

The purpose of this work is development and implementation of methods for reliability analysis of adhesive composite joints under different failure modes to calibrate partial safety factors to be used in the deterministic design. Furthermore, a new risk-based methodology for the design of parts of composite wind turbine blades with the objective of obtaining cost-efficient blades with a more uniform reliability is introduced.

The manufacturing process may introduce wrinkles, dry spots, laminate thickness and fibre orientation defects, resulting in local stress concentrations that may result in a decrease of the structural performance of the composite joints. These factors must be taken into consideration when designing with respect to laminate stacking sequences, joint dimensions, choice of materials, etc. Therefore, the main uncertainties related to all components of a wind turbine blade such as strength and stiffness parameters, geometry, computation, and also load are identified and an appropriate stochastic model for each uncertain parameter is chosen. To this end, one of the following six stochastic models are usually selected, namely the Normal, Log-Normal, Weibull, Gamma and the asymptotic extreme value distributions type I for the smallest and largest elements. The results of literature study on stochastic distribution and experimental evaluations in composite materials are used to conduct the reliability calculations of the adhesive joints. Stress and strain analysis is performed for the joints and an appropriate failure criterion is employed to assess the failure of each component.

Different reliability techniques are examined and finally Monte Carlo simulation and Asymptotic Sampling methods are used. Reliability techniques are coupled with FEA analysis to present an efficient and accurate approach to predict the probability of failure and the reliability index of adhesive joints.

Generally, development of statistical models for all components of wind turbine blades and obtaining the system reliability can imply less uncertainty on estimation of the load bearing capacities (implying smaller and more accurate partial safety factors).

Different failure modes such as ultimate strength and fatigue are considered and different failure criteria compatible with the failure mode are chosen.

A simple and easy to use methodology for calculating the reliability and probability of failure for adhesive bonded joints is proposed which can be used in a similar manner to calculate the reliability for most components of wind turbine blades.

DANSK RESUME

Formålet med dette arbejde har været udvikling og implementering af metoder for pålidelighedsanalyse af sammensatte samlinger/limninger under forskellige fejltilstande for at kalibrere partialkoefficienter til brug i deterministisk design. Endvidere introduceres en ny risikobaseret metode til design af komposit vindmøllevinger med den målsætning at opnå omkostningseffektive vinger med en ensartet pålidelighed.

Fremstillingsprocessen kan medføre rynker, 'tørre' pletter, defekter i laminattykkelser og fibervinkler, som kan reducere de strukturelle bæreevner af sammensatte samlinger/limninger. Disse faktorer må medtages i designovervejelserne med hensyn til laminat stakkesekvens, dimensioner, valg af materialer osv. Dernæst identificeres de væsentligste usikkerheder relateret til alle parametre i en vindmøllevinge, såsom styrke- og stivhedsparametre, geometri, belastninger og modeller. For de usikre parametre etableres en passende stokastisk model for hver af de usikre parametre. Følgende stokastiske modeller er anvendt: Normal, Log-Normal, Weibull, Gamma og en asymptotisk ekstremværdi fordeling af type I.

Baseret på et litteraturstudie af stokastiske fordelinger og eksperimentelle undersøgelser af kompositmaterialer er der formuleret metoder til pålidelighedsberegninger af limsamlinger. Spændingsanalyser er gennemført for hver komponent, og et passende svigtkriterium er anvendt til at modellere svigt af hver komponent. Forskellige pålidelighedsteknikker er undersøgt, dog således at Monte Carlo simuleringer og asymptotiske Samplings metoder er anvendt i de fleste analyser. Pålidelighedsteknikkerne er kombineret med FEA analyser med henblik på at udvikle en effektiv og præcis metode til at estimere sandsynligheden for svigt og det tilhørende sikkerhedsindeks for limsamlingerne.

En generel udvikling af statistiske modeller for alle komponenter i vindmøllevinger og estimering af systempålideligheden kan resultere i en mindre usikkerhed på estimering af bæreevnen, hvilket igen kan resultere i lavere partielkoefficienter.

Forskellige svigtmåder såsom brud i forbindelse med ekstremlast og udmattelse er undersøgt, og forskellige kompatible svigtkriterier er valgt.

En simpel metodologi er udviklet til beregning af påldeligheden af sammensatte limsamlinger. Denne metode kan endvidere benyttes til at beregne påldeligheden af de fleste øvrige svigtformer for komponenterne i en vindmøllevinge.

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CHAPTER 1. INTRODUCTION

In this chapter the background of the research and research objectives are described and the perspectives of application of reliability-based design optimization (RBDO) are discussed. Afterwards, a short introduction of the uncertainties related to the models and reliability techniques is presented and finally, the PhD thesis is outlined.

1.1. BACKGROUND AND MOTIVATION

Composite structures are under a great attention for wind turbine blades due to their excellent specific stiffness and strength properties compared to the weight and reduced energy cost. The quality and performance of the composite products can be affected by different factors such as variations and errors / defects in the manufacturing process and environmental aspects, which consequently affect the material behaviour and geometric characteristics (shape, thicknesses etc.) and also the structural load-response behaviour. These factors are subject to uncertainty and random variations, and therefore probabilistic methods are needed for a rational modelling and subsequent decision making. This implies need for reliability analysis, and reliability-based design optimization of composite structures which is currently a very important area of research [1&2]. In addition, modelling the uncertainties and sensitivity analyses of the input parameters are important parts of studying complex systems such as laminated composite structures and adhesive joints. Specifically, uncertainty analysis refers to the assessment of the uncertainty in response results due to uncertainties in the input parameters, and sensitivity analysis refers to the evaluation of the contributions of individual uncertainties in the input parameters to the uncertainties in the response results [3&4].

A complete statistical modelling of the uncertainties is necessary for reliability-based design (RBD). The uncertainties can be modelled in solution algorithms by stochastic models and assumed to follow certain probability distributions. It should be noted that in real world, the distributions of some random variables may not be precisely known, or probability distributions cannot appropriately represent the uncertainties.

During the last 5-10 years new and improved computational, deterministic methods and models for estimation of the load bearing capacity and behaviour of wind turbine blades have been developed. They assume that the strength and stiffness parameters are known but that knowledge with respect to size, shape and distribution of blade defects, which may be induced during manufacturing or during service, is inadequate. Sensitivity analyses are performed assuming certain defects and damage tolerant design principles are applied. However, these parameters are associated with large uncertainties. It is known that defects may have a significant influence on the strength of a wind turbine blade, but almost no statistical models are available and most researches are based on deterministic models (i.e. models with randomness and based on no statistical data) [5-7].

A real structure consists in general of many elements and for each element several failure modes might occur [8]. The approach to determine the overall reliability for wind turbine blades includes deriving the probability of failure for all the individual components. The overall system reliability can be estimated when the individual failure modes are combined in a series and/or parallel systems of failure elements, based on which upper and lower bounds for the probability of failure can be estimated.

Adhesive bonded joints, as one of the main elements of wind turbine blades, are being extensively and increasingly used for a large variety of applications in other industries such as automotive, aerospace, civil engineering and marine [9-10]. In comparison with mechanical fastening techniques, adhesive bonded joints are being preferred because of mostly their light weight [11], while mechanical fasteners are involved with screws, nuts, bolts and rivets, etc. which add significantly to the weight of the structures, requires more maintenance and torque checking and also reduce the load bearing capacity. In addition, mechanical fastening needs to have holes in structures leading to severe stress concentrations including peeling and interface/interlayer shear stresses and finally reducing the lifetime of the components. Moreover, to reduce the manufacturing costs, large composite structures of complex shape can be manufactured by adhesive joining of separately manufactured parts, albeit this technique has not been accepted for all types of applications.

There are several different types of structural adhesive joints and the main difference between the various joint types is their geometrical configuration such as single lap joint, the single strap joint, the double lap joint, the double strap joint, the stepped lap joint and various types of scarfed adhesive joints [11] as shown in Fig. 1.1. Scarf and stepped joints have more structural efficiency compared to other joint configurations due to the joint load path eccentricities (which ultimately act as stress raisers) are eliminated when compared with simple single or double lap joints (see Fig.1.1). A scarf joint is the structurally most efficient adhesive joining method when compared with other adhesive joint configurations because the stress concentrations at the ends of the overlap area are minimized. On the other hand, a stepped lap joint can have the same mechanical/structural efficiency as a scarf joint from the view point of fatigue and joint strength [12]. In the overlap section of the stepped and the scarfed lap joints, the composite laminate strength is usually reduced when compared with the un-notched laminate strength. This is due to the discontinuity of the fiber reinforcement over the overlap length of the joint, as well as the presence of significant stress concentrations in the adhesive and laminate layers. The stepped lap composite joints can be manufactured with relative ease compared with scarf joints because it is relatively straight forward to make the ply and sub-laminate steps/drops at the end of a composite substructure/part [13&14].

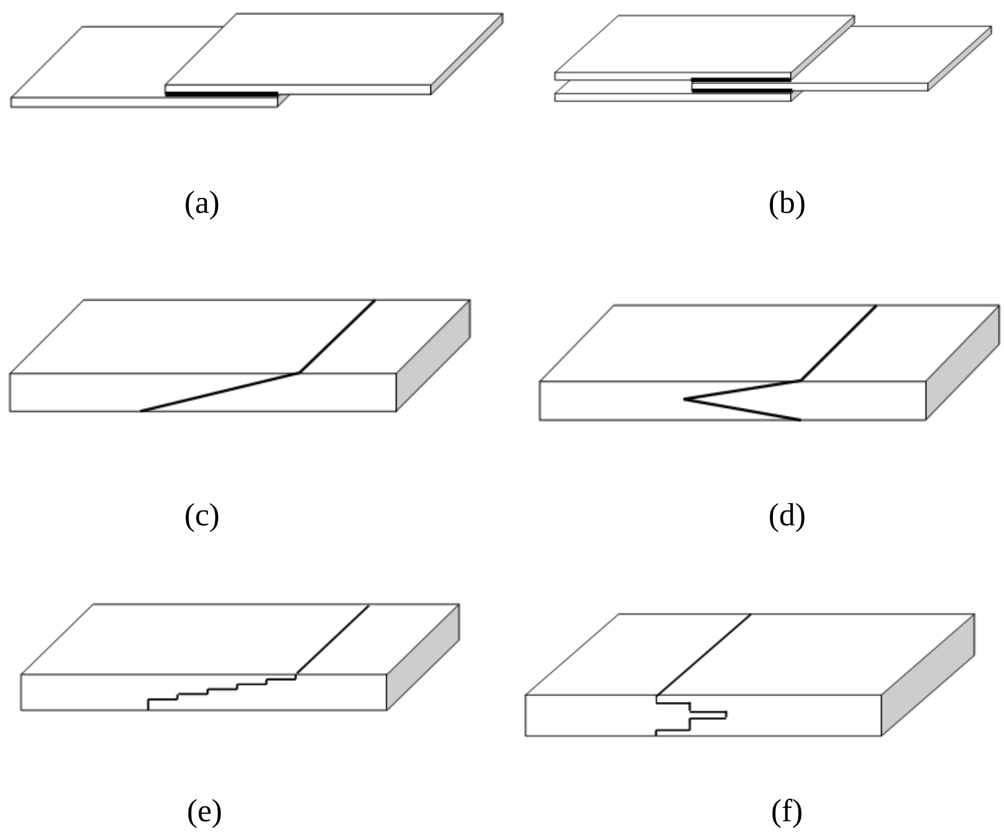

Fig. 1.1. Various types of adhesive joints, (a) single lap joint, (b) double lap joint, (c) scarfed lap joint, (d) double sided scarfed joint, (e) stepped lap joint, (f) double sided stepped lap joint.

The focus in this PhD research is on uncertainty modelling and reliability analysis of adhesive bonded lap joints in composite structures for wind turbine blades. Design of bonded lap joints subjected to mechanical and thermal service loads during processing, constitutes a major technical challenge [14]. Thus, the design of composite adhesive joints is a complex engineering task, which involves a multitude of factors that include the uncertainty related to scattering of the physical (geometric and material) properties, as well as subjective uncertainties including neglect, mistakes, incorrect modeling and manufacturing defects. These factors must be taken into consideration when designing with respect to laminate stacking sequences, joint dimensions, choice of materials, etc. Reliability assessment is also of crucial importance from an economical point of view, since accidents and failures can lead to significant economic loss. Accordingly, the establishment of a reliability based design methodology is important for a rational design [15].

There are not that much studies in the literature in which structural reliability algorithms are incorporated into deterministic finite element codes and used to calculate the probability of failure of a structure. A major main reason is due to high computational cost of the calculations [16-18]. There are several works on estimating the probability of failure or reliability of composite laminates and structures in the literature [19-22]. To the best of the author's knowledge, there is no study available on the reliability analysis of the adhesive composite joints with a detailed stress analysis and taking into account the uncertainties. On the other hand if a time efficient approach can be developed to estimate the probability of failures which can be applied to all wind turbine components, then reliability based calibration of partial safety factors is possible which may lead to more cost efficient blades with a satisfactory reliability level.

1.2. RESEARCH OBJECTIVES

As it was mentioned before, the objective of this PhD project is to develop a new reliability-based methodology for the design of composite wind turbine blades and composite components with the aim to obtain cost-efficient blades with a uniform reliability. The primary objectives and key methods of the project can be specified as follows:

1) Data compilation:

- Objective: Compilation of the information required for the reliability analysis and validating the models.

- Methods: Data related to the following aspects will be compiled: literature related to the mechanical property variability in composite materials (statistical data and models), test results (experimental data) and results derived from simulation models (geometry details, load conditions).

2) To identify and develop statistical models for the main uncertainties related to each component:

- Objective: The main uncertainties related to all components of a wind turbine blade such as strength and stiffness parameters, geometry, and also load are identified and an appropriate stochastic model for each uncertain parameter should be chosen.

- Methods: Experimental tests are performed to statistically model the mechanical properties of the composite parts. Some research has been done in this area which can be used as basis. The model uncertainties related to the load carrying capacity are also modelled by stochastic models.

3) State-of-the-art review of methods for assessment of blade reliability including reliability analysis of different blade parts:

- Objective: Based on a literature review, finding the most efficient and compatible reliability techniques with FEM to formulate a reliability model for the selected blade parts and composite components.

- Methods: Literature study is performed on recent reliability techniques that have been used and have capability to be combined with FEM. Due to the finite element based algorithm and thereby computational highly demanding procedure, different reliability techniques are used and examined to stablish an efficient approach to conduct the reliability evaluation.

4) <u>Reliability calculation for each component:</u>

- Objective: Reliability analysis of blade parts / components.

- Methods: Monte Carlo simulation to estimate the reliability will be applied. In addition, the Asymptotic Sampling technique is to be applied.

5) <u>Reliability-based calibration of partial safety factors</u>

- Objective: Reliability-based calibration of the partial safety factors with the aim to obtain more cost efficient blades.

- Method: Generally, development of statistical models for all components of wind turbine blades and obtaining the system reliability can imply less uncertainty on estimation of the load bearing capacities (implying smaller and more accurate partial safety factors). In addition, quality control by Non Destructive Inspection (NDI) such as visual inspection or ultrasound scanning to detect larger defects in the blade is carried out. The probability of detection has an influence on the reliability level of the system. This means that the required reliability level could be lower if "better quality control" (more and better inspections) is performed. Therefore, the partial safety factors will be calibrated at the end part of the project. This may lower the partial safety factors, which will in turn cause material savings and thereby achieving more cost-efficient blades.

1.3. UNCERTAINTIES

As mentioned above, reliability-based design (RBD) requires statistical information and modelling of the uncertainties. The uncertainties are typically modelled by random variables, treated by stochastic models and assumed to follow certain probability distributions [22]. It is tried to select the most appropriate statistical distributions which fit to a set of random data, when available. However, in many practical engineering applications, there are cases where distributions of some random variables may not be exactly known, or uncertainties may not be properly represented with probability distributions. This lack of knowledge can in many cases be modelled by Bayesian stochastic methodologies.

A description by stochastic fields is needed to model the spatial distribution of the defects taking into account e.g. information from quality control performed in connection with the fabrication [23]. The most applied methods for manufacturing of wind turbine blades are variants of the vacuum infusion. This is a closed process in which a polymer resin is pulled into a mould by vacuum (negative pressure), where the liquid resin impregnates the dry fibres laid out in the mould tool. This manufacturing process may introduce wrinkles, dry spots, laminate thickness and fibre orientation defects, resulting in local stress concentrations that may in turn result in a decrease of the structural performance of the blade. Thus, there may be uncertainties related to analysis models used to estimate the load bearing capacity using perfect / defect-free strength and stiffness parameters. The defects and uncertainties can be modelled by stochastic field models, thus implying the possibility to assess the uncertainties and to estimate the reliability. The modelling of these defects and uncertainties can be based on application of a hierarchical test model consisting of coupon, component and full-scale tests combined with various non-destructive inspection techniques.

Generally the uncertainties can be divided in the following groups:

- Physical (aleatory) uncertainty: uncertainty representing physical uncertainties that cannot be reduced.
- Model, Statistical and Measurement (epistemic) uncertainty: uncertainty related to approximate mathematical models, limited number of data and uncertainty related to measurements / observations.

In addition of the above uncertainties, there are some other uncertainties which are very difficult to quantify such as human / gross errors (including mistakes, incorrect modeling) and they are usually not accounted for in the reliability assessment. It is tried to minimize the influence of the mentioned uncertainties by quality control procedures during design, execution, and manufacturing. Accordingly, the implementation and development of a reliability-based design methodology is of crucial importance for rational design [23].

In the design of composite components / parts of wind turbine blades such as adhesive joints, scattering and physical as well as subjective uncertainties including neglect, mistakes, incorrect modelling and manufacturing errors must be considered when designing for materials, stacking sequence, dimensions, etc.

> Gelma et al. [24] state that "State of knowledge about anything unknown is described by a probability distribution".

It implies that probability distributions are to be employed to model the uncertainties in this study. The following uncertainties are taken into account:

- *Geometrical uncertainties* are the variations in geometrical parameters such as fiber misalignment, variations in composite layer thickness, variation in adhesive bondline and etc. As there is no recorded data for the geometrical uncertainties, Normal distribution functions with COV=0.1 are in general considered for all the parameters. Ply thickness, adhesive thickness, initial length, end length, fiber angle, adhesive angle and adhesive thickness are the parameters considered stochastic in this study.

- *Physical uncertainties* such as variation in Young's modulus, strength parameters and etc. Mean values and standard deviations are obtained through experimental analysis and a proper distribution function is attributed to each parameter. The considered physical uncertainties and associated distributions are summarized in Table 1.1.

- *Load uncertainties* which depend on the operational situations., Some of these uncertainties can be summarized as the uncertainty related to the modelling of the dynamic response for the wind turbine (such as damping ratios and eigenfrequencies), the uncertainty related to the modelling of the exposure (such as the terrain roughness and the landscape topography), the statistical uncertainty related to the limited amount of wind data, the uncertainty in the assessment of lift and drag coefficients, etc. (see Table 1.2).

- *The uncertainty in computational models* such as solution algorithms or simplified assumptions.

Table 1.1. Representative stochastic variables for composite and adhesive material properties [25 & 26].

	Parameter	Mean	COV	Distribution	Characteristic value
UD E-glass/epoxy	E_1 (GPa)	39	10.6%	Lognormal	39
	E_2 (GPa)	14.5	13.6%	Lognormal	14.5
	E_3 (GPa)	9.8	13.6%	Lognormal	9.8
	ν_{12}	*0.29*	*18.0%*	*Lognormal*	*0.29*
	ν_{13}	0.07	18.0%	Lognormal	0.07
	ν_{23}	0.29	18.0%	Lognormal	0.29
	G_{12} (GPa)	4.2	10.7%	Lognormal	4.2
	G_{13} (GPa)	4.2	10.7%	Lognormal	4.2
	G_{23} (GPa)	2.7	10.7%	Lognormal	2.7
	X_T (MPa)	779	13.8%	Normal	602 (5% quantile)
	X_C (MPa)	526	14.3%	Normal	402 (5% quantile)
	Y_T (MPa)	54	10.4%	Weibull	44 (5% quantile)
	Y_C (MPa)	165	11.2%	Weibull	131 (5% quantile)
	S (MPa)	56	10.6%	Weibull	45 (5% quantile)
Adhesive	E (GPa)	2.21	10.0%	Lognormal	2.21
	ν	0.4	18.0%	Lognormal	0.4
	S_{ult} (MPa)	45	10.6%	Weibull	37 (5% quantile)
Graphite/epoxy	E_1 (GPa)	131	10.60%	Lognormal	131
	E_2 (GPa)	8	13.60%	Lognormal	8
	E_3 (GPa)	8	13.60%	Lognormal	8
	ν_{12}	0.3	18.00%	Lognormal	0.3
	ν_{13}	0.3	18.00%	Lognormal	0.3
	ν_{23}	0.07	18.00%	Lognormal	0.07
	G_{12} (GPa)	5	10.00 %	Lognormal	5
	G_{13} (GPa)	5	10.00%	Lognormal	5
	G_{23} (GPa)	4	10.00%	Lognormal	4
	X_T (MPa)	1150	13.5%	Normal	895 (5% quantile)
	X_C (MPa)	750	13%	Normal	590 (5% quantile)
	Y_T (MPa)	47	10.4%	Weibull	38(5% quantile)
	Y_C (MPa)	68	11.0%	Weibull	54 (5% quantile)
	S_g (MPa)	59	10.0%	Weibull	46(5% quantile)

Table 1.2. Representative stochastic variables for the model and physical uncertainty related to the loading [27].

Variable	Description	Distribution	Mean	COV
X_R	Load carrying capacity	Lognormal	1	5%
X_{st}	Limited wind data	Lognormal	1	10%
X_{dyn}	Dynamic response	Lognormal	1	5%
X_{exp}	Exposure	Lognormal	1	10%
X_{aero}	Lift/Drag coefficients	Gumbel	1	10%

The density and distribution functions for a stochastic variable X are expressed: $f_X\left(x|\alpha_1,\cdots\alpha_m\right)$ and $F_X\left(x|\alpha_1,\cdots\alpha_m\right)$ where $\alpha_1,\cdots\alpha_m$ are statistical parameters. If data $x_1,\cdots x_n$ are available then generally the statistical parameters can be estimated using the Maximum-Likelihood Method where the Likelihood function is defined as:

$$L(\alpha_1,\cdots\alpha_m)=\prod_{i=1}^{n} f_X\left(x_i|\alpha_1,\cdots\alpha_m\right) \tag{1.1}$$

and the Log-Likelihood function is given as:

$$\ln L(\alpha_1,\cdots\alpha_m)=\ln\left(\prod_{i=1}^{n} f_X\left(x_i|\alpha_1,\cdots\alpha_m\right)\right)=\sum_{i=1}^{n}\ln\left(f_X\left(x_i|\alpha_1,\cdots\alpha_m\right)\right) \tag{1.2}$$

The optimal parameters are obtained from an optimization algorithm where the Log-Likelihood function is maximized. The optimization problem can be solved using a standard nonlinear optimizer.

1.4. RELIABILITY METHODS

Among all the reliability analysis methods, the Crude Monte Carlo and asymptotic sampling methods were chosen to perform the analysis. The Monte Carlo method is widely used in engineering and other areas for sensitivity and probabilistic analysis. The asymptotic sampling technique proposed by Bucher [28] uses the asymptotic behaviour of the reliability index on the basis of a number of realizations while artificially increases the standard deviation of the basic variables in standard Gaussian space. This method together with Sobol randomized sequences is applied to the models to calculate the probability of failure. This method has been described in papers II and III in the appendix.

1.5. OUTLINE OF THESIS

This thesis is organized as three scientific papers preceded by an extended summary that provides an overview of the topic, highlights the methods and theories, reviews the papers, and highlights the most significant scientific results achieved. Besides this introduction, the extended summary is continued by explaining the ultimate failure and fatigue failure as the failure modes and how they are combined with a stochastic approach to conduct the reliability calculations. Finally, Chapters 3 to 6 summarize the papers and the scientific contributions. The three scientific papers are presented in appendix.

CHAPTER 2. FAILURE MODES AND CRITERIA

In this chapter the failure modes of the adhesive joints are described and the failure criteria used to describe the failure modes are briefly defined.

For a wind turbine blade and composite components, different failure modes can be mentioned such as buckling, fatigue, ultimate strength, critical deflection, etc. For adhesive bonded composite joints, the failure occurs in the adhesive layers (cohesive failure) layers, at the interface (interface failure), or in the adherends. The failure might happen in the matrix under tension/compression, in the fiber under tension/compression, delamination, etc. Ultimate quasi-static failure and fatigue are the two failure modes considered in this study. With respect to the failure mode, different failure criteria are employed to predict the failure of the adhesive or composite layers.

2.1. FAILURE CRITERIA

For failure prediction of composite laminates subjected to a complex extreme load condition a number of failure criteria have been proposed for the ultimate limit state. Each failure criterion has its own advantages and disadvantages. With respect to the application different failure criteria can be used. It is usually necessary to obtain the stress components in the material directions (fiber direction and perpendicular to the fiber) before applying any failure criterion. Among all the criteria, the following criteria have been employed in this study.

2.1.1. MAXIMUM STRESS CRITERION

One of the basic and easiest criteria to apply is the Maximum Stress failure criterion which is a non-interactive failure criterion which is used for failure analysis of an individual composite ply. Due to this criterion, failure happens when any one of the stress components in the material coordinate system (material direction) exceeds the corresponding strength in the same direction. Non-interactive means that the obtained results using Maximum Stress failure criterion are based on a single stress component and do not take into account the influence of multi-axial stress state and how the combination of different stress components affects the failure initiation in a laminate. The most significant advantage of this failure criterion is identifying the exact mode of failure in a ply. Three general failure modes are considered in the Maximum Stress criterion which are longitudinal failure (fiber failure), transverse failure (matrix failure) and finally shear failure.

2.1.2. TSAI WU FAILURE CRITERION

The Tsai-Wu failure criterion, which was first introduced in 1971 [29], is a phenomenological failure theory and it is widely used for anisotropic composite materials. Among its features is that it can account for the difference between the tensile and compressive strengths observed for most composite materials. The Tsai-Wu failure criterion has been found to be one of the more accurate failure theories for composite materials [30 & 31], except for a marked deficiency in predicting compressive failure modes. However, in the present PhD study only tensile loading is considered.

Some of the advantages of this criterion can be expressed as, simplicity to apply, represented by a scalar equation and taking into account the interaction between failure modes. Some of the disadvantages of this criterion can be summarized as, not representing any physical models, no description of failure modes and it is very difficult to calculate the coefficient F_{12} (the interaction coefficient of stress in fiber direction and perpendicular to it).

2.1.3. MODIFIED VON MISES

It is clear that polymeric structural adhesives have nonlinear responses and plastic residual strains are often induced in adhesive joints even at low levels of external loading due to the large stress concentrations at the ends of the adhesive layer. Accordingly, a plastic yield hypothesis can be applied. Thus, it is assumed that the mechanical behavior up to failure of ductile structural adhesives can be represented by an effective stress/strain relationship based on a plastic yield hypothesis. It is further assumed that the plastic residual strains are large compared with the creep strains at normal loading rates [32]. For the current PhD study a modified von Mises criterion in accordance with Gali et al. [33] is adopted for the adhesive layers in the joints. The modified von Mises criterion includes the influence of both deviatoric and hydrostatic stresses.

2.2. FAILURE MODES

The integrity of the load-carrying capacity components of the wind turbine blades should be verified and the safety level should be confirmed through the design process. Ultimate failure and fatigue failure are two failure modes in ULS (Ultimate Limit State) and FLS (Fatigue Limit State) that are considered in order to assess the reliability of adhesive composite joints.

2.2.1. ULTIMATE FAILURE

Ultimate failure of adhesive joints under extreme loads cannot happen until the progressively accumulated damage exceeds the strength of the joint. The process of damage growth in composite components is quite complex and not easy to predict but normally in adhesive joints a crack starts to grow from the adhesive layers or interface and propagates into the outer composite layers of the laminate at the same location and continues in this layer until reaching the small gap on the opposite side of the joints. For the failure prediction of composite laminates subjected to a complex stress state, a number of failure models and criteria have been proposed. In some studies the first ply failure (FPF) concept has been considered to define failure or a Last Ply Failure (LPF) procedure has been applied [34-35]. In this study, the first ply failure (FPF) is chosen to define failure under extreme loads.

It is assumed that the failure probability of a composite laminate can be approximated by the maximum failure probability estimated in any layer of the laminate. Therefore, the probability of failure of the laminates, P_f , is estimated by:

$$P_f = \max_i \left\{ P_f^i \right\} \tag{2.1}$$

where P_f^i is the probability of failure of layer no *i*.

Thus, the probability of failure for the adhesive or composite layers can be estimated by:

$$P_f = P\left(X_R S - S_e \leq 0\right) \tag{2.2}$$

where S is the load carrying capacity and X_R models the model uncertainty related to the load carrying capacity. The equivalent extreme stress S_e is obtained by FEM analysis.

A design equation for deterministic design can be derived by using the limit state equation in Eq. (2.2) where partial safety factors are introduced to secure sufficient safety, and also, a load model relevant for wind turbine blades is applied. A number of stochastic variables are employed to model the uncertainties in the loads on wind turbine blades [36].

A design equation can be formulated in the following form for the situation where it is assumed that the wind turbine is in operation:

$$G = \frac{1}{\gamma_n} \frac{S_c}{\gamma_m} - \gamma_f S_e(L_c) = 0 \tag{2.3}$$

where γ_n, γ_m and γ_f are partial safety factors for the consequences of failure, material properties and loading, respectively, see Table 2.1. Here, only the basic uncertainties and the related partial safety factors are modelled. It is further assumed that the characteristic load carrying capacity S_c can be obtained by inserting characteristic material properties. The characteristic material properties are determined by 50% or 5% quantiles [37]. Usually, the characteristic wind load is determined as a 98% quantile in the distribution function for the annual maximum wind load, corresponding to a return period of 50 years.

Table 2.1. Partial safety factors according to IEC 61400-1 [36].

Partial Safety Factor	**Ultimate**
γ_n – Consequences of failure	1.00
γ_m – Material properties	1.30
γ_f – Load	1.35

The way to obtain the characteristic load has been explained in [36] and the papers in the appendix. The final stochastic load is described in terms of a number of stochastic variables:

$$L = L_s X_{dyn} X_{\exp} X_{st} X_{aero} \tag{2.4}$$

where X_{dyn} models the uncertainty related to the modelling of the dynamic response for the wind turbine (such as damping ratios and eigenfrequencies), $X_{\exp}$ stands for the uncertainty related to the modelling of the exposure (such as the terrain roughness and the landscape topography), X_{st} is the statistical uncertainty related to the limited amount of wind data, X_{aero} accounts for the uncertainty in the assessment of lift and drag coefficients, and L_s stands for the physical uncertainty related to the extreme load during normal operation, and L is the final stochastic variable modelling the load. The stochastic variables used in the limit state function were given in Table 1.2 [36].

The above approach is used to calculate the reliability index of a joint under ultimate loading.

2.2.2. FATIGUE FAILURE

Life prediction for composite structures under cyclic loading has been a subject of interest for more than thirty years. However, numerous papers have been published, a large amount of experimental data on different materials is available, but still there is no definite method / specific fatigue predictive algorithm. There are several available books [38] and some review articles [39] in which the focus is on improving fatigue life prediction for Wind Turbine Rotor Blades design. Generally, the implementation of the numerical procedure for fatigue analysis is very complicated due to their inhomogeneous and anisotropic nature results in the formation of various damage mechanisms and a very early stage of the materials fatigue life [34]. Therefore, most fatigue models proposed until now are founded on an empirical or phenomenological basis. To be able to combine a fatigue approach with reliability techniques and having an efficient computational procedure, two phenomenological fatigue approaches are chosen; the first model is a three-dimensional progressive damage model proposed by Tserpes et al. [40] and the second one is FADAS (FAtigue DAmage Simulator) proposed by Philippidis et al. [41].

2.2.2.1. A three-dimensional progressive damage model

Gradual degradation of the composite material is due to cyclic loading and it is applied on the basis of material stiffness and strength [40]. A linear equation was proposed [42] for modelling the stiffness degradation for each stress level as follows:

$$E_{ij}^{F}(n) = \left[G\frac{n}{N_f^{ij}} + 1 \right] E_{ij}^{S} \tag{2.5}$$

where E_{ij}^{F} and E_{ij}^{S} are the residual stiffness as a function of number of cycles and the static stiffness, respectively, n is the number of cycles, N_f^{ij} is the number of cycles to failure, and G is an experimental fitting parameter.

The general form of the polynomials in terms of normalized residual strength and normalized number of cycles ($\frac{n}{N_f^{ij}}$) is [40]:

$$T_{ij}^{F}(n) = \left[B(\frac{n}{N_f^{ij}})^2 + C(\frac{n}{N_f^{ij}}) + 1 \right] T_{ij}^{S} \tag{2.6}$$

where T_{ij}^{F} and T_{ij}^{S} are the residual and static strengths, respectively, and B, C experimental fitting parameters. It should be noted that adhesive properties remain constants during calculations. Moreover, the model uncertainties can be estimated on basis of test results and corresponding model predictions with deterministic realizations of the stochastic variables in the model according to the test plan using a procedure as described in e.g. Eurocode EN 1990, annex D [43]. Due to lack of available test results, it is not possible to estimate the model uncertainty in this study.

The failure approach is based on the element failure. When failure is predicted in a composite layer by the failure criteria, its elastic properties and strengths are degraded by implementing an appropriate sudden degradation rule as shown in Table 2.2 [40].

Table 2.2. Sudden material properties degradation rules.

Failure mode	**Failure Criterion**	
Matrix tensile cracking	$E_{yy}^{d} = 0.2 * E_{yy}, E_{xy}^{d} = 0.2 * E_{xy}, E_{yz}^{d} = 0.2 * E_{yz}$	(2.7)
Matrix compressive cracking	$E_{yy}^{d} = 0.4 * E_{yy}, E_{xy}^{d} = 0.4 * E_{xy}, E_{yz}^{d} = 0.4 * E_{yz}$	(2.8)
Fiber tensile failure	$E_{xx}^{d} = 0.07 * E_{xx}$	(2.9)
Fiber compressive failure	$E_{xx}^{d} = 0.14 * E_{yy}$	(2.10)
Delamination in tension or compression	$E_{zz}^{d}, E_{yz}^{d}, E_{xz}^{d} = 0$	(2.11)

2.2.2.2. FADAS

The FADAS (FAtigue DAmage Simulator) algorithm is a simple phenomenological model to describe strength and stiffness degradation at each ply due to fatigue loading. It is also used to predict damage progression generated by different failure mechanisms. The algorithm can be used for non-linear material behavior, pseudo-static loading-unloading reloading response, constant life diagrams and strength and stiffness degradation due to cyclic loading based on the extensive experimental database for a unidirectional Glass/Epoxy ply. In this PhD study, a linear form of FADAS is coupled with a reliability algorithm to calculate the probability of failure.

In-plane stiffness of each composite layer degrades due to several reasons, for example sudden stiffness reduction could be due to some kind of failure or progressive stiffness reduction as a consequence of cyclic loading. In general, the latter is nonlinear and several formulations were proposed in the literature to describe it.

The stiffness/strength degradation model in this study is based on the model introduced by Philippidis et al. [41] which is the outcome of a wide range of experimental studies during UPWIND and OPTIMAT projects (research funded by the European Commission in the framework of the specific research and technology development program Energy, Environment and Sustainable Development). A wide range of tests for different lay-ups and *R*-ratio (the ratio of minimum load to maximum) were performed [44] where the following stiffness degradation formula was introduced as a non-linear function of stress redistribution due to fatigue in the following form:

$$\frac{E_i}{E_{i0}} = 1 - (1 - \alpha_i)\left(\frac{n}{N_i}\right)^{\beta_i} \tag{2.12}$$

where α_i and β_i are constant parameters fitted to stiffness degradation data from fatigue testing, and E_{i0} is the initial value of the corresponding elastic modulus, $i = 2,3$. It can be easily seen that the stiffness degradation depends only on the fatigue life fraction but it should be noted that the stress and *R*-ratio are indirectly taken into account while calculating the fatigue life, *N*. It should also be pointed out that the constant parameters, α_i and β_i, are different in tension and compression and stiffness degradation in fiber direction is insignificant and therefore ignored [45].

Table 2.3. Constant parameters in stiffness reduction under tension and compression

Parameter	E_2 **(tension)**		E_2 **(Compression)**		G_{12} **(tension)**	
	Mean value	**Standard deviation**	**Mean value**	**Standard deviation**	**Mean value**	**Standard deviation**
α	0.75	0.0015	0.95	0.12	0.68	0.2
β	3.17	0.0012	0.62	0.13	1.65	0.3
ε	0	0.001	0	0.06	0	0.09

To study the strength degradation due to stress cycling, comprehensive experimental tests were carried out by Philippidis et al. in the research project OPTIMAT BLADES in order to study, amongst other things, the static strength, fatigue life and residual strength behavior of wind turbine rotor blade materials [46].

A linear formulation is used for the residual strength degradation. The strength degradation for different R-ratios is different [34]. Therefore the following equations are used:

$$S_{iiT}^{n} = S_{iiT}^{0} - \left(S_{iiT}^{0} - \sigma_{ii\,\max}\right)\left(\frac{n}{N_{ii}}\right) \tag{2.13}$$

$$S_{iiC}^{n} = S_{iiC}^{0} - \left(S_{iiC}^{0} - \left|\sigma_{ii\,\min}\right|\right)\left(\frac{n}{N_{ii}}\right)^{p} \tag{2.14}$$

$$t_{ij}^{n} = t_{ij}^{0} - \left(t_{ij}^{0} - \sigma_{ij\,\max}\right)\left(\frac{n}{N_{ij}}\right) \tag{2.15}$$

Here S_{iiT}^{n} and S_{iiC}^{n} are the strength components in tension and compression respectively ($i = 1,2,3$) and t_{ij}^{n} is shear strength ($ij = 12,13,23$). S_{iiT}^{0}, S_{iiC}^{0} and t_{ij}^{0} are initial strength parameters in tension, compression and shear, respectively. The exponent p in Eq. (2.14) for the compressive residual strength assumes a high value, e.g. 25, to model appropriately what is known as sudden death behavior.

A huge number of tests were performed for Constant Amplitude (CA) cyclic loadings, parallel and transverse to the fibers and also in shear for three stress ratios, *R*, by Philippidis et al. [45], [47] in the OPTIMAT project. It was shown that the experimental results lead to the following S-N curve for the CA loadings and in all directions:

$$\sigma_a = \sigma_0 N^{\left(-\frac{1}{k}\right)} \tag{2.16}$$

In Eq. (2.11), σ_a is the stress range obtained from constant life diagram (CLD), *N* is the number of cycles to failure, σ_0 and *k* are constant parameters which are dependent on the *R*-ratios and the stress level of the element. The S-N curve equation can be rewritten in the following form:

$$\log N = \varepsilon - k \log \sigma_a - \log \sigma_0 \tag{2.17}$$

where ε is introduced as a parameter which models the lack of fit and is assumed Normal distributed with the mean values and standard deviation as indicated in table 2.4. It should be also pointed out that the Goodman approach for CLD is considered in this study.

Table 2.4. Constant parameters in S-N curve equation for R= -1.

Parameter	m	$\log k$	ε_1
Mean value	6.72	21.36	0
Standard deviation	0.88	0.09	0.07

The failure of the joint is estimated by Eq. (2.1). Thus, the final failure for the adhesive or composite layers is estimated by the following event:

$$P_{f,i} = \{S^i - S_e^{\ i} \le 0\} \tag{2.18}$$

where S^i is the load carrying capacity of failure event *i*. When a failure event was observed, the number of cycles to failure is compared with the designed lifetime of the joint. Therefore, the probability of failure can be written as follows:

$$P_f(t) = P\left(N - N(t)_{lifetime} \le 0\right) \tag{2.19}$$

where *N* is the number of cycles to failures and $N_{lifetime}$ is the expected number of cycles up to time *t*.

CHAPTER 3. RELIABILITY ANALYSIS OF SCARF JOINTS

3.1. ABSTRACT

This chapter roughly describes paper I where a probabilistic model for the reliability analysis of adhesive bonded scarfed lap joints was developed under prescribed displacement condition. A three dimensional (3D) finite element analysis (FEA) is employed for the structural analysis. As it was mentioned before, for the reliability analysis a design equation was considered which is related to a deterministic code-based design equation together with partial safety factors. The failure criteria were chosen among those explained in Chapter 2 such as a von Mises, a modified von Mises and a maximum stress failure criterion. In all the considered cases in this PhD study, the implicit target reliability level in the wind turbine standard IEC 61400-1:2005 is assumed to be β=3.1. Note that in the current revision of IEC 61400-1 the target reliability level has recently been slightly increased to 3.3 with reference time equal to one year, see [48].

A number of factors make the design of composite adhesive scarf joints a complex engineering task. These factors include the uncertainty related to scattering of the physical (geometric and material) properties, as well as subjective uncertainties including neglect, mistakes, incorrect modeling and manufacturing defects. These factors must be taken into consideration when designing with respect to laminate stacking sequences, joint dimensions, etc. In this paper it has been tried to take into account the uncertainties associated with the design and calibrate the partial safety factors considered in the design equation. On the other hand the choice of failure criterion has a great influence on the probability of failure where the presented results in this study verify this influence.

3.2. GEOMETRY AND SOLUTION PROCEDURE

All the FEA modeling and analysis in this PhD research is conducted using the FEA package ANSYS 12.1. The common approach is that a parametric 3D FEA model is developed using a macro file to generate the geometry, FE meshing, material properties and boundary conditions. In the first paper a scarf joint has been considered where the detailed geometry design can be found in paper I at Appendix. A stochastic algorithm has been developed to construct the scarf joint for any value of thicknesses, material properties and mesh division.

It has been tried to consider most of the effective stochastic parameters in this study. The geometrical properties typically follow a Normal distribution, therefore all geometrical parameters have been considered to be normally distributed (see Table 3.1). Due to lack of knowledge and available information, the coefficients of variation (COV) are chosen to 10%.

Eight layers are considered for the scarf joint and a stacking sequence of [0/90]2s is assumed. It should also be pointed out that the composite plies are glass/epoxy and that an epoxy adhesive is used. The mechanical properties of the glass/epoxy and the adhesive are considered stochastic as shown in Tables 1.1 based on recommendations in [25 & 26 & 45-47].

Table 3.1. Stochastic variables for the geometry of the composite scarfed lap joint.

Parameter	**Symbol**	**Mean value**	**COV**	**Distribution**
Ply thickness (mm)	t_L	0.125	10%	Normal
Adhesive thickness (mm)	t_A	0.125	10%	Normal
Initial length (mm)	L_1	30	10%	Normal

End length (mm)	L_2	30	10%	Normal
Fibre angles	-	-	10%	Normal
Adhesive angle (°)	α	10	10%	Normal

As it was explained in Chapter 2, the same approach with the same load multipliers has been considered in this paper, see Table 1.2. To obtain the characteristic load as it was explained in [36] first the 5% quantile of the strength properties is calculated, and then the maximum allowable characteristic load for failure of the joint is obtained through FEA. When the characteristic load is estimated, it is used that it is a 98% quantile in the distribution for the annual maximum load and afterwards the stochastic load (L_s) is assumed to be modelled by a Weibull distribution. Finally the stochastic load used in the solution algorithm together with load multipliers is formulated in equation (2.4).

The modified von Mises criterion was considered for the adhesive part and the maximum stress criterion for the composite layers. It has been assumed that failure occurs when the equivalent stress exceeds the allowable stress. It should be noted that, in the considered case, the adhesive bond line is chosen and nodes attached to the lines are selected except the first and last node which display excessively high stress values due to the presence of stress singularities at these positions in the FEA model (see paper I at Appendix). The average stresses, principal or equivalent, associated with each node over the bond lines are read and compared with the ultimate strength. This process is repeated for 10000 simulations as considered in the Monte Carlo simulations and finally the number of failures is calculated. In the design equation, partial safety factors are introduced together with characteristic values for the strength. The design equation is defined based on equation (2.3). The limit state equation corresponding to the design equation is derived as:

$$g = X_R S_{ultimate} - S_V(Q) \tag{3.1}$$

In the above equation, $S_{ultimate}$ is a function of material and geometrical parameters as defined in Tables 1.1 and 1.2. Therefore, the annual probability of failure corresponding to the limit state equation can be expressed by:

$$P_f = P\left(X_R S_{ultimate} - S_V(Q) \le 0\right) \tag{3.2}$$

Before estimating the reliability, a convergence study has been performed to verify the accuracy of the FEA model.

3.3. RESULTS AND DISCUSSION

The influence of different failure criteria for the adhesive bond line was investigated. The probability of failure of the joint was assessed based on the stochastic variables and the limit state equation. The solution convergence of the Monte Carlo simulation was studied for different failure criteria and it was presented that the solution converged after almost 8000 simulations for all cases. The results are presented in table 3.2.

Table 3.2. Probability of failure for different failure criterion.

Failure criteria	Von Mises (λ=1)	Modified von Mises λ=1.4	Max stress
Probability of failure	0.0024	0.0024	0.0021
Reliability index	2.82	2.82	2.86
Standard error	4.89×10^{-4}	4.89×10^{-4}	4.57×10^{-4}
Probability bounds (95% confidence)	[0.0019, 0.0029]	[0.0019, 0.0029]	[0.0016, 0.0026]
Reliability index bounds (95% confidence)	[2.75, 2.89]	[2.75, 2.89]	[2.79, 2.94]

It was mentioned before that the required reliability level for wind turbines is implicitly corresponding to an annual reliability index $\beta = 3.1$, and the partial safety factors can then be calibrated accordingly. It can be approximately done by linearizing the limit state equation. By increasing the partial safety factor related to the material properties, γ_m, from 1.3 to 1.35 the target reliability level can be achieved.

3.4. CONCLUSIONS AND SCIENTIFIC CONTRIBUTION OF THIS PAPER

- A simple approach has been presented to take into account the influence of variations in the material strength over an adhesive bonded composite scarfed lap joint through an accurate 3D FEA.
- It was shown that the choice of failure criterion exerts some influence on the predicted probability of failure or the predicted reliability index. Failure mode and choice of failure criterion are two important parameters that need to be considered when conducting reliability analysis.
- A simple and easy to use methodology for calculating the reliability and probability of failure for adhesive bonded joints has been proposed. The methodology can further be used to assess the partial safety factors to be used in deterministic design.
- The proposed methodology can be used in a similar manner to calculate the reliability for most components of wind turbine blades.

CHAPTER 4. RELIABILITY ANALYSIS OF STEPPED JOINTS

4.1. ABSTRACT

This chapter describes roughly paper II. Reliability analysis coupled with finite element analysis (FEA) of composite structures is computationally very demanding due to the need of a huge number of elements to obtain an accurate computational model. On the other hand it requires a large number of simulations to achieve an accurate prediction of the probability of failure with a small standard error. In this part of the PhD study Asymptotic Sampling, which is a promising and time efficient tool to calculate the probability of failure, has been employed to calculate the reliability analysis of adhesive bonded stepped lap composite joints. The same approach is chosen for the reliability analysis, a three dimensional (3D) FEA is used for the structural analysis together with a design equation and also partial safety factors are taking into accounts. The two considered failure criteria are Tsai-Wu and the modified von Mises criteria to predict failure in the composite and adhesive layers, respectively. To investigate the accuracy and efficiency of Asymptotic Sampling a comparison is made with predictions obtained using the Monte Carlo technique. The same method as described in the previous chapter is used to calibrate the partial safety factors.

4.2. GEOMETRY AND SOLUTION PROCEDURE

A model of the stepped lap composite joint can be found in paper II at Appendix. To save computational time and shorten solution procedure the considered stepped lap joint includes only two steps. The constituent materials considered are epoxy adhesive, carbon/epoxy plies oriented in x-direction and finally outer and inner ±45 winding of glass/epoxy as introduced in Chapter 1. The geometrical properties are typically assumed to be Normal distributed. No data is available for the coefficients of variation (COV). Therefore 10% COV has been chosen for all the geometrical parameters. A prescribed horizontal displacement is applied at the right side as loading condition, and a simple support boundary condition is applied for the left side of the joint.

Before starting the reliability calculations a FEA model has to be built. To do this a macro is used to generate a parametric model where the details have been described in paper II. The adhesive material is assumed to be homogeneous and isotropic and the load is calibrated with respect to the linear elastic analysis.

More information about the materials and the applied COVs can be found in the appendix. To find out the most critical bond-line of the joint and also the failure initiation point, a stress analysis was performed and the stress distributions along the bond-lines were obtained. The non-dimensional adhesive/composite stress distributions along the most critical horizontal interfaces between the adhesive and the composite layers were analyzed. The stresses were normalized with respect to the far field average tensile stresses in the E-glass/epoxy. Maximum principal stress criterion was used to predict failure in epoxy layers and Tsai-Wu failure theory was employed for the composite layers.

Table 4.1. Stochastic variables for the stepped lap joint geometry.

Parameter	Mean	COV	Distribution	Characteristic value
Lamina thickness, t_l (mm)	0.125	10%	Normal	0.125
Joint width (mm)	5.00	10%	Normal	5.00
Adhesive thickness, t_a (mm)	0.125	10%	Normal	0.125
Adhesive bondline length, t_A (mm)	2.00	10%	Normal	2.00
Step length, S_L (mm)	40.0	10%	Normal	40.0
Initial length, L_1 (mm)	70.0	10%	Normal	70.0
Lateral length, L_2 (mm)	70.0	10%	Normal	70.0
Fibre angles	-	10%	Normal	-

Asymptotic sampling as an efficient reliability approach was used in this study which significantly decreased the simulation time. The Finite Element Analysis (FEA) showed that the outer glass/epoxy layer fails with a higher probability before the adhesive. The carbon/epoxy layers and the failure location are at the interface to the glass/epoxy layer located to the left in the stepped lap joint configuration [see paper II in appendix].

To obtain the probability of failure or the reliability index, two methods were used, the Crude Monte Carlo simulation technique and the Asymptotic Sampling technique. The FEA code ANSYS 12.1 was run in batch mode from Matlab where the geometric parameters, material properties and loads were simulated using distribution functions describing the stochastic variables. Each simulated parameter is read by ANSYS using a macro file, and the results are exported back to Matlab where a post processing based on computed stresses and strains is carried out. The average Tsai-Wu failure index is calculated over the critical bondline/interface as was identified before, and finally the number of failures is calculated. This procedure is repeated for 10,000 realisations in the Monte Carlo simulations, 1280 simulations using the Asymptotic Sampling technique, and finally the probability of failure, P_f is calculated.

It is investigated how to obtain the annual probability of failure, P_F , and the corresponding reliability index, $\beta = -\Phi^{-1}(P_F)$, by a confidence interval due to uncertainties in the solution procedure. The standard error associated with the Crude Monte Carlo simulation is obtained from:

$$S.E = \sqrt{\frac{P_f(1-P_f)}{N}} \tag{4.1}$$

In Tables 4.2 and 4.3 the results of this paper are shown for the probability of failure and corresponding reliability index together with the confidence interval. As it was mentioned above, 3.1 is considered as the minimum annual reliability index for structural wind turbine components. In the considered example the reliability level is computed as 3.53 which is satisfactory, and further indicates that the partial safety factors could be decreased slightly. By taking into account the uncertainty in the computational procedure the upper and lower interval of the predicted reliability indices is $[3.39, 3.85]$, which is still in the 'safe' region as stated in IEC-61400-1.

Table 4.2. Predicted probability of failure based on 10000 simulations (Monte Carlo method).

Method	Probability of failure	Reliability index	Standard error	Computational time
Monte Carlo	2×10^{-4}	3.54	1.41×10^{-4}	~15 days

To reduce the computational time and present an efficient technique as accurate as the Monte Carlo method with its high number of simulations with respect to FEA based evaluation of the limit state equations, Asymptotic Sampling was used.

To predict the uncertainties associated with the Asymptotic Sampling method the same simulation procedure (explained above) was repeated 10 times, and then the mean value and COV were calculated and presented in Table 4.3.

Table 4.3. Predicted probability of failure based on 1280 simulations (Asymptotic Sampling method).

Method	Probability of failure	Reliability index	COV	Computational time
Asymptotic Sampling	4.24×10^{-5}	3.93	8.3%	~2 days

4.3. CONCLUSIONS AND SCIENTIFIC CONTRIBUTION OF THIS PAPER

- The uncertainties and imperfections in the design of stepped lap composite joints were taken into account where the influences of variations in the geometrical, physical, strength parameters and external loading over the joint were included in the design.
- A reliability analysis for composite adhesive stepped lap joints was conducted using the Crude Monte Carlo simulation and Asymptotic Sampling technique on the basis of a 3D FEA model to predict the probability of failure.
- Asymptotic Sampling was coupled with FEA analysis for the first time to present an efficient and accurate approach to predict the probability of failure and the reliability index of stepped lap joints.
- In summary, for the assessment of the reliability and probability of failure for adhesive bonded composite stepped lap joints a novel and simple method was shown, and it was also explained how partial safety factors for semi-probabilistic design can be calibrated.

CHAPTER 5. PROGRESSIVE DAMAGE MODELLING FOR RELIABILITY ANALYSIS OF ADHESIVE BONDED COMPOSITE STEPPED LAP JOINTS

5.1. ABSTRACT

This chapter gives an overview of paper III. It is obvious that, with increasing damage, degradation of stiffness and strength occurs [45]. Numerous works and approaches have been presented in the literature that attempt to predict such degradation. Among all the studies and models, FADAS (FAtigue DAmage Simulator) is a progressive damage model which has been successfully applied for different fatigue problems [46, 47]. This model is based on a ply to laminate approach for linear and non-linear material behaviour, pseudo-static loading response, constant life diagrams and strength and stiffness degradation due to cyclic loading. The model was implemented on a robust and comprehensive experimental database for a unidirectional Glass/Epoxy ply. In this paper a probabilistic approach to calculate the reliability of adhesive bonded composite stepped lap joints loaded in fatigue by using progressive damage modeling is described. It should be noted that a linear form of FADAS was used together with 3D Finite Element Analyses. Linear and nonlinear materials models from available experimental data for the rotor wind turbine blades (OPTIMAT BLADES) were used to model material degradation as described in Chapter 2 of this thesis. Statistical uncertainties on the experimental data, geometrical uncertainties, physical and load uncertainties were modelled using appropriate stochastic distributions and also through the procedure described in Chapter 2. A design equation for fatigue failure of wind turbine blades exposed to out of plane bending moments was introduced together with partial safety factors. Asymptotic Sampling (AS) with randomized Sobol sequences was chosen as the reliability technique. The predicted reliability level was compared with minimum target reliability level defined by the wind turbine standard IEC 61400-1.

5.2. GEOMETRY AND SOLUTION PROCEDURE

The geometry and layup in this part is the same as the stepped joint considered in paper II at the appendix, and the only difference is the selected materials which are glass-epoxy due to lack of experimental data for carbon-epoxy.

The stiffness/strength degradation model was described in Chapter 2. Stiffness degradation is a non-linear function of stress redistribution due to fatigue and a linear formulation was used for the residual strength degradation.

In previous chapters and papers were addressed the effective failure criterion, failure initiation point and also an approach to identify the failure. Herein, three failure modes are considered such as bondline failure, adhesive failure and the failure of composite layers or structural stiffness loss. The first failure mode is due to stress concentration on the bondline and two last failure modes result in losing overall stiffness and as consequence of it, large deformation of the joint. It should be also pointed out that the maximum stress criterion was used for both adhesive and composite layers and the failure as presented in paper III in appendix.

The first failure event considered in this study is when all the elements attached to this bondline have failure. It means that when all the elements have failed, it is considered as the final failure and thus joint failure.

A simulation approach is used and structural failure is defined when the difference in displacement is significant between simulation no i and i+1.

The third failure event is the adhesive failure. To investigate the third failure mode, a line in the adhesive layers is chosen and average stress over this line is calculated. Based on the obtained stress the material degradation is applied and a failure index is calculated. This procedure is repeated until the first failure is observed.

The equivalent stress S_e, which is obtained from the failure criteria, is compared with the ultimate strength. Thus, the final failure for the adhesive or composite layers is estimated by equation (2.4). When a failure event was observed, the number of cycles at the failure event is calculated and compared with the designed lifetime of the joint.

The adapted algorithm to calculate the probability of failure has been shown in paper III in appendix.

5.3. RESULTS AND DISCUSSION

First of all, the accuracy of the solution procedure should be approved. Therefore a deterministic analysis is carried out and the number of cycles is counted with respect to the increase in applied load. The outcome results should follow the typical S-N curve behaviour where by increasing the load the lifetime should decrease as reported in [41] where Fig. 6.1 shows a complete agreement with the reference.

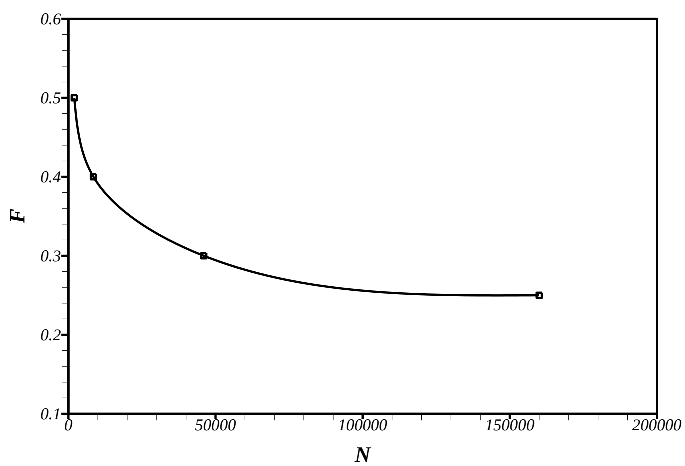

Fig. 6.1. Force-number of cycles (F-N) curve to investigate the accuracy of FADAS algorithm for the joint.

It is also expected to observe uniform strength degradations until failure and at the moment of failure the structure loses the stiffness; therefore a huge jump in the joint displacement must be recorded as reported in paper III.

For the lifetime of a wind turbine blade 10^9 cycles should be considered. But in this study to save some computational time and due to FEM based simulations only 10^5 cycles is considered, however the procedure is the same. When the number of cycles was chosen, the characteristic load is calculated and applied to the model through the FADAS algorithm. Asymptotic Sampling [28 & 49] with 5 support points is conducted to calculate the probability of failure. For the scaling factor, f, several numbers were chosen $\left(f = 0.8, 0.7, 0.6, 0.55, 0.5\right)$ and 128 iterations per scaling factor were performed. The procedure was performed for 5, 10 and 20 years lifetime and the accumulated reliability index of the joint was calculated as shown in Fig. 6.2. it should be pointed out that the scatter of the scaling factor points, Implies some small uncertainty on the method and solution procedure which should be further investigated.

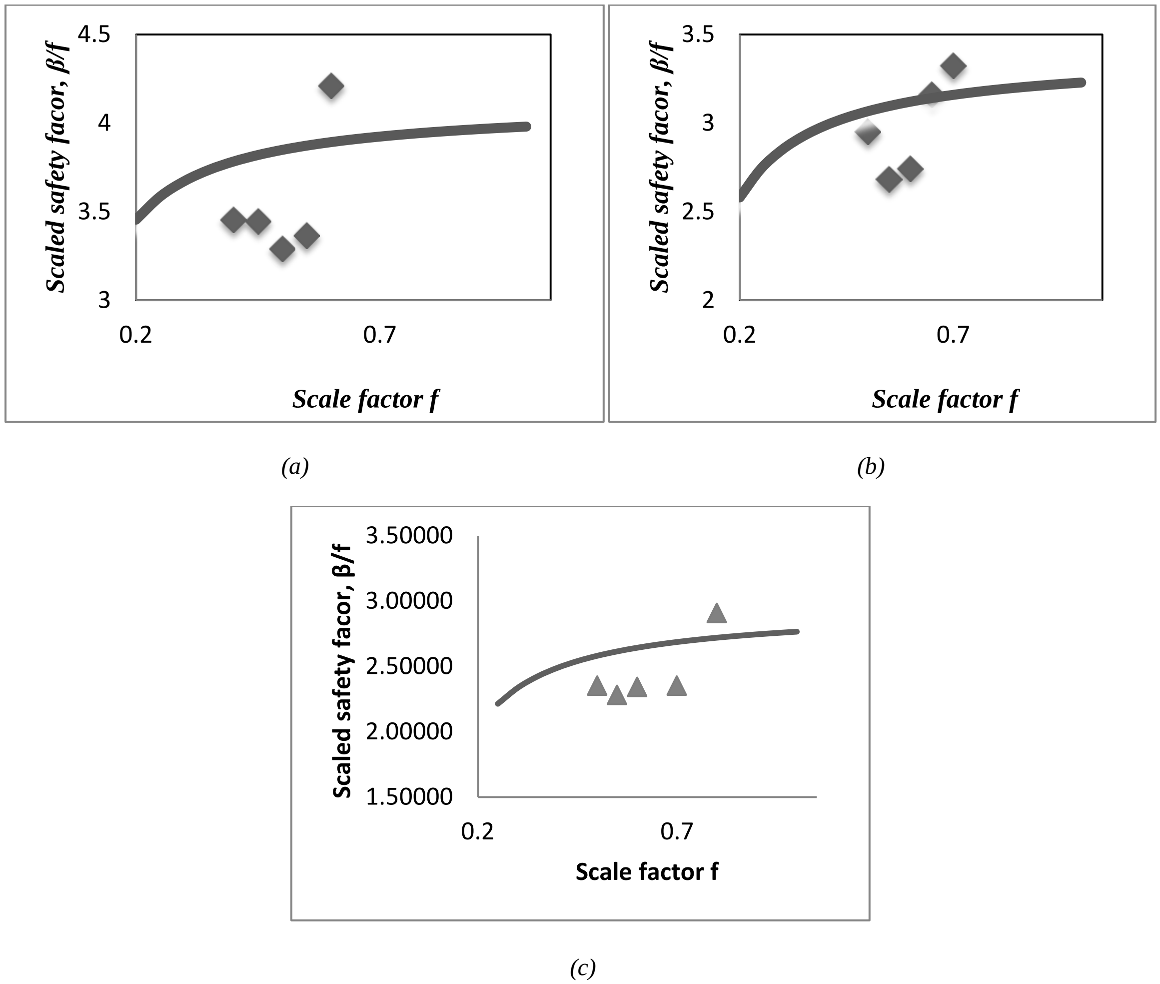

Fig. 6.2. Asymptotic Sampling results based on 5 supporting points for T equal to 20 years lifetime (a) $\frac{t}{T} = 0.25$*, (b)* $\frac{t}{T} = 0.5$*, (c)* $\frac{t}{T} = 1.0$

As the life time of wind turbine components should be 20 years, the partial safety factors should be increased to meet the IEC requirements for this joint.

5.4. CONCLUSIONS AND SCIENTIFIC CONTRIBUTION OF THIS PAPER

- Uncertainties and imperfections were taken into account in assessment of the fatigue life of stepped lap composite joints.
- The reliability analysis of the stepped lap composite joint loaded in fatigue was performed.
- A linear form of FADAS for constant amplitude was used together with 3D Finite Element Analyses (FEA) combined with probabilistic approach to estimate the reliability index and probability of failure.

- Generally, fatigue analysis in composite materials through FE analysis is very time consuming and when combined with stochastic variables modelling uncertainties it demands a huge number of simulations and computational capacity. In this study an approach for the assessment of the reliability and the probability of failure for adhesive bonded composite stepped lap joints loaded in fatigue was presented. It has been shown how the algorithm can be used to estimate the probability of failure of stepped joint through a stochastic FEA approach and taking into account experimental results. It has also been illustrated how partial safety factors for semi-probabilistic design can be calibrated. The introduced methodology is illustrated in an example to estimate the reliability level of wind turbine blade components loaded in fatigue.

CHAPTER 6. CONCLUSION AND FUTURE RESEARCH

6.1. CONTRIBUTIONS AND IMPACT

Uncertainties and imperfections may affect the predicted structural performance and reliability in the design of composite adhesive joints and should therefore be considered in the design. In this PhD thesis it was investigated how to address the uncertainties in the design process, and a probabilistic model for the reliability analysis of adhesive bonded composite joints, in which the influence of variations in the geometrical, physical, strength parameters and external loading over the joint, has been developed.

Data related to the composite materials (statistical data and models), test results (experimental data) and results derived from simulation models using literature review and existing experimental results were investigated and applied to the model. The main uncertainties related to all components of a wind turbine blade such as strength and stiffness parameters, geometry, and also load were identified and an appropriate stochastic model for each uncertain parameter was chosen.

A reliability assessment for composite adhesive joints was presented using stochastic models for the uncertain parameters, and the crude Monte Carlo simulations and Asymptotic Sampling techniques as a very time efficient method based on the use of a 3D FEA model were used to estimate the probability of failure.

Asymptotic Sampling was coupled with FEA analysis together with Sobol randomizes sequences to present an efficient approach to calculate the probability of failure and the reliability index of composite adhesive joints.

To optimize the solution procedure and reduce the computational time, a sensitivity analysis was carried out and FEA calculations were controlled based on the sensitivity results. The proposed algorithm significantly reduced the computational time with the same accuracy.

Different failure modes such as ultimate strength and fatigue were considered for each adhesive joint. In any failure mode (ultimate and fatigue) different failure events such as fiber failure, matrix failure and adhesive failure were assessed.

It was tried to present an approach for the assessment of the reliability and probability of failure for adhesive bonded composite joints under different load cases. It has been shown how an algorithm can be used to calculate probability of failure and the reliability level of composite components of a wind turbine blade.

There is no study available on the reliability analysis of adhesive composite joints with a detailed stress analysis and taking into account the uncertainties. In summary, a simple and novel approach for the assessment of the reliability and probability of failure for adhesive bonded composite joints has been presented, and it was illustrated how partial safety factors for semi-probabilistic design can be calibrated.

6.2. FUTURE RESEARCH

A wide range of experimental analysis could be performed to validate the FE model and also to find the correlation between the stiffness/strength parameters. The results of the experimental results can directly be used to update the results presented in this study.

The same procedure can be used for other parts of a wind turbine blade such as main spar, inner/outer shells, shear web, root and sandwich structures to calculate the reliability index and also calibrate the partial safety factors.

A system reliability analysis can be performed for a wind turbine blade when a reliability calculation is performed for all the components to calibrate the safety factors.

Manufacturing defects, neglect, mistakes and incorrect modeling can be added to the solution algorithm. Generally, these should be taken care of by quality control in design and manufacturing and by application of robustness / damage tolerance principles in the design. However, smaller defects and model uncertainties can be included in the probabilistic model by application of stochastic models for the relevant material parameters that includes the effect of smaller defects etc.

The solution algorithm can still be modified and optimized by using other efficient techniques or less number of elements in the FE model. A study on the convergence of asymptotic sampling and the interval of the support points could be helpful to increase the accuracy of the algorithm.

The failure analysis under fatigue loading studied here includes lots of simplifications. To validate the assumptions, experimental data and also more calculations should be performed. On the other hand, other failure modes such as buckling could be taken into account.

A thermal analysis could be added to the reliability calculations due to rough environment and working temperature conditions of wind turbines.

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Appendix

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