R E G I O N E   C A M P A N I A

P r o v i n c i a   d i   A v e l l i n o

C O M U N I   D I   L a c e d o n i a   (A V)   –   M o n t e v e r d e   (A V)

PROGETTO

PROGETTO DI REBLADING DEL
PARCO EOLICO LACEDONIA-MONTEVERDE (39,60 MW)

PROGETTO DEFINITIVO

COMMITTENTE:

ERG Wind 4

ERG EVOLVING ENERGIES

PROGETTISTA:

GOLDER
Via Sante Bargellini, 4
00157 - Roma (RM)

OGGETTO DELL'ELABORATO:

RELAZIONE DI CALCOLO STRUTTURALE DELLA PALA DI PROGETTO

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Storia delle revisioni del documento

REV.	DATA	DESCRIZIONE REVISIONE	REDATTO	VERIFICATO	APPROVATO
00	**03/2019**	PRIMA EMISSIONE			

INDICE

1. PREMESSA

La presente relazione rappresenta il certificato del costruttore in cui si forniscono le indicazioni relative alle analisi di verifica di resistenza, rigidezza e stabilità della pala ETA4X. Tali analisi sono state eseguite, dove applicabile, facendo riferimento alla Germanischer Lloyd Guideline per la certificazione delle turbine eoliche 2010.

Le analisi di resistenza sono state eseguite rifacendosi al metodo degli elementi finiti.

La valutazione della resistenza a fatica è stata eseguita utilizzando le matrici Markov secondo le linee guida Germanischer Lloyd 2010.

Sono inoltre riportati i risultati di analisi separate, basate sul metodo degli elementi finiti, per: rottura inter-fibra, stabilità, frequenze di risonanza e deflessione massima della punta.

Nel documento di seguito riportato tutte le analisi, eccetto la verifica della resistenza statica per rottura delle fibre, sono state eseguite con riferimento al fattore di riserva, definito come il rapporto tra il valore ammissibile (di sforzo, deformazione o altro parametro) comprensivo dei fattori parziali, ed il valore calcolato effettivo. Pertanto, un valore del fattore di riserva pari o superiore a 1,00 individua una condizione di verifica accettabile.

L'analisi della resistenza statica per rotture delle fibre, invece, fa riferimento al margine di sicurezza anziché al fattore di riserva. Il margine di sicurezza è dato dal rapporto tra la deformazione misurata e la deformazione accettabile diminuita di 1 unità. Pertanto, la verifica risulta soddisfatta se il margine di sicurezza risulta negativo.

L'analisi della pala è stata eseguita da TSR e Gurit. In particolare, a TSR è stata affidata la progettazione del design complessivo della pala mentre Gurit era responsabile della progettazione di dettaglio di quest'ultima.

Le analisi eseguite sulla pala sono:

- Analisi col metodo degli elementi finiti sul carico di rottura limite dovuto a carichi statici;
- Analisi col metodo degli elementi finiti e con le matrici Markov sulla resistenza a fatica;
- Analisi separate, basate sul metodo degli elementi finiti, per:
    - Rottura inter-fibra;
    - Stabilità
    - Frequenze di risonanza;
    - Massima deflessione della punta;
    - Progettazione dei giunti.

Insieme ai test eseguiti sui componenti strutturali e sull'intera pala, i risultati analitici riportati nel documento in basso dimostrano che la struttura possiede margini di sicurezza adeguati.

Technical Report

ETA 24m Blade Certification Report

GU4507- 4003

Circulation:ETA,TSR ,GL, File
Author: Menaga Mohan(Gurit) & Alessandro Croce(TSR)

Issue and Amendments

ISSUE	AMENDMENTS	DATE	APPROVED	INITIAL
A	Issued for Certification	13/05/13	Richard Evans (Gurit)	

Executive Summary

This document provides a report on the strength, stiffness and stability verification analysis of the ETA 24m Blade and is provided, together with the blade laminate drawings, to Germanischer Lloyd as a basis for the structural certification of the blade to Germanischer Lloyd Guideline for the Certification of Wind Turbines 2010.

Table of Contents

1. Introduction

This document reports the strength, stiffness and stability verification analysis of the ETA 24m blade and is provided, together with the blade laminate drawings, to Germanischer Lloyd as a basis for the structural certification of the blade to Germanischer Lloyd Guideline for the Certification of Wind Turbines 2010 (1).

Strength analyses were performed for static strength by FEA. Fatigue strength analyses were performed by the use of Markov Matrices as per GL 2010 guidelines . Separate analyses, based on finite element analysis are presented for inter-fibre failure, stability, natural frequencies and maximum tip deflection.

In this document, reserve factor is defined as the allowable value (of stress, strain or other parameter) including all partial factors divided by the actual calculated value. Consequently a reserve factor value of 1.00 or above is acceptable.

The static strength analysis for fibre failure in Section 9 presents Safety Margins instead of Reserve Factors. The Safety Margin is MeasuredStrain / AdmissibleStrain – 1; therefore the verification is satisfied if the safety margin is negative.

The blade analysis was performed by both TSR and Gurit where broadly speaking TSR were responsible for the overall blade design and Gurit were responsible for the blade detail design. Table 1 shows the different analyses that were performed on the blade and the parties responsible for the each of the analyses.

Analysis	Responsible Party
Finite Element Analysis Model	TSR
Load Generation	TSR
Material Properties	Gurit
Non Structural Masses	TSR
Static Strength Analysis for Fibre Failure	TSR
Fatigue Strength Analysis for Fibre Failure	TSR
Markov Matrix Fatigue Analysis	Gurit
Inter-Fibre Failure Analysis	Gurit
Stability Analysis	TSR
Tip Deflection Analysis	TSR
Natural Frequency Analysis	TSR
Blade Balancing	Gurit
Bonded Joints	Gurit
Root Bolt Joint	Gurit
Root – Spar Capping Joint	Gurit

Table 1 Blade Analysis

2. Analysis Methods (TSR)

2.1 Finite Element Analysis

A Finite Element model (2) is used to perform the verification of ultimate loads, fatigue and buckling.

Two analysis types are performed: linear static and linear buckling analysis. The analyses are performed with MSC Nastran 2012.1 and MD Nastran 2011.1. Data postprocessing is performed by Matlab R2011b from the Nastran analysis results. Further model details can be found in the next paragraphs. The full model with a static load condition is reported in Figure 1.

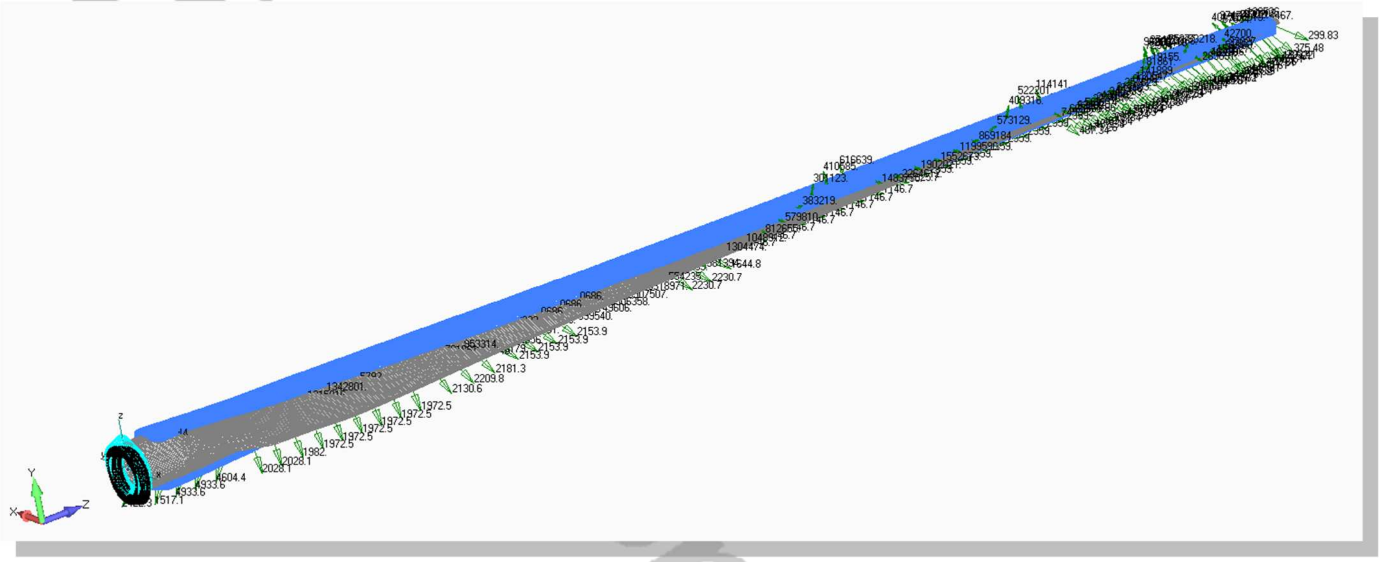


Figure 1 Finite element model

2.1.1 Mesh

The model geometry is reproduced by NURBS surfaces generated by Matlab R2011b and exported in IGES format. The external and shear web surfaces lie on the mid thickness laminates.

The meshing process is performed by Altair Hypermesh v11.0. Shell laminates are discretized by CQUAD4 and CTRIA3. The element size is between 25mm and 15mm, depending on the region of the model. Adhesive at the trailing edge is modelled by solid tetrahedral elements CTETRA, their dimensions being chosen so as to match the external surface dimensional mesh.

Non-structural masses not included in the laminate are modelled as concentrate masses by CONM2 Nastran elements connected to the spar caps nodes. The distribution of non-structural masses is estimated based to the blade geometry and using values suggested by the manufacturer.

Table 2 reports the number of elements by type.

Element type	*Number*
CTRIA3	*44985*
CQUAD4	*112158*
CTETRA	*82895*
CONM2	*51955*

Table 2 Number of elements of the finite element model

2.1.2 Loads

Load distributions are obtained from dynamic simulations, and discretized along the blade span using a suitable number of grid points. The number of spanwise grid pints is 89 for the static strength analysis for fibre failure, while 20 point are used for fatigue strength analysis for fibre failure.

Loads are defined as static forces (FORCE) and moments (MOMENT) at these grid points, and applied to the structure by RBE3 elements connected to the spar caps nodes.

2.1.3 Boundary Conditions

The model is constrained at the blade root by fixing the node translations in all three directions by SPC1 constraints, as shown in Figure 2.

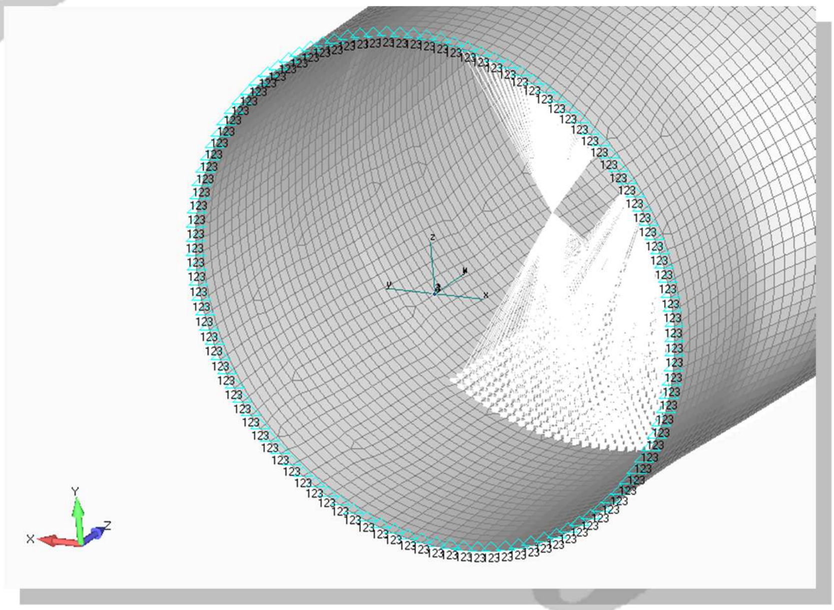


Figure 2 Applied nodal constraints at the blade root

2.1.4 Laminate Definition

Laminate properties are defined by the PCOMP Nastran card. Different laminate properties are defined depending on the local lamination sequence. The leading edge, trailing edge and shear web bonding flanges are not represented in the current model.

3. General Description (TSR)

The blade shells are manufactured in two halves from infused E-glass epoxy material. The shells each incorporate a single spar cap made primarily of unidirectional fabric interleaved with triaxial material and a triaxial root. Two shear webs are infused separately and bonded between the shells. Cores of the shell are of foam and cores of the shear webs are of foam.

Table 3 shows the main blade parameters.

	Blade Geometry
Blade Length (m)	*23.9*
Max. Chord (m)	*1.8368*
IEC Wind Class	*A1*
Rated Power (MW)	*660*
PCD Diameter (m)	*0.94*
No of Bolts	*60*
Bolt Size	*M20*

Table 3 Main Blade Parameters

4. Co-ordinate Systems (TSR)

Strength analyses are typically performed with respect to local section co-ordinates as shown in below.

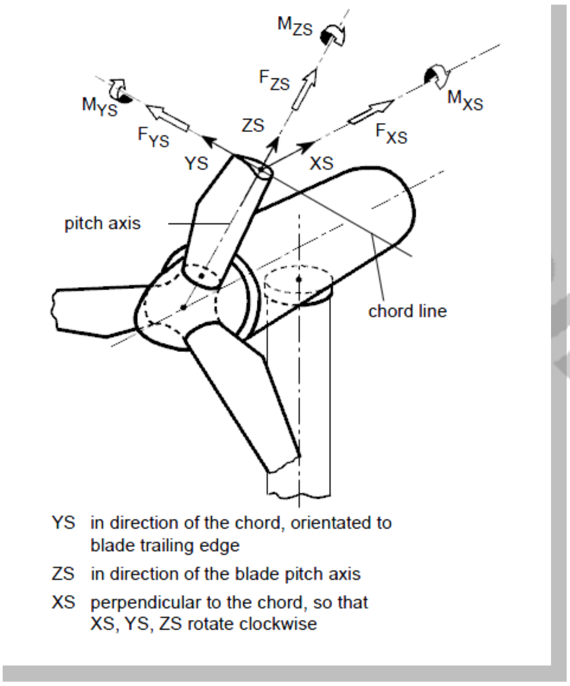


Figure 3 Local Section Coordinate System

5. Loads (TSR)

In order to evaluate the loads of the ETA4X blade, an aeroelastic model of the machine is set up and several Design Load Cases (DLCs) according to the GL2010 (1) were performed. The model was developed in a multi-body/FEM simulation environment (see ref. Figure 3 Local Section Coordinate System).

5.1 DLCs

The DLCs considered to compute the ultimate and the fatigue loads on the blades are the 1.2, 1.3, 1.4, 1.5, 1.6, 1,7 2.2, 2.3 and 6.2 (see Ref. [GL2010]). All of these are used to compute the ultimate loads. DLCs 1.2 are also used to estimate fatigue loads.

5.1.1 DLC12

Power production, Normal Turbulence Model with an up-tilt of 8deg, mean wind speed between 5m/s and 23m/s (with a step of 2m/s), 2 different seeds.

5.1.2 DLC13

Power production, Extreme Coherent gust with Direction change, with an up-tilt of 8deg, wind at V_{rated}, V_{rated}± 2m/s, $V_{cut-out}$ (i.e. 13, 15, 17 and 25m/s).

5.1.3 DLC14

Power production, Normal Wind Profile, with an up-tilt of 8deg, wind at V_{rated}, V_{rated}± 2m/s, $V_{cut-out}$ (i.e. 13, 15, 17 and 25m/s), grid loss.

5.1.4 DLC15

Power production, Extreme Operating Gust 1 year period, with an up-tilt of 8deg, wind at V_{rated}, V_{rated}± 2m/s, $V_{cut-out}$ (i.e. 13, 15, 17 and 25m/s), and grid losses in different gust points (see Fig.Figure 4 DLC15, grid loss times (red points).).

5.1.5 DLC16

Power production, Extreme Operating Gust 50 years period, with an up-tilt of 8deg, wind at V_{rated}, V_{rated}± 2m/s, $V_{cut-out}$ (i.e. 13, 15, 17 and 25m/s).

5.1.6 DLC17

Power production, Extreme Wind Shear, with an up-tilt of 8deg, wind at V_{rated}, V_{rated}± 2m/s, $V_{cut-out}$ (i.e. 13, 15, 17 and 25m/s).

5.1.7 DLC22

Power production, Normal Wind Profile, with an up-tilt of 8deg, wind at V_{rated}, V_{rated}± 2m/s, $V_{cut-out}$ (i.e. 13, 15, 17 and 25m/s) and short circuit or pitch actuator faults.

5.1.8 DLC23

Power production, Normal Turbulence Model with an up-tilt of 8deg, wind at V_{rated}, V_{rated}± 2m/s, $V_{cut-out}$ (i.e. 13, 15, 17 and 25m/s) and grid losses.

5.1.9 DLC62

Parked, Extreme Wind Speed Model with an up-tilt of 8deg, wind at V_{e50}, (50 years extreme wind speed) and electrical loss (i.e. yaw misalignments of ±180deg with a step of 30deg).

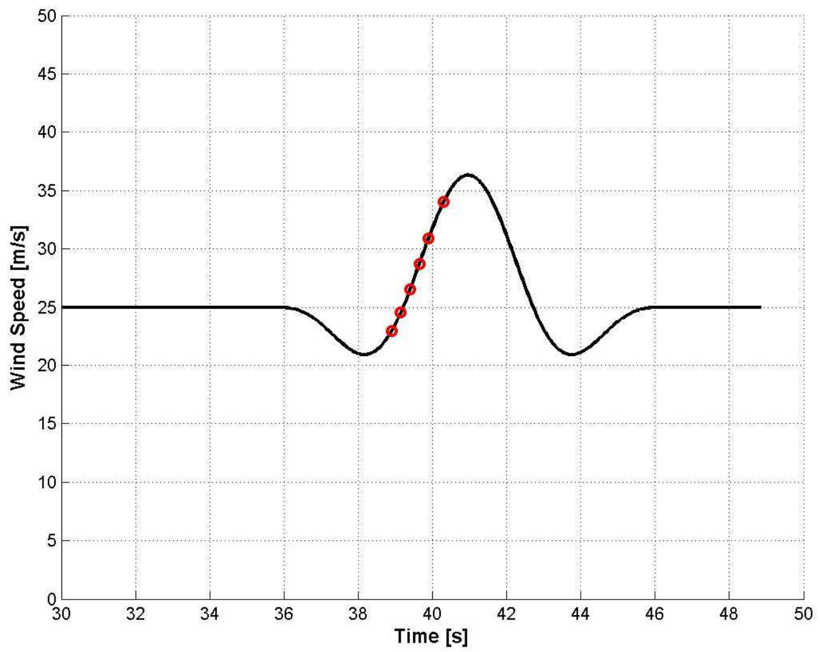


Figure 4 DLC15, grid loss times (red points).

5.2 Load Envelope

Loads are computed along the blade span at the following blade sections.

Sensor ID	Distance from root [m]	Spanwise location
1	0,00	0,0000
2	0,30	0,0126
3	1,20	0,0500
4	2,39	0,1000
5	3,39	0,1419
6	6,17	0,2580
7	0,00	0,0000
8	8,96	0,3750
9	10,76	0,4500
10	11,95	0,5000
11	15,54	0,6500
12	19,12	0,8000
13	22,00	0,9205
14	23,66	0,9900

Table 4 Sensor positions along the blade span.

The envelope matrices computed in some of these sections are summarised in Appendix B.

The max/min flapwise and edgewise (My and Mx) bending moments are summarized in the following figure (Figure 5 Positive/Negative Flap/edgewise bending moments)

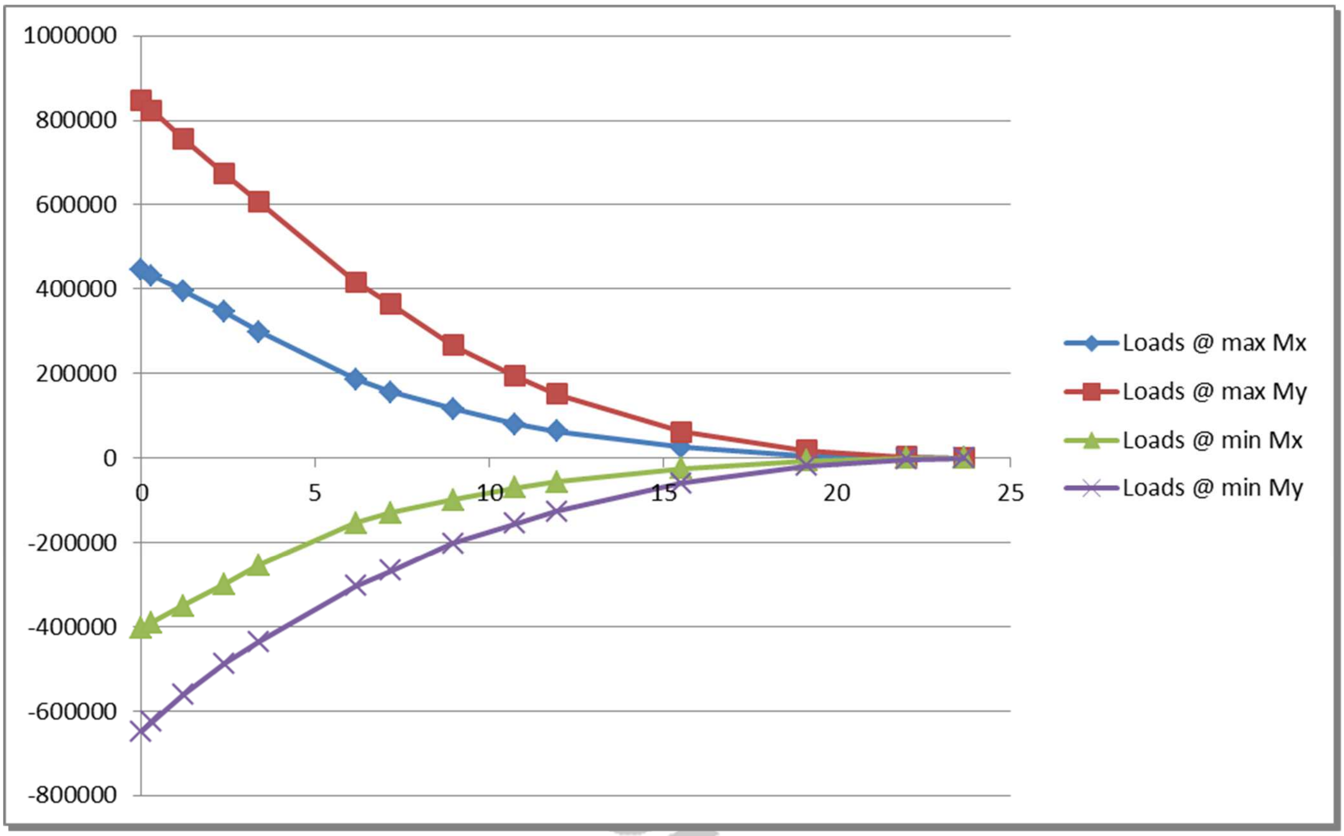


Figure 5 Positive/Negative Flap/edgewise bending moments.

6. Materials (GURIT)

6.1 Material Name Designations

Example: YE900
First letter describes fabric type (Material orientation as shown in Figure 6):

- Y – triaxial material, 50% of fibre weight at 0° to the roll direction, 25% at +45°, 25% at -45°
- U – unidirectional material, 100% of fibre weight at 0° to the roll direction
- X – biaxial material, 50% of fibre weight at +45° to the roll direction, 50% of fibre weight at -45°

Second letter describes reinforcement material type:

- E – E-glass fibres
- C – carbon fibres

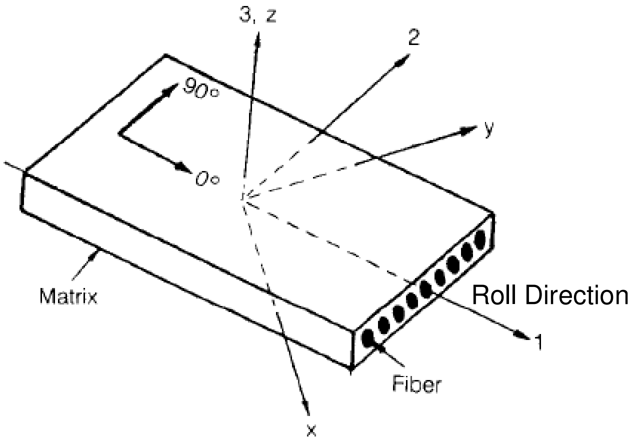


Figure 6 Material Orientation

Number describes nominal fibre weight; actual fibre weight may differ slightly from this number, please refer to table of properties for actual fibre weight. Scaffold material or weight of stitching is not included in the nominal or actual fibre weight. All materials are assumed to be infused material with vacuum consolidation other than /w designating wet layup.

6.2 Material Utilisation

Table 5 shows the material utilisation throughout the blade.

Blade Zone	Material Name	Material Type
Root	YE900 UC500	Infused
Spar Cap*	UC500 XE600	Infused
Shear Webs	XE600 SAN T400 Core	Infused
Shell	YE900 SAN T500 Core	Infused
Bonding	XE600/w	Wet Lay

Table 5 Material Utilisation

* Interleave 1 ply of XE600 for every 3000g of carbon or every 5000g of glass in the spar capping

6.3 Material Partial Factors

The partial safety factor for materials, γ_{Mx}, also known as the material factor, is used to derive the design strength by factoring down the material characteristic strength. The material factor is calculated by an empirical approach using a number of reduction factors, C_{ix}, listed in Paragraph 2 (Ultimate Limit State) and Paragraph 3 (Fatigue Limit State), Section 5.5.2.4 of the GL 2010 (1). The reduction factors, C_{ix}, for the stability analysis are listed in Paragraph 2, Section 5.5.3.2.3 of the GL 2010 (1) .

6.3.1 ULS

The ULS partial safety factors selected for the composite materials are summarised in Table 6 and are based on the factors given in the GL 2010 **(1)**. The ULS material factor γ_{Mx} (where x = a for fibres/cores and x=d for adhesive) is calculated by multiplying together all the reduction factors.

Fibre types		Glass/Carbon Fibres				Core	Adhesive
Manufacturing Process		Infusion	Wet Layup	Infusion	Wet Layup		
Failure Description	Factor	Fibre Failure	Fibre Failure	Matrix Failure	Matrix Failure		
Base Material Factor	γ_{M0}	1.35	1.35	1.0	1.0	1.35	1.35
Influence of Ageing	C_{1x}	1.35	1.35	1.35	1.35	1.35	1.5
Temperature Effect	C_{2x}	1.1	1.1	1.1	1.1	1.1	1.0
Laminating Method	C_{3a}	1.1	1.2	1.1	1.2	-	-
Bonding Surface (Adhesives Only)	C_{3d}	-	-	-	-	-	1.1
Post-curing of Laminate[1]	C_{4x}	1.0	1.0	1.0	1.0	1.0	1.1
ULS Material Factor	γ_{mx}	**2.21**	**2.41**	**1.63**	**1.78**	**2.00**	**2.45**

Table 6 ULS Material Factors

[1] Value of 1.0 implies that the laminate undergoes a post-cure.

6.3.2 FLS

The FLS reduction factors selected for the composite materials are summarised in Table 7 below. The total FLS material factor γ_{Mx} (where x = b for fibres/cores and x=e for adhesive) is calculated by multiplying together all the material reduction factors. The Wohler coefficients (m) used for glass and carbon are based on the GL 2010 (1) recommended values whilst the value for core is based on in house test data.

GL recommend an additional local reduction factor for the trailing edge as shown below in Table 7 and the requirement to use this additional reduction factor should be reviewed by TSR.

Fibre types		Glass Fibres		Carbon Fibres	Core
Processing		Infused	Wet Lay	Infused	
Fabric Type		Stitched Fabric	Stitched fabric	UD	
Failure Description	Factor				
Base Material Factor	γ_{M0}	1.35	1.35	1.35	1.35
Number of cycles	**N**	10^7	10^7	10^7	10^7
Slope Parameter	**m**	10	10	14	10
Curve of high cycle fatigue for the load cycle number N and slope parameter m ($N^{1/m}$)	C_{1x}	5.01	5.01	3.16	5.01
Single Lap Test (Adhesive Only)	C_{1e}	-	-	-	-
Temperature Effect	C_{2x}	1.1	1.1	1.1	1.1
Reinforcement Type	C_{3x}	1.1	1.1	1.0	1.0
Bonding Surface Reproducibility (Adhesive Only)	C_{3e}	-	-	-	-
Post-curing	C_{4x}	1.0	1.1	1.0	1.0
FLS Material Factor	γ_{mx}	**8.18**	**9.00**	**4.69**	**7.44**
Local partial safety Factor for Blade Trailing Edge (FE Calculation)	C_{5x}	1.1	1.1	1.1	1.1
Local Trailing Edge FLS Material Factor (To be reviewed)	γ_{mx}	**9.00**	**9.9**	**5.16**	**8.18**

Table 7 FLS material factors

6.3.3 Stability

The GL 2010 (1) partial safety factors selected for the composite materials are summarised in Table 8 for both linear and non-linear buckling analyses. The total buckling analysis material factor γ_m is calculated by multiplying together all the reduction factors. The Moduli used are average values derived from GURIT's test database.

Material	Factor	Skin/Core
GL Base material Factor	γm_0	1.35
GL Material factor for scatter of moduli in stability analysis	$C1_c$	1.1
GL Temperature Factor	$C2_c$	1.1
Non Linear Buckling Material Factor	**γm non-linear**	**1.63**
GL factor for linear FE analysis	$C3_c$	1.25
Linear Buckling Material Factor	**γm linear**	**2.04**

Table 8 Buckling Material Factors

6.3.4 Inter-Fibre Failure

The GL 2010 (1) partial safety factors selected for the composite materials are summarised in Table 9 for the inter-fibre failure analysis. The total inter-fibre failure material factor γ_m is calculated by multiplying together all the reduction factors and used factor down the Puck Failure envelope.

Material	Factor	Skin/Core
GL Base material Factor	γm_0	1.35
GL Material factor for changes in material properties due to temperature, ageing etc	C_{IFF}	1.25
Inter Fibre Failure Factor	γ_{IFF}	**1.69**

Table 9 Inter-Fibre Failure Material Factors

6.4 Cured Fibre Properties

The material properties shown in this section represent the minimum design material properties which must be met or exceeded by the blade builder.

6.4.1 General Properties

Table 10 shows the general specifications and moduli of the fabrics used for the design. All the properties are shown in the fibre direction. For the XE600 material the fibres are aligned in the 0°/90° orientation and the properties given are in this direction. Moduli shown are mean values whilst strengths shown are characteristic values. Infused properties are assumed values for material laminated with Gurit Prime20.

The derived properties for the XE600 at ±45° are shown in Table 11.

Material name	YE900	XE600	UC500	XE300/w
Material Type	Infused	Infused	Infused	Wet Lay
Fibre Volume Fraction (%)	0.46	0.46	0.48	0.42
Fabric Weight (g/m²)	900	600	500	300
Longitudinal Tensile Modulus (MPa)	22780	21220	112110	19530
Longitudinal Compressive Modulus (MPa)	22780	21220	107540	19530
Transverse Tensile Modulus (MPa)	10520	21220	6350	19530
Transverse Compressive Modulus (MPa)	10520	21220	6350	19530
In-Plane Shear Modulus (MPa)	6294	3050	3390	2790
Interlaminar Shear Modulus (MPa)	3120	3050	3390	2790
Poisson's Ratio (Longitudinal Strain)	0.477	0.12	0.333	0.122
Poisson's Ratio (Transverse Strain)	0.22	0.12	0.018	0.122
Structural Ply Thickness (mm)	0.74	0.5	0.58	0.29
Density (kg/m³)	1786	1786	1436	1729

Table 10 Fabrics Moduli and General Specification

Property	XE600 at ±45°
Longitudinal Modulus (N/mm²)	9737
In-Plane Shear Modulus (N/mm²)	9471
Characteristic Shear Strain (%)	1.5

Table 11 XE600 Material Properties with fibres at ±45°

6.4.2 ULS Design Strain

The ULS design strains shown in Table 12 are derived by dividing the Gurit material assumed characteristic strains by the ULS material factors given in Section 6.3.1. Characteristic strains shown are based on Gurit's in-house material test database.

The design longitudinal tensile strain is the lower value of the factored characteristic tensile strain of the fibre and the factored characteristic tensile strain of the matrix. The design longitudinal compressive strain is the factored characteristic compressive strain of the fibre.

Material name	YE900	XE600 ±45	UC500	XE300/w
Material Type	Infused	Infused	Infused	Wet Lay
Characteristic Longitudinal Tensile Strain (*f) (%)	1.8	1.85+	0.91	1.5
Characteristic Longitudinal Tensile Strain (*m) (%)	0.8	-	0.8	0.55
Characteristic Longitudinal Comp. Strain (%)	-1.25	-1.85+	-0.61	-1.15
Characteristic Transverse Tensile Strain(*f) (%)	0.45	1.85+	0.45	1.5
Characteristic Transverse Tensile Strain(*m) (%)	-	-	-	0.55
Characteristic Transverse Comp. Strain (%)	-1.5	-1.85+	-1.5	-1.15
Characteristic In-Plane Shear Strain (%)	1.2	1.5	1.2	1.43
Characteristic Interlaminar Shear Strain (%)	1.2	1.5	1.2	1.2
ULS Material Partial Factor (*f)	2.21	2.21	2.21	2.41
ULS Material Partial Factor (*m)	1.63	1.63	1.63	1.78
Design Longitudinal Tensile Strain (%)	0.49 (*m)	0.84	0.41 (*f)	0.31
Design Longitudinal Comp. Strain (%)	-0.57	-0.84	-0.28	-0.48
Design Transverse Tensile Strain (%)	0.28	0.84	0.28	0.31 (*m)
Design Transverse Comp. Strain (%)	-0.92	-0.84	-0.92	-0.65
Design In-Plane Shear Strain (%)	0.54	0.68	0.54	0.59
Design Interlaminar Shear Strain (%)	0.54	0.68	0.54	0.50

*In Table 12 the notation (*f) stands for fibre or primary matrix dominated failure and (*m) for matrix dominated failure*

+ *Axial characteristic strain is based on Section 5.5.4 paragraph (14), GL 2010* (1)

Table 12 ULS Material Design Strains

6.4.3 FLS Design Strain

The FLS design strains shown in Table 13 are derived by dividing the Gurit material assumed characteristic strains by the FLS material factors given in Section 6.3.2. Characteristic strains shown are based on Gurit's in-house material test database.

Material name	YE900	XE600	UC500	XE300/w
Material Type	Infused	Infused	Infused	Wet Lay
Characteristic Longitudinal Tensile Strain (%)	1.8	1.5	0.91	1.5
Characteristic Longitudinal Comp. Strain (%)	-1.25	-1.2	-0.61	-1.15
FLS Material Partial Factor	8.18	8.18	4.69	9.00
Local Trailing Edge FLS Material Factor	9.00	9.00	5.16	9.9
Design Longitudinal Tensile Strain (%)	0.22	0.18	0.19	0.17
Design Longitudinal Comp. Strain (%)	-0.15	-0.15	-0.13	-0.13
Design Longitudinal Tensile Strain - TE (%)	0.20	0.17	0.18	0.15
Design Longitudinal Comp. Strain - TE (%)	-0.14	-0.13	-0.12	-0.12

Table 13 FLS Material Design Strains

6.5 Resin Properties

A GL certified epoxy infusion resin that is able to produce laminates with the minimum design values specified in Section 6.4 shall be used. Resin must be mixed, applied and cured in accordance with the manufacturer's recommendations to avoid significant variations in mix ratio, voids or residual thermal stresses.

6.6 Core

The material properties shown in this section represent the minimum design material properties which must be met or exceeded by the blade builder. Only GL approved core materials may be used and must, on average, meet or exceed these average strength and modulus properties.

6.6.1 General Properties

Table 14 shows the assumed core moduli and strengths based on published Gurit datasheets. It should be noted that the requirement is that the core compressive modulus is measured to ASTM D 1621 2004 standard which usually results in a lower measured modulus than the 1973 standard.

	T400	T500
Density (kg/m^3)	71	94
Longitudinal Shear strength (MPa)	0.51	1.01
Transverse Shear Strength (MPa)	0.51	1.01
Longitudinal Shear Modulus (MPa)	28	40
Transverse Shear Modulus (MPa)	28	40
Tensile Strength (MPa)	0.97	1.30
Tensile Modulus (MPa)	85	118
Compressive Strength (MPa)	0.62	1.19
Compressive Modulus (MPa)	45	69

Table 14 Core Properties

6.6.2 ULS Design Strains

Table 15 shows the core ULS design strains that were used to analyse the blade. The designs strains were obtained by dividing characteristic strains by the ULS Material Partial Factor (see Table 6).

	T400	T500
Characteristic Longitudinal Tensile Strain (%)	1.14	1.10
Characteristic Longitudinal Compressive Strain (%)	-1.38	-1.72
Characteristic Shear Strain (%)	1.82	2.50
ULS Material Partial Factor	2.0	2.0
Design Longitudinal Tensile Strain (%)	0.57	0.55
Design Longitudinal Compressive Strain (%)	-0.69	-0.86
Design Shear Strain (%)	0.91	1.25

Table 15 ULS Core Design Allowables

6.6.3 FLS Design Strains

Table 16 shows the core FLS design strains that were used to analyse the blade. The designs strains were obtained by dividing characteristic strains by the FLS Material Partial Factor.

Based on in house test data carried out on Corecell material a minimum m value of 10 has been assumed. For 10^7 cycles, this gives a C1b value of 5.01 as shown in Table 7. This factor combined with the material factors gives a total FLS material factor of 7.44 as summarised in Table 7.

	T400	T500
Characteristic Longitudinal Tensile Strain (%)	1.14	1.10
Characteristic Longitudinal Compressive Strain (%)	-1.38	-1.72
Characteristic Shear Strain (%)	1.82	2.50
FLS Material Partial Factor	7.44	7.44
FLS Material Partial Factor -TE	8.18	8.18
Design Longitudinal Tensile Strain (%)	0.15	0.15
Design Longitudinal Compressive Strain (%)	-0.19	-0.23
Design Shear Strain (%)	0.24	0.34
Design Longitudinal Tensile Strain -TE (%)	0.14	0.13
Design Longitudinal Compressive Strain -TE (%)	-0.17	-0.21
Design Shear Strain-TE (%)	0.22	0.31

Table 16 FLS Core Design Allowables

6.7 Adhesive

The material properties shown in this section represent the minimum design material properties which must be met or exceeded by the blade builder.

A multi-component thermosetting adhesive that is approved by GL shall be used to bond the webs to the shells and the two halves of the shells together. Adhesive must be mixed, applied and cured carefully and in accordance with the manufacturer's recommendations to avoid significant variations in mix ratio, voids or residual thermal stresses.

6.7.1 General Property

Table 17 shows the adhesive properties of Spabond SP340LV epoxy based adhesive with Extra Slow hardener. The Spabond SP340LV properties are based on Gurit internal test data.

	Spabond SP340LV Extra Slow
Nominal Density (kg/m^3)	1150
Tensile Modulus (MPa)	2670

Table 17 Adhesive General Properties

6.7.2 ULS Design Strength

Table 18 shows the adhesive ULS design strength that was used to analyse the blade. The adhesive characteristic shear strength is as given in Paragraph 5, Section 5.5.6, GL 2010 (1). The designs strength was obtained by dividing characteristic strength by the ULS Material Partial Factor.

	GL Adhesive
Characteristic Shear Strength (MPa)	7
ULS Material Partial Factor	2.45
Design Shear Strength (MPa)	2.9

Table 18 ULS Adhesive Design Allowables

6.7.3 Fatigue Limit State (FLS)

Table 19 shows the adhesive ULS design strength that was used to analyse the blade. The adhesive design shear strength is as given in Paragraph 8, Section 5.5.6, GL 2010 (1) for 10^7 load cycles and Wohler exponent between m = 4 and m = 14.

	GL Adhesive
Design Shear Strength -Range (MPa)	1
Design Shear Strength -Amplitude (MPa)	0.5

Table 19 FLS Adhesive Design Allowables

7. Non Structural Masses (NSM) (TSR)

The non-structural masses included in the blade model are summarised in the following table (Table 20). The non-structural masses along the blade span are reported in Appendix A (**Table 53 - Mass distributions**).

Location	Items	NSM	Unit
Shells in way of Spar Cap	Paint	0.9	kg/m^2
Shells not in way of Spar Cap	Paint, Core incl Resin Uptake	4.9	kg/m^2
Shear Webs	Core incl Resin Uptake	2.4	kg/m^2
Blade Length	Adhesive, Bonding Plies, Lightning Protection	11.9	kg/m
Blade Tip	Lightning Protection	2.0	kg

Table 20 Non Structural Masses

8. Mass, Stiffness & Centre of Gravity (TSR)

The mass, centre of gravity and stiffness distribution are reported in Appendix A. The Table 21 shows the structural component mass breakdown which excludes metalwork.

Component	Mass (kg)
Shells - Skins	671
Shells - Core	51
Spar Cap	431
Webs - Skin	80
Webs - Core	8
NSM	196
TOTAL	**1437**

Table 21 Structural Component Mass Breakdown (Excl metalwork)

9. Static Strength Analysis for Fibre Failure (TSR)

Static strength analysis is performed for load conditions obtained from envelope matrices. These load conditions are characterized by the maximum and minimum bending moments in the edgewise and flapwise direction. This choice generates four load conditions, each associated to the maximum (or minimum) of one load. The following figures show isocontour plots of safety margins for different blade components.

Safety margin are computed as

Safety factor = MeasuredStrain / AdmissibleStrain – 1;

therefore the verification is satisfied if a safety margin is negative.

Blade component	***Safety factor***
Upper spar capping	*-0.396*
Lower spar capping	*-0.338*
Shell	*-0.156*
Leading Edge shear web	*-0.482*
Trailing Edge shear web	*-0.374*

Table 22 Worst safety factor for blade component

9.1 Upper Spar Capping safety factor

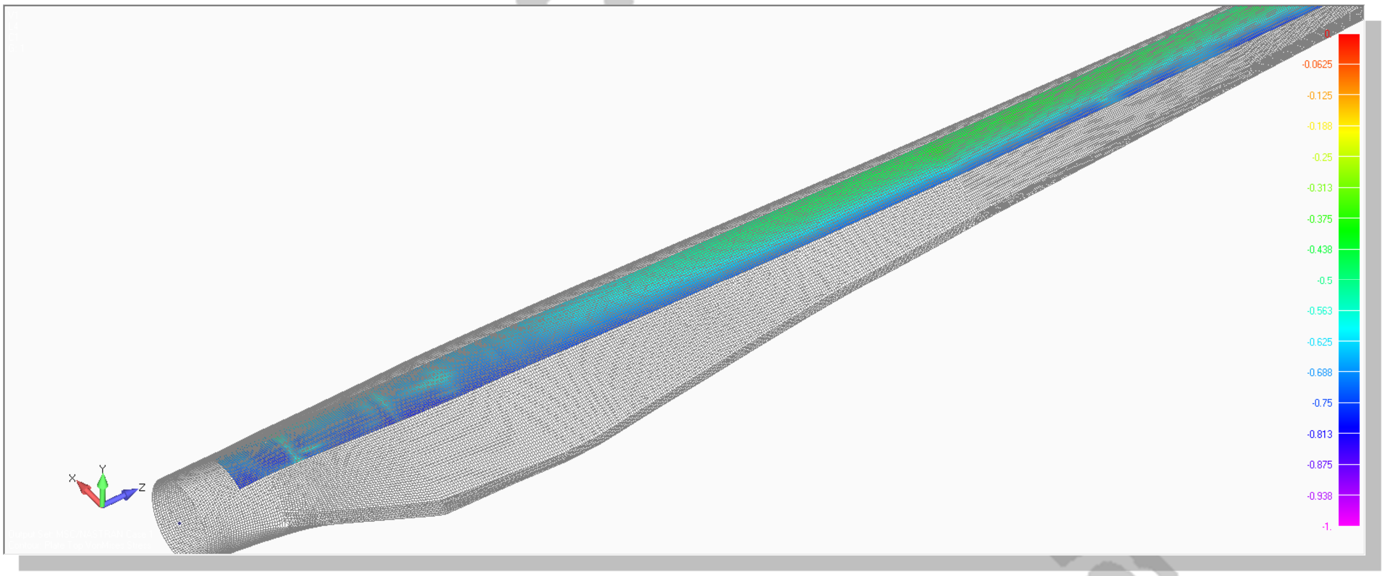


Figure 7 Upper spar capping safety margin, root region

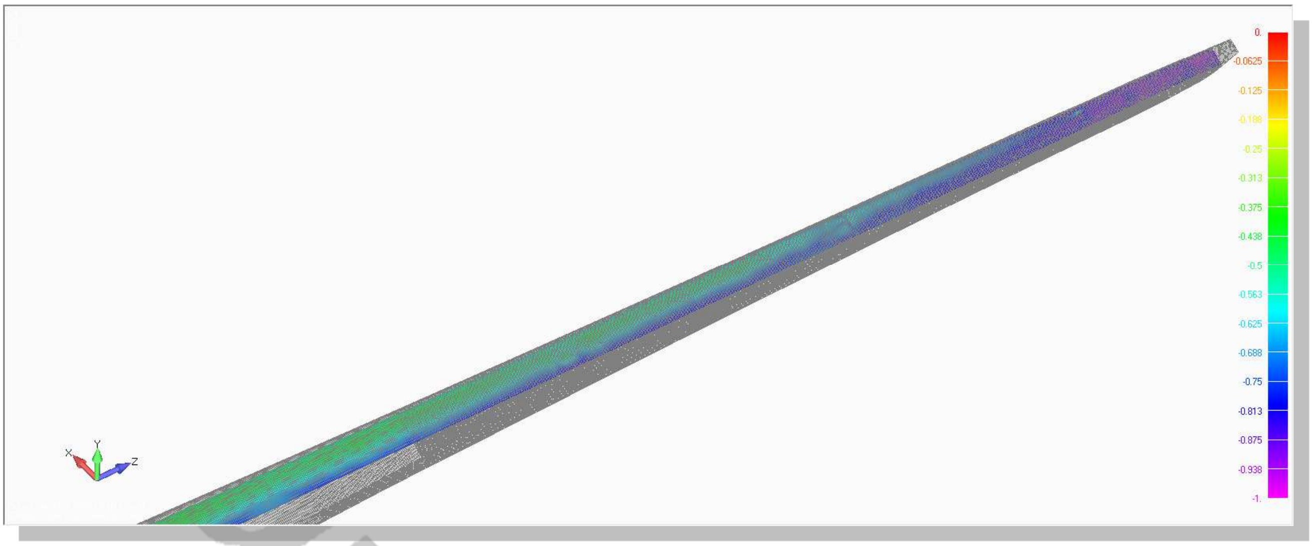


Figure 8 Upper spar capping safety margin, tip region

9.2 Lower Spar capping safety factor

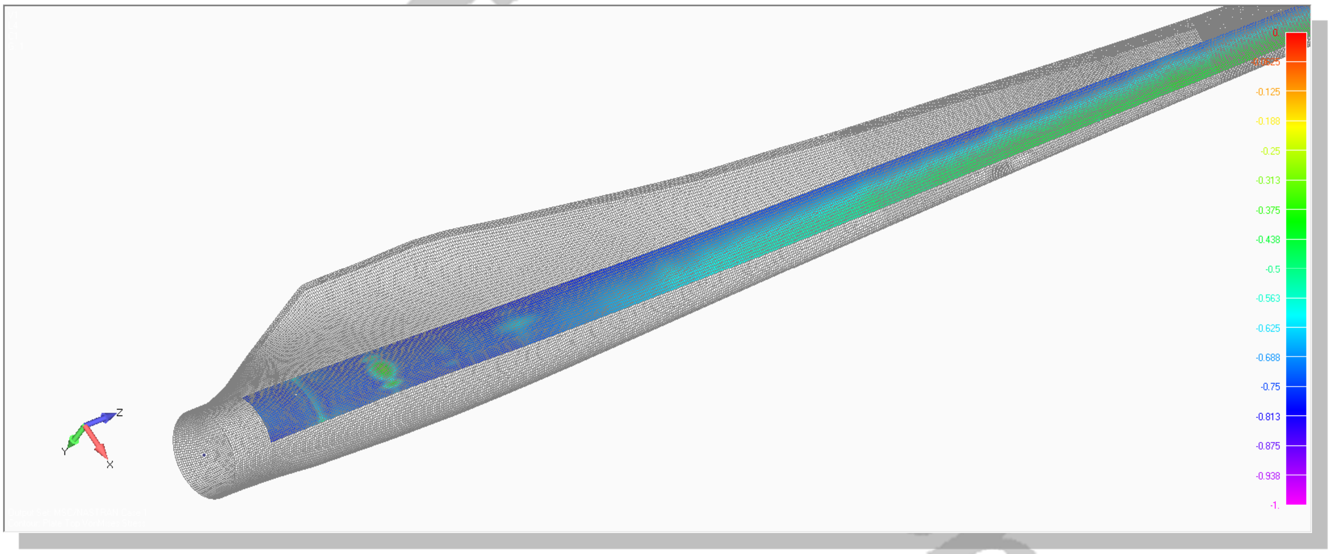


Figure 9 Lower spar capping safety margin, root region

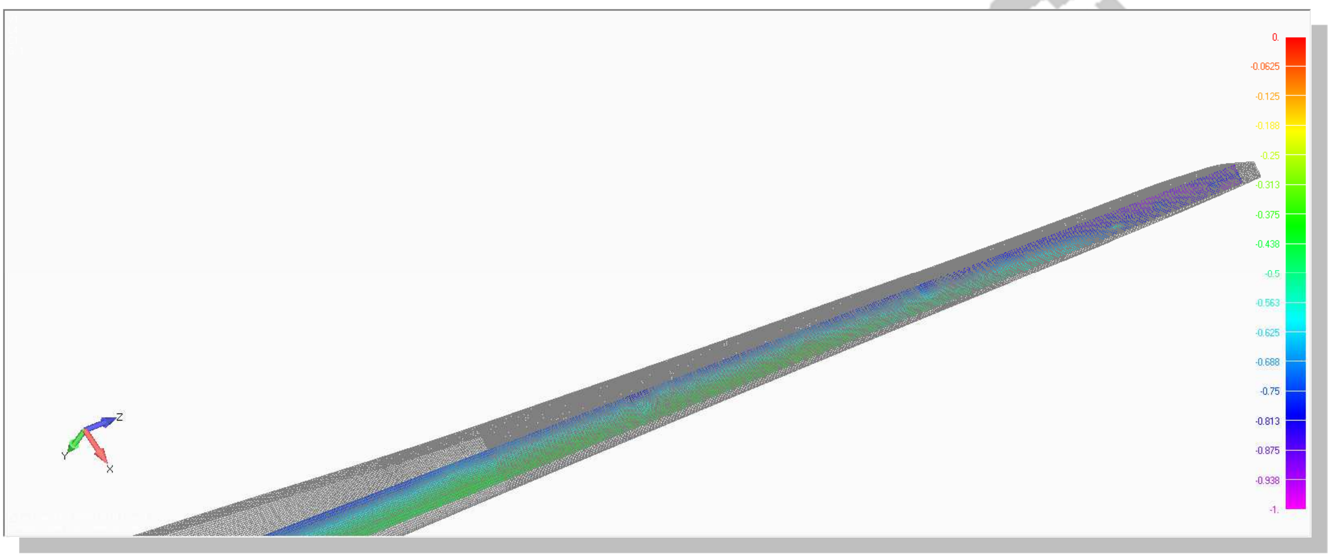


Figure 10 Lower spar capping safety margin, tip region

9.3 Shell safety factor

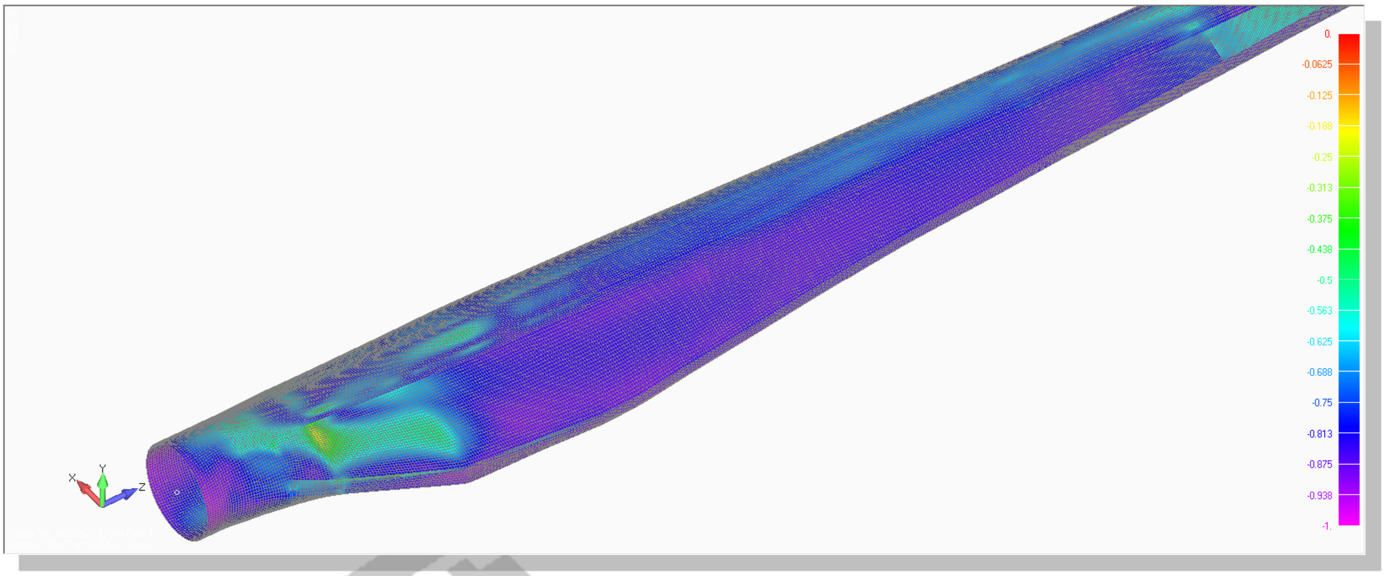


Figure 11 Shell suction side safety margin, root region

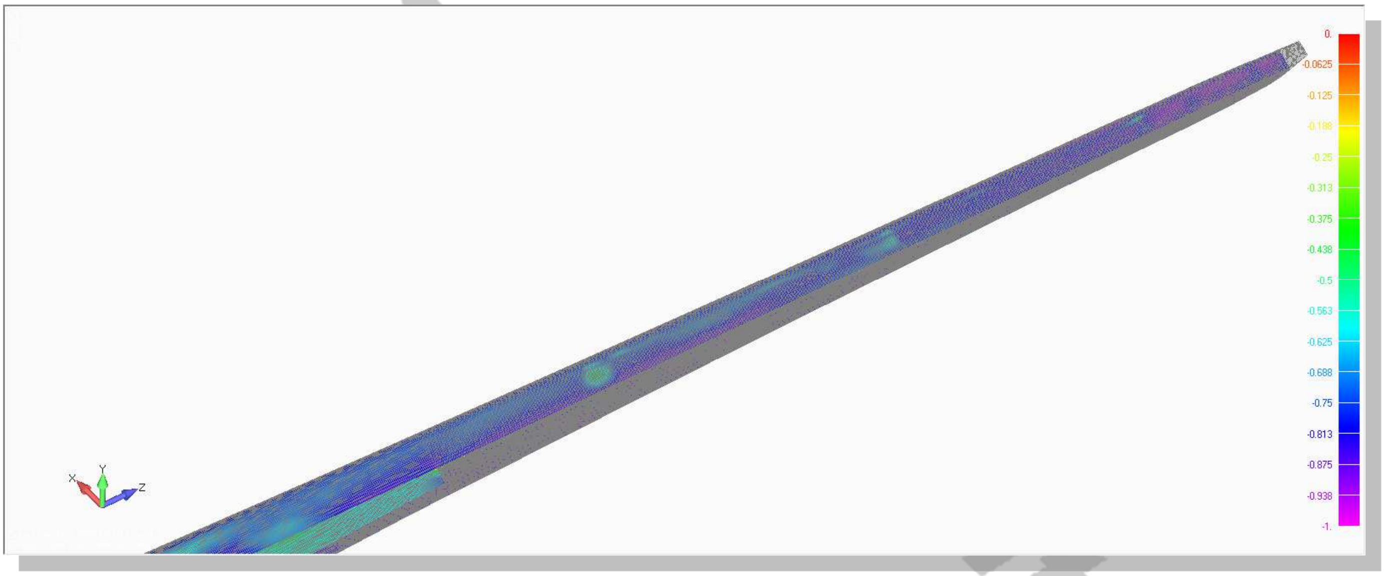


Figure 12 Shell suction side safety margin, tip region

9.4 Shear webs safety factor

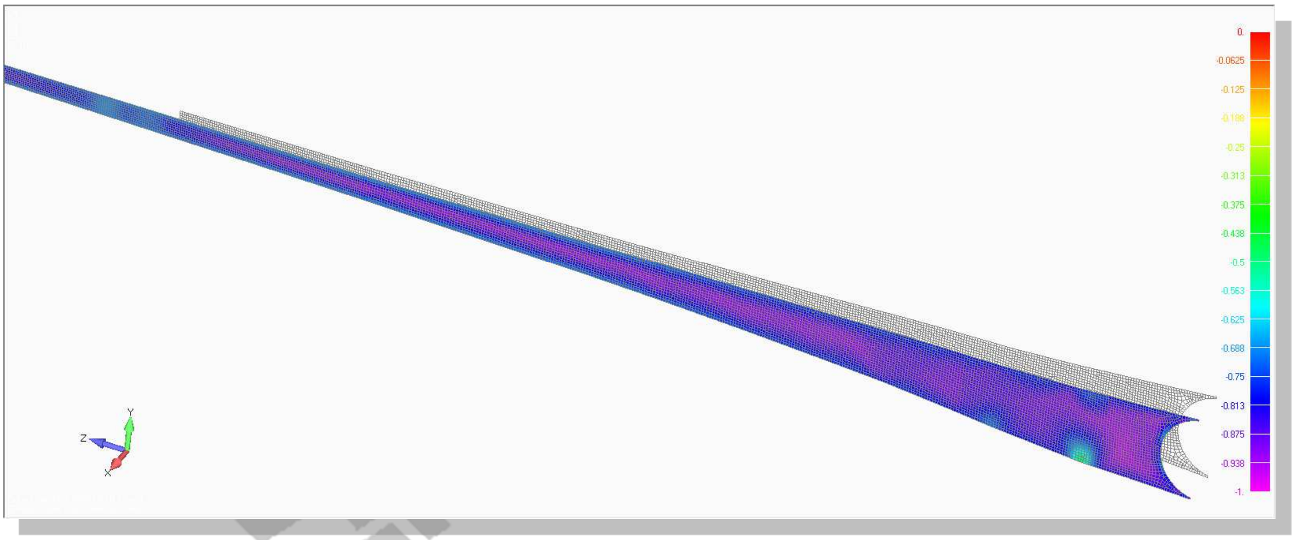


Figure 13 Leading edge shear web safety margin, root region

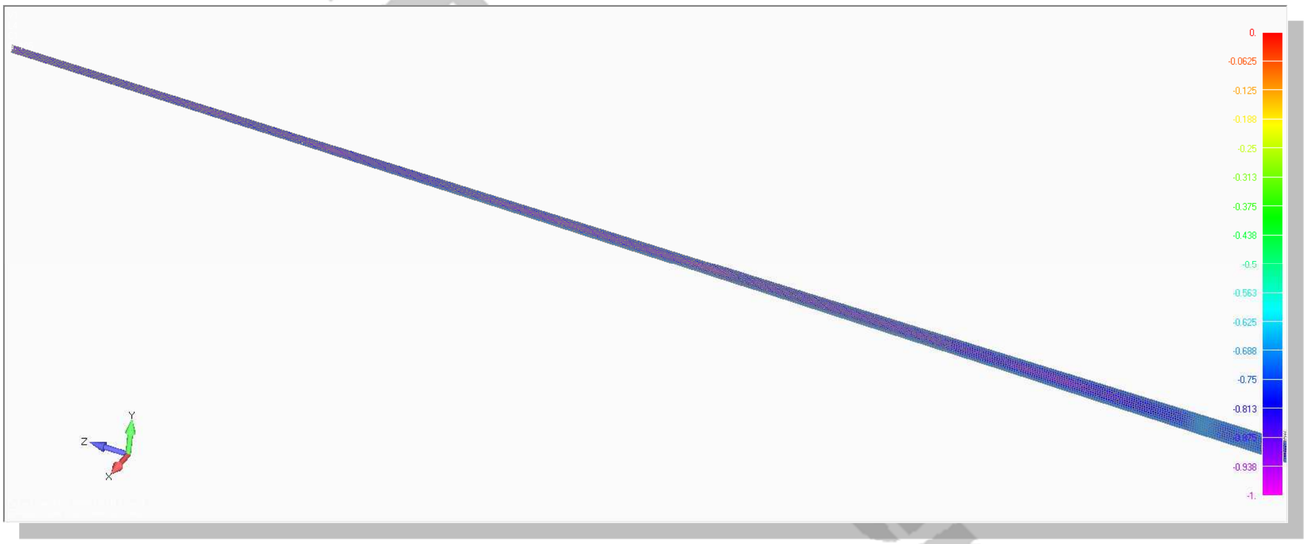


Figure 14 Leading edge shear web safety margin, tip region

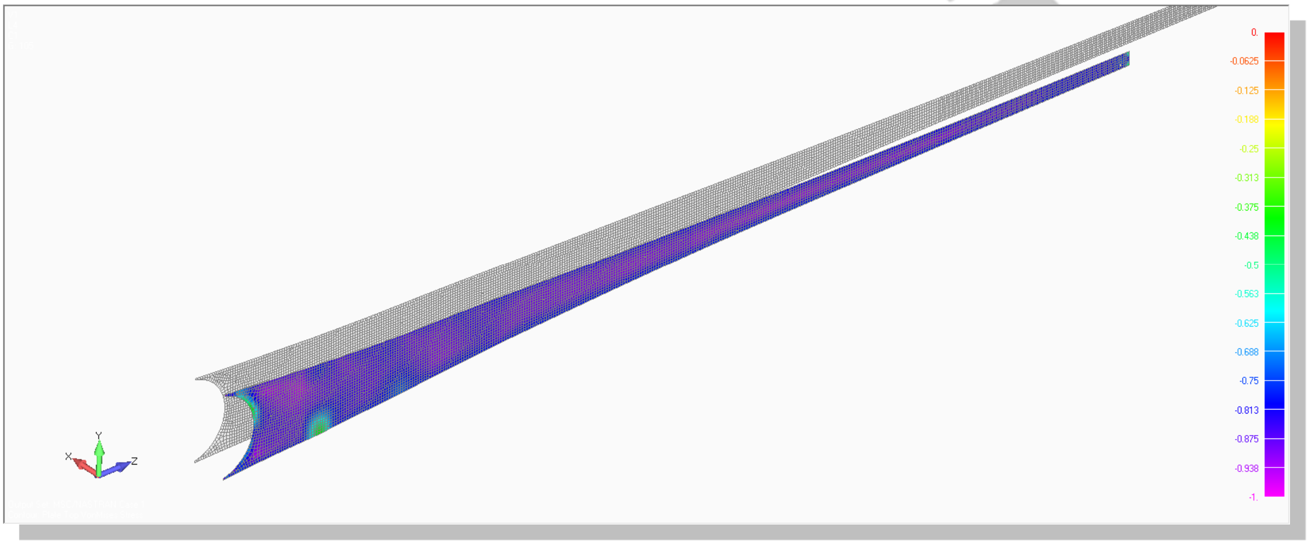


Figure 15 Trailing edge shear web safety margin

10. Fatigue Strength Analysis for Fibre Failure (TSR)

Fatigue analysis is performed by superposition of effects. Load multipliers are retrieved by static analysis for each considered element. These coefficients allow one to compute the stress time histories from load distributions obtained from DLC12, described in 5.1.1. Rainflow counting is used and fatigue damage is computed for each stress component (i.e. longitudinal, transversal and shear) on each element. These multi-axial conditions are combined in a unique index as reported in 'Complex stress state effect on fatigue life of GPR laminates' (3) the verification being satisfied if the resulting damage index is lower than 1.

Being a relatively expensive verification, fatigue strength analysis is performed only on strips of elements at different blade span coordinates as reported in Table 23.

Fatigue sensor number	Blade non-dimensional coordinate
1	0
2	0.013
3	0.05
4	0.10
5	0.14
6	0.26
7	0.30
8	0.37
9	0.44
10	0.49
11	0.63
12	0.73
13	0.91
14	0.99

Table 23 Fatigue virtual sensor position in per cent of blade span

10.1 Upper spar capping damage index

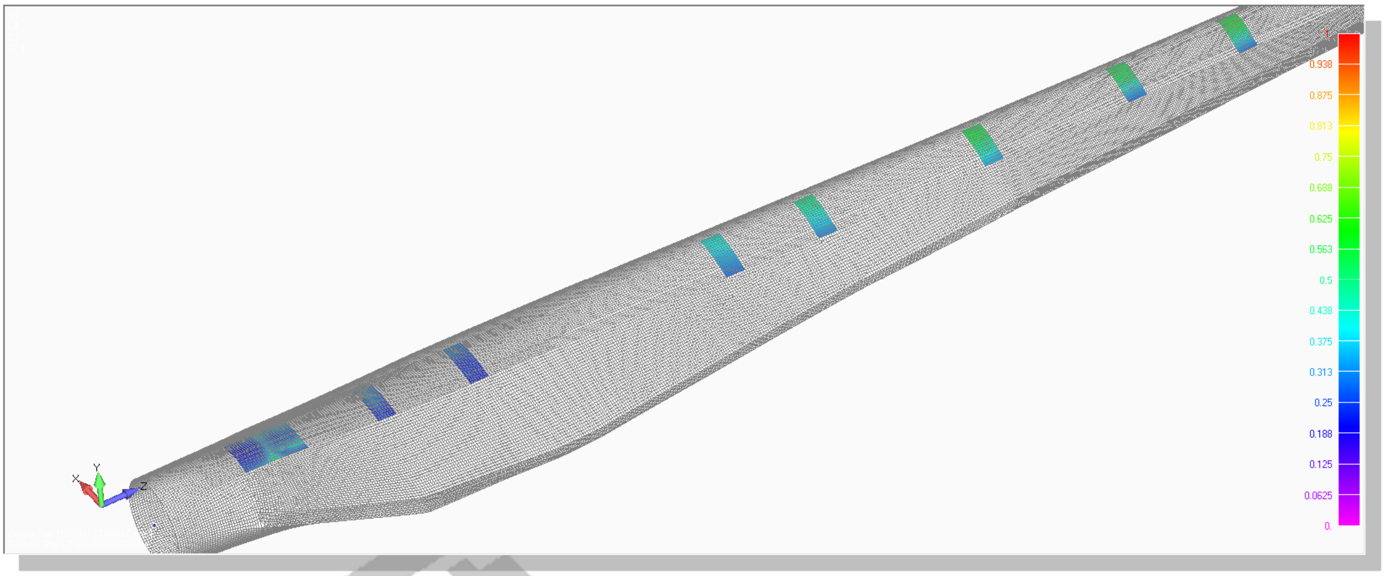


Figure 16 Upper spar capping damage index, root region

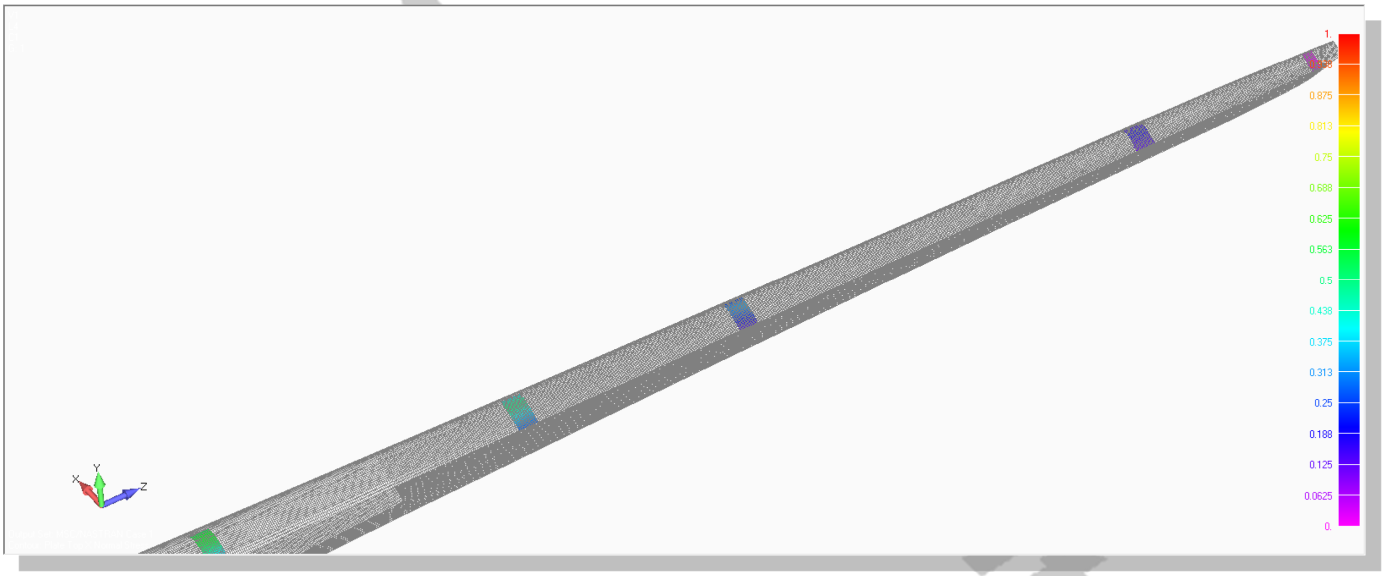


Figure 17 Upper spar capping damage index, tip region

10.2 Lower spar capping damage index

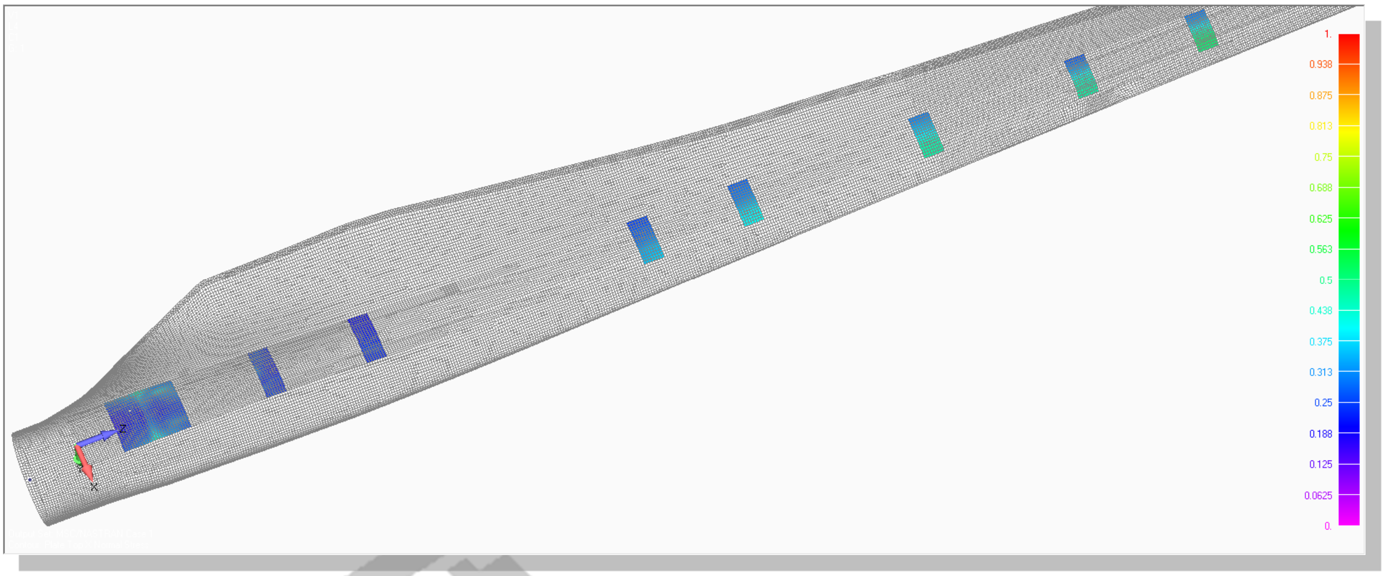


Figure 18 Lower spar capping damage index, root region

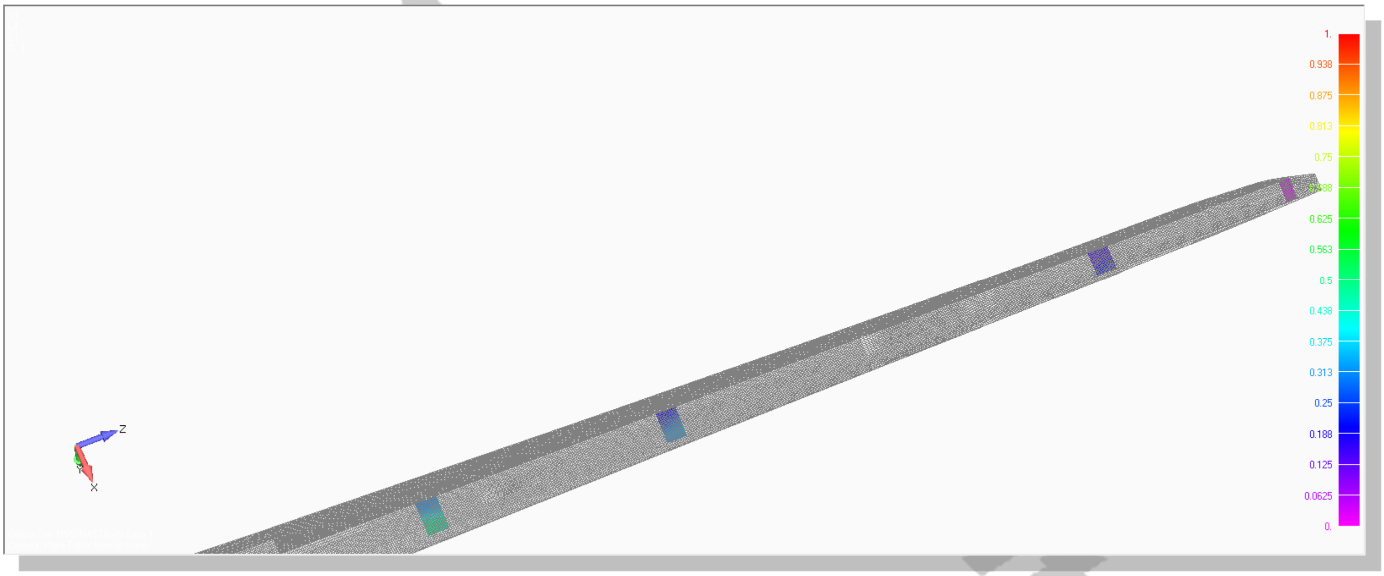


Figure 19 Lower spar capping damage index, tip region

10.3 Shell damage index

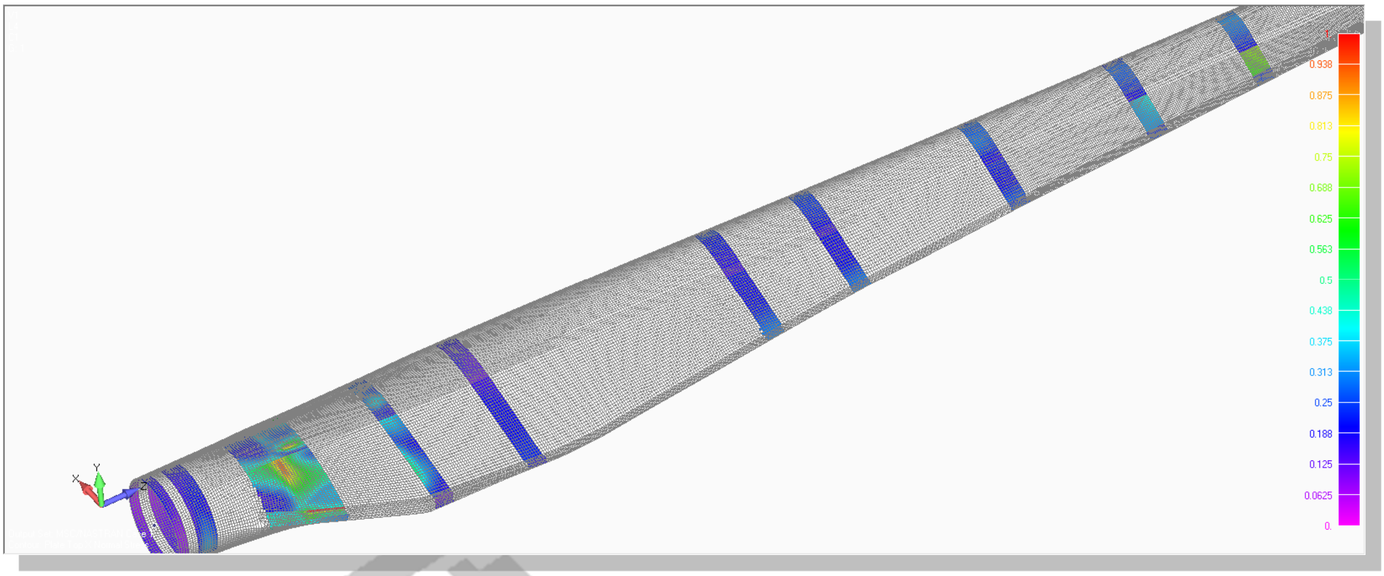


Figure 20 Shell suction side damage index, root region

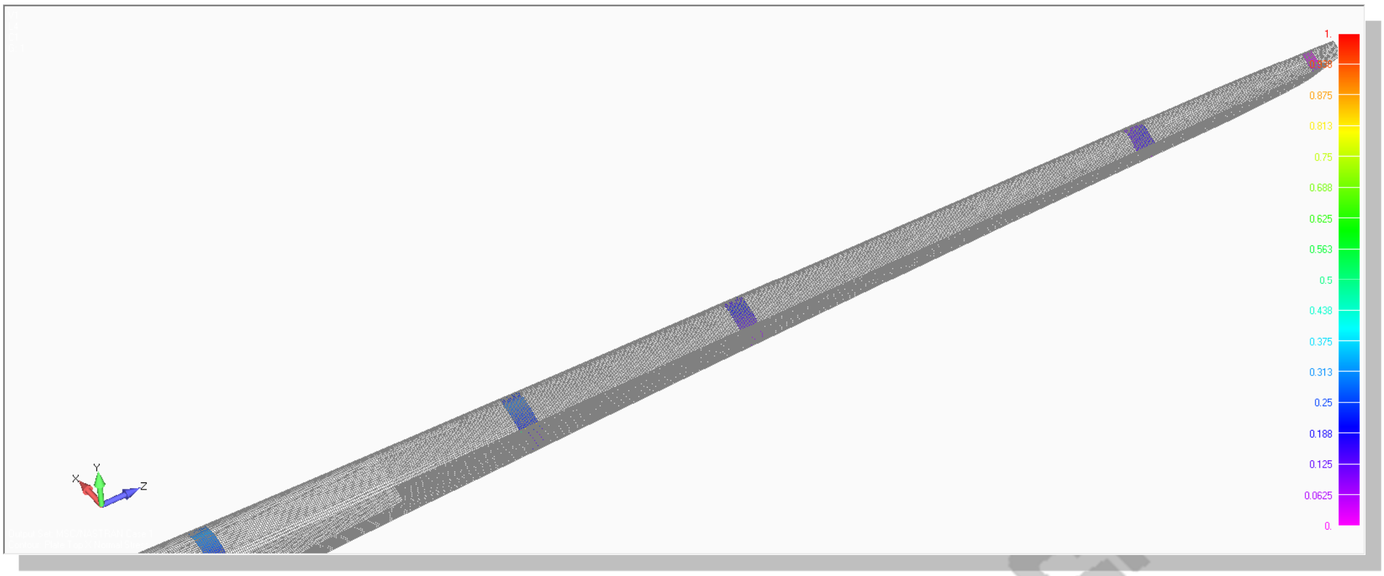


Figure 21 Shell suction side damage index, tip region

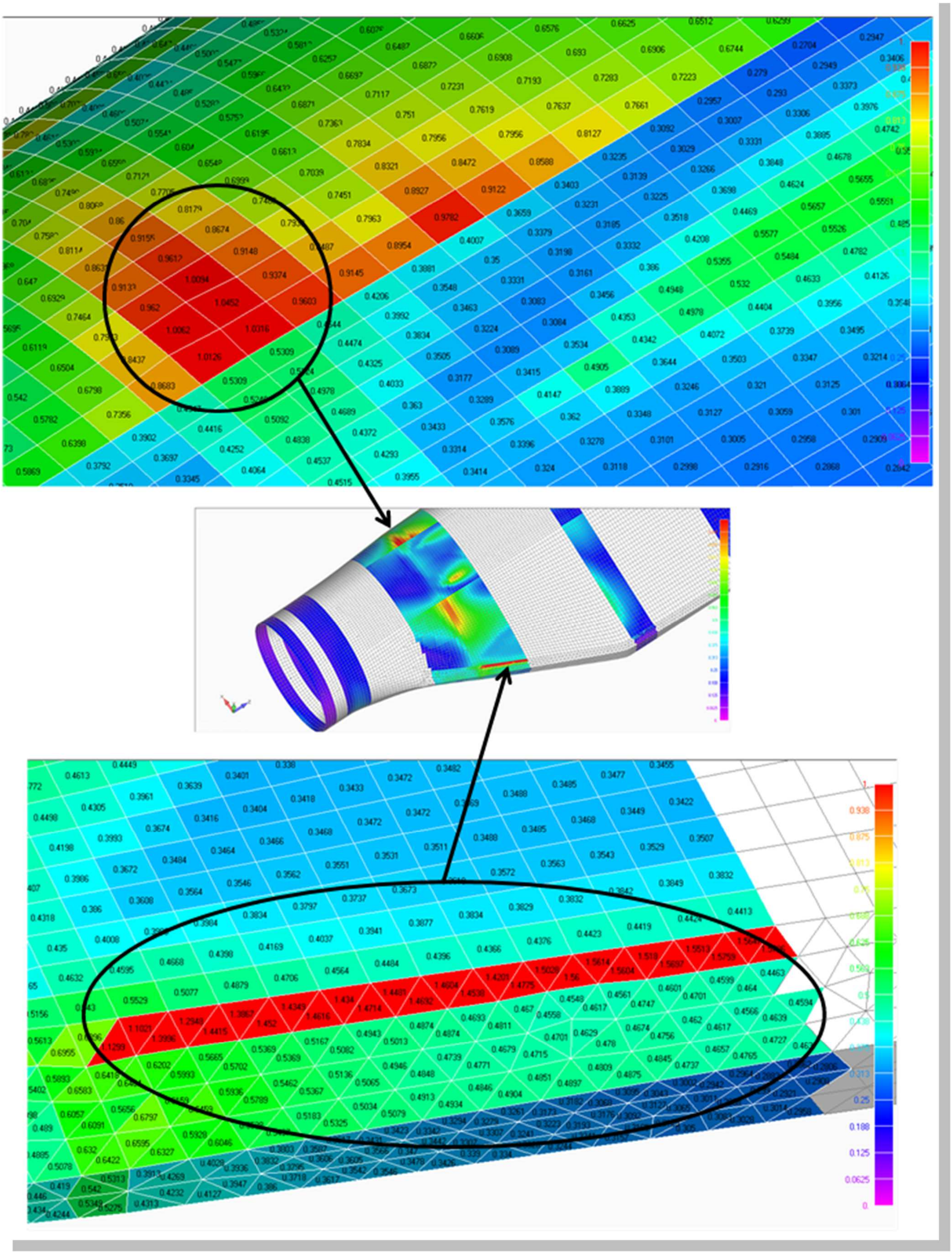


Figure 22 Shell suction side damage index, root region details

10.4 Shear webs damage index

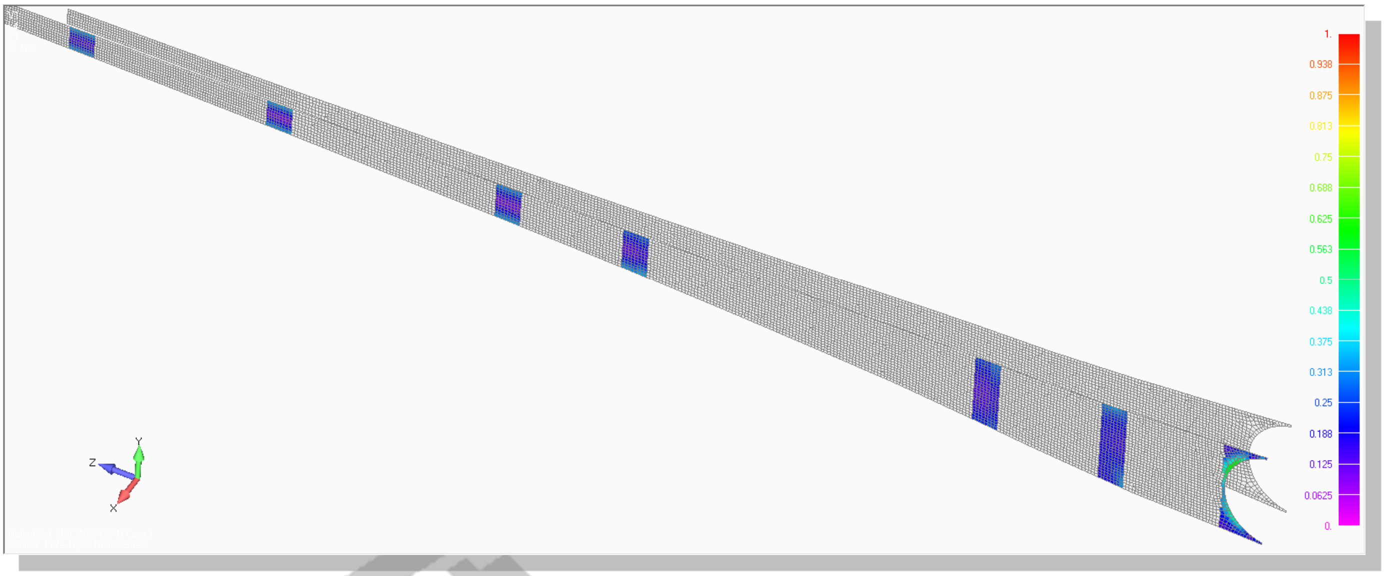


Figure 23 Leading edge shear web damage index, root region

Figure 24 Leading edge shear web damage index, tip region

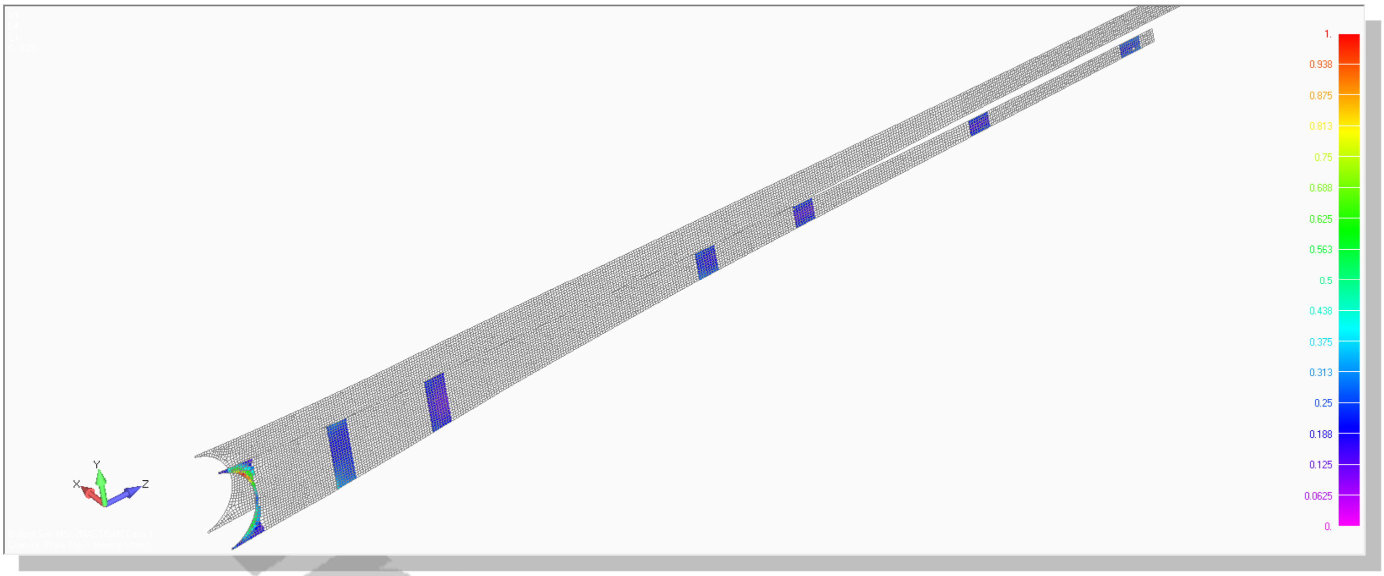


Figure 25 Trailing edge shear web damage index

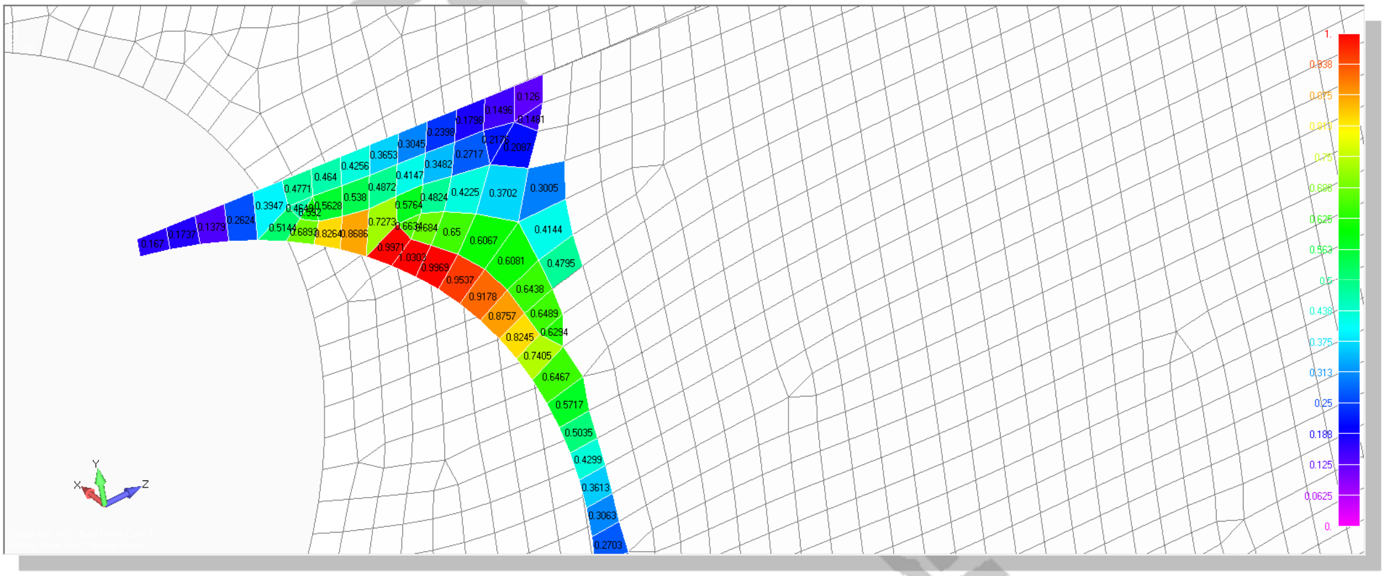


Figure 26 Trailing edge shear web damage index - detail at web start

The fatigue analysis for fibre failure is verified almost everywhere on the blade. There are some localized regions where the damage index exceeds the unit value; these areas are located on the skin and at the beginning of the rear shear web.

Considering the shell, the critical points are located in proximity of the beginning of the shear webs, as shown in Figure 22. The top part of the figure displays the critical points between the upper spar cap and the leading edge. The damage index exceeds the unit value only on 2-3 elements, corresponding to a region of 50mm^2. This effect is due to an approximation in the finite element model of the transition in the number of plies in this region, and it is not considered critical. A second region of damage violation is located at the trailing edge and it is characterized by a strip of whose depth is of one single element. In this area the model exhibits two discontinuities: the end of the shell core and the beginning of the trailing edge solid adhesive, both meeting at the same point. This modelling approximation causes the observed increment of damage index, which is here again not considered as critical for the final result. This conclusion is further supported by the extremely reduced values of damage index in the adjacent elements.

If the rear shear web is considered, the critical zone is limited to only one element (a region of 25mm^2) and the damage index is almost equal to one. Here again, the result is judged to be acceptable due to the very limited extension of the area where the fatigue damage constraint is not satisfied.

11. Markov Matrix Analysis (GURIT)

11.1 Analysis Method

The blade was analysed using the Markov Matrix method specified in Section 5.5.3.3, GL 2010 (1). Since no S/N curves were available for the laminate, a Goodman Diagram for $1x10^7$ cycles was constructed with data given in Paragraph 13, Section 5.5.4; Paragraph 6, Section 5.5.5 and Paragraph 3, Section 5.5.2.4 of the GL 2010 (1).

The part of the shells that are not in way of the spar cap only consist of YE900 so the Markov Analysis for this part of the blade was performed using the YE900 strains. The part of the blade in way of the spar cap consists of YE900, XE600 and UC500. It can be seen from Figure 27 that the UC500 is the critical material out of the three types of material. Hence the analysis of this part of the blade was performed using the UC500 strains. The XE600 derived strains at ±45° were used to perform the Markov Matrix analysis on the shear webs.

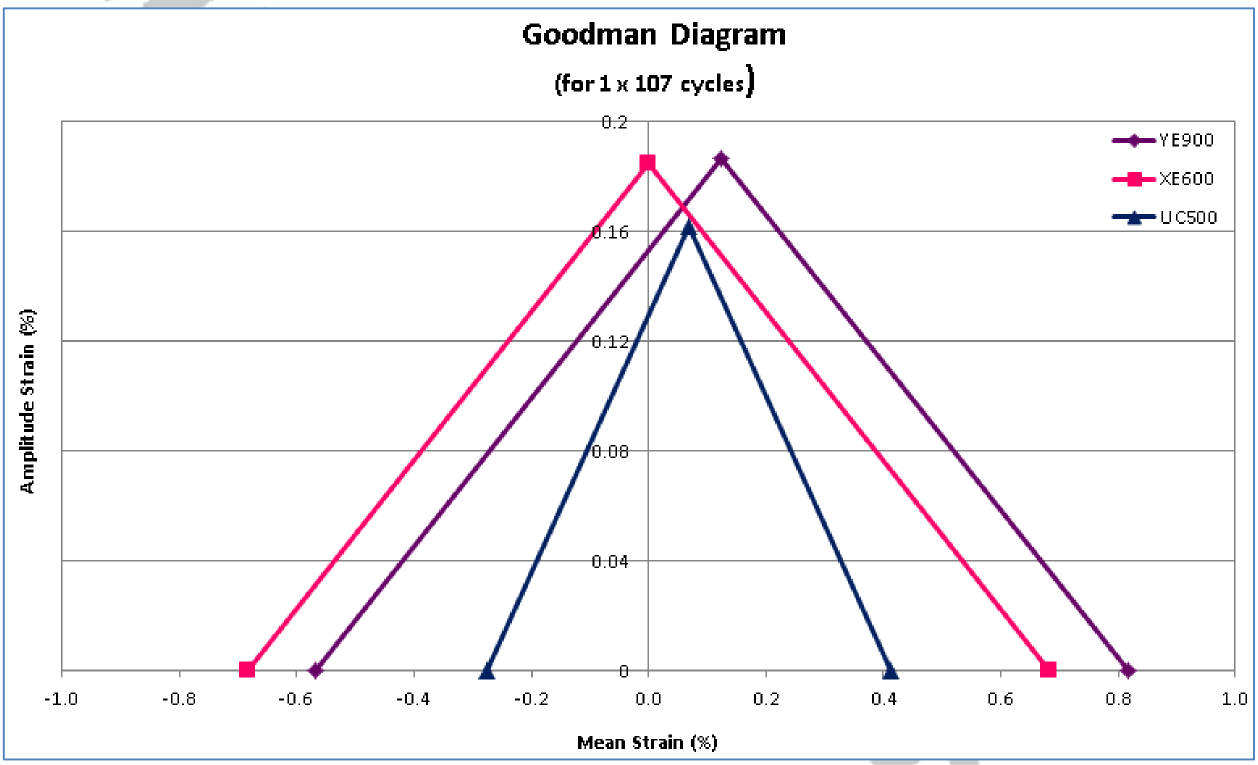


Figure 27 Goodman Diagram for Blade Materials

The allowable number of cycles for each bin of the Markov Matrices was calculated using the method shown in Figure 28 as given in GL 2010 (1). The Markov Matrices (4) which were supplied at discrete radial were analysed in combination with the FE Model (2) to obtain the strain mean ($S_{k,M}$) and strain amplitude ($S_{k,A}$) for this analysis – explained in detail in Section 11.2

$$N = \left[\frac{R_{k,t} + |R_{k,c}| - |2 \cdot \gamma_{Ma} \cdot S_{k,M} - R_{k,t} + |R_{k,c}||}{2 \cdot (\gamma_{Mb}/C_{1b}) \cdot S_{k,A}} \right]^m$$

Figure 28 Method for Calculating Number of Permissible Load Cycles

Using the number of permissible load cycle (N) and number of existing number of load cycles (n), the Damage (D) occurring each blade station was found using the method shown in Figure 29.

$$D = \sum_i \frac{n_i}{N_i}$$

Figure 29 Method for Calculating Damage

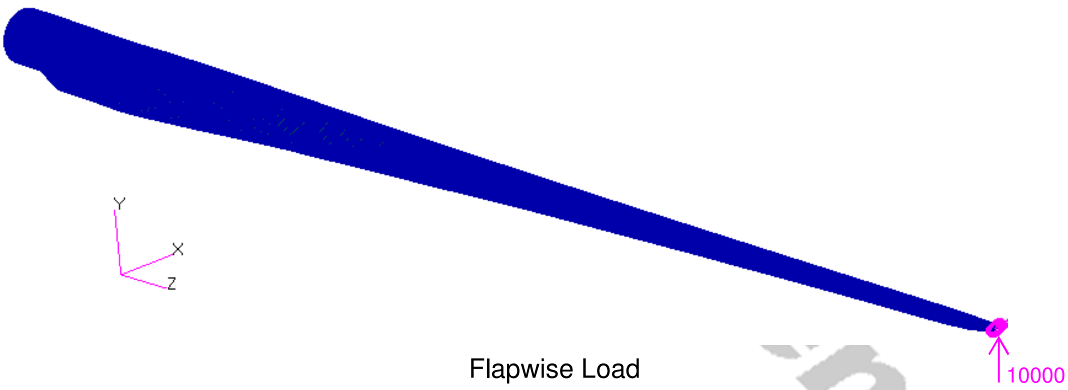
From this known Damage at each blade station, a Reserve Factor (RF) was then calculated using the following method: RF = $D^{-1/m}$ (where slope parameter of the S/N curve, m =10 for carbon and m=14 for glass). These RFs along the length of the blade for each loadcase are presented in the next section.

11.2 Strain Mean and Strain Amplitude

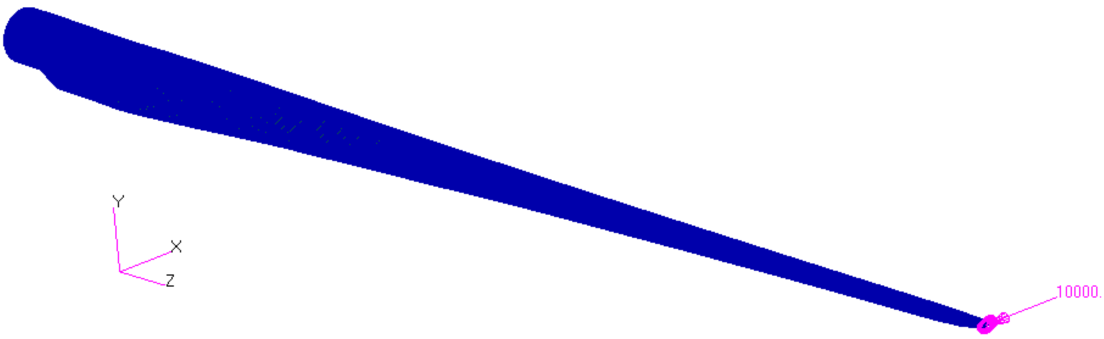
The supplied Markov Matrices contained bending moment mean and amplitudes. To derive the strain mean ($S_{k,M}$) and the strain amplitude ($S_{k,A}$) required to calculated the number of permissible load cycles (N) the bending moments were multiplied by a strain per unit bending moment as shown below:

Strain Mean ($S_{k,M}$) = Mean Bending Moment x FEA Strain per Applied Bending Moment
Strain Amplitude ($S_{k,A}$) = Amplitude Bending Moment x FEA Strain per Applied Bending Moment

The same method as shown above was used to calculate the $S_{k,M}$ and $S_{k,A}$ for the Flapwise Shear Force Markov Matrix analysis. The Strain per Applied Bending Moment and Strain per Applied Shear Force were obtained from the FE model by applying a point load of 10kN at the tip in global +Fy for flapwise load and global –Fx for edgewise load as shown in Figure 30.



Flapwise Load



Edgewise Load

Figure 30 FE Applied Loads for Markov Matrix Analysis

Table 24 shows the peak direct strains obtained from the FE model at the Markov Matrix stations under the flapwise load and edgewise load as shown in Figure 30.

Z (m)	FE Applied Bending Moment (kNm)	FE Applied Shear Force (kN)	Flapwise Loadcase Strains					Edgewise Loadcase Strains	
			Suction Side Spar Capping $(\mu\varepsilon)$	Pressure Side Spar Capping $(\mu\varepsilon)$	Suction Side Shell $(\mu\varepsilon)$	Pressure Side Shell $(\mu\varepsilon)$	Webs $(\mu\gamma)$	Leading Edge Shell $(\mu\varepsilon)$	Trailing Edge Shell $(\mu\varepsilon)$
0.00	239.0	10	-313	274	-298	261	-	249	-270
0.30	236.0	10	-290	276	-286	273	-	212	-185
1.20	227.1	10	-400	480	-415	431	1430	1776	-1890
2.39	215.1	10	-214	253	-226	253	692	630	-787
3.39	205.1	10	-297	273	-297	270	465	511	-742
6.17	177.3	10	-477	487	-477	487	620	701	-1320
7.17	167.3	10	-547	587	-547	587	482	827	-1420
8.96	149.4	10	-672	724	-653	700	324	927	-1280
10.76	131.5	10	-723	800	-765	822	200	1067	-1640
11.95	119.5	10	-877	953	-833	935	187	1231	-1820
15.54	83.7	10	-1674	1621	-1654	1621	623	1526	-2180
19.12	47.8	10	-2096	2307	-2096	2307	1613	2199	-2090
22.00	19.0	10	-1250	1528	-1250	1528	1849	2796	-2050
23.66	2.4	10	-2603	10403	5510	10403	-	6331	-3630

Table 24 Blade FE Strains

The blade FE strains were used to obtain strains per applied bending moment (BM) and strains per applied shear force (SF) and are shown in Table 25. This was then used to obtain the $S_{k,M}$ and $S_{k,A}$.

	Strain / Flapwise BM $(\mu\varepsilon\ /$kNm)				Strain / Flapwise SF $(\mu\gamma\ /$kNm)	Strain / Edgewise BM $(\mu\varepsilon\ /$kNm)	
Z (m)	Suction Side Spar Capping	Pressure Side Spar Capping	Suction Side Shell	Pressure Side Shell	Webs	Leading Edge Shell	Trailing Edge Shell
0.00	-1.3	1.15	-1.25	1.09	-	1.04	-1.13
0.30	-1.2	1.17	-1.21	1.16	-	0.898	-0.784
1.20	-1.8	2.11	-1.83	1.90	143.0	7.82	-8.32
2.39	-1.0	1.18	-1.05	1.18	69.2	2.93	-3.66
3.39	-1.4	1.33	-1.45	1.32	46.5	2.49	-3.62
6.17	-2.7	2.75	-2.69	2.75	62.0	3.95	-7.44
7.17	-3.3	3.51	-3.27	3.51	48.2	4.94	-8.49
8.96	-4.5	4.85	-4.37	4.69	32.4	6.21	-8.57
10.76	-5.5	6.09	-5.82	6.25	20.0	8.12	-12.5
11.95	-7.3	7.97	-6.97	7.82	18.7	10.3	-15.2
15.54	-20.0	19.4	-19.8	19.4	62.3	18.2	-26.1
19.12	-44.0	48.3	-43.8	48.3	161.0	46.0	-43.7
22.00	-66.0	80.4	-65.8	80.4	185.0	147.0	-108.0
23.66	-1100.0	4350.0	-2310.0	4350.0	-	2640.0	-1510.0

Table 25 Blade Strains per applied Bending Moment & Strains per applied Shear Force

11.3 Results

11.3.1 Flapwise

The blade Reserve Factors (RF) for the Flapwise Bending Moment Markov Matrix are shown in Table 26

Wohler Coefficient (m)	14	14	10	10
Z (m)	Suction Side Spar Capping	Pressure Side Spar Capping	Suction Side Shell	Pressure Side Shell
0.00	4.5	6.2	6.2	7.8
0.30	5.0	6.2	6.6	7.5
1.20	3.6	3.9	4.7	5.1
2.39	7.7	7.4	9.4	8.9
3.39	5.7	7.2	7.5	8.8
6.17	4.1	4.8	5.5	5.8
7.17	3.8	4.1	5.0	5.1
8.96	3.5	3.7	4.7	4.7
10.76	3.7	3.7	4.6	4.5
11.95	3.4	3.4	4.7	4.4
15.54	**2.9**	**3.2**	**3.9**	**4.1**
19.12	4.6	4.2	6.0	5.4
22.00	25.3	20.4	32.5	26.4
23.66	276.9	69.2	152.8	80.9
Minimum RF	**2.9**	**3.2**	**3.9**	**4.1**

Table 26 Flapwise Bending Moment Markov Matrix Reserve Factors

Figure 31 shows that all the blade RFs are above 1 which is acceptable.

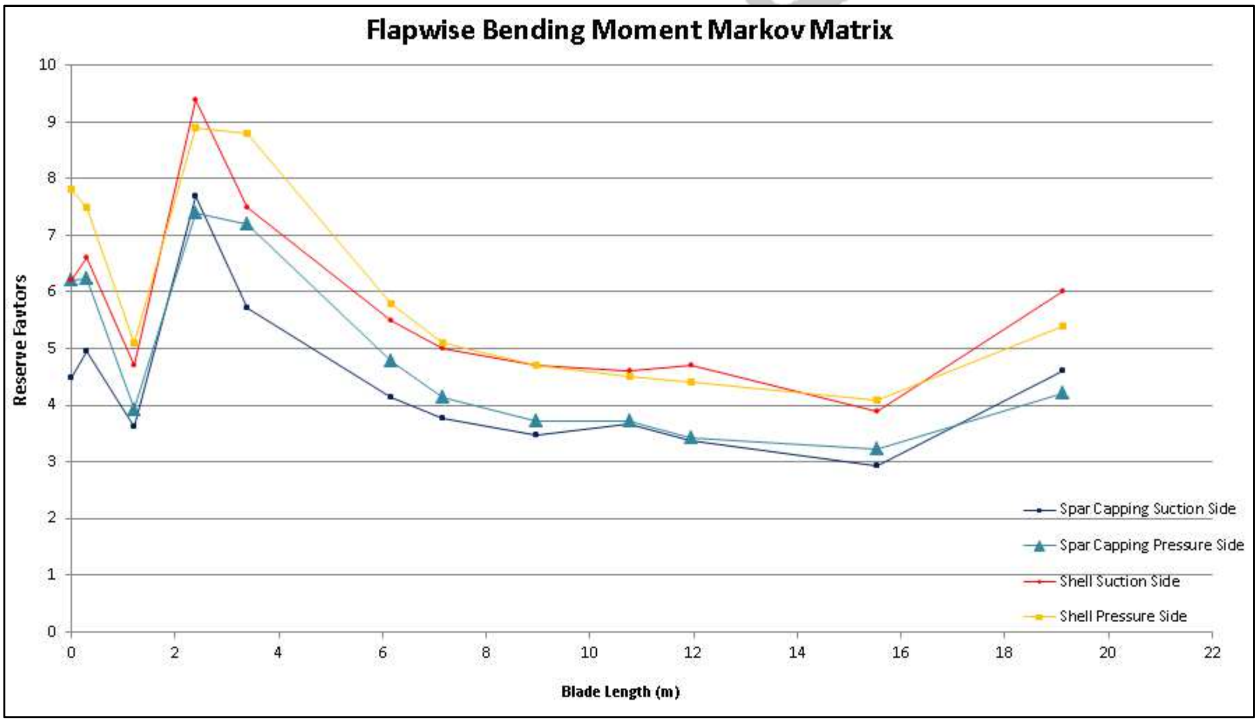


Figure 31 Flapwise Bending Moment Markov Matrices Reserve Factors

The blade RFs for the Flapwise Shear Force Markov Matrix are shown in Table 27. Only the webs carry the applied shear force so the RF shown is the minimum value of the leading edge web and the trailing edge web.

Z (m)	RF	Location
0.00	-	-
0.30	-	-
1.20	0.4	Trailing Edge Web
2.39	1.3	Trailing Edge Web
3.39	2.3	Trailing Edge Web
6.17	2.0	Trailing Edge Web
7.17	3.0	Trailing Edge Web
8.96	5.1	Trailing Edge Web
10.76	9.7	Trailing Edge Web
11.95	11.1	Leading Edge Web
15.54	5.0	Leading Edge Web
19.12	4.0	Leading Edge Web
22.00	10.0	Leading Edge Web

Table 27 Flapwise Shear Force Markov Matrix Reserve Factors

Figure 32 shows that all of the blade RFs are above 1 and acceptable except at Z = 1.2m where the RF is below 1.

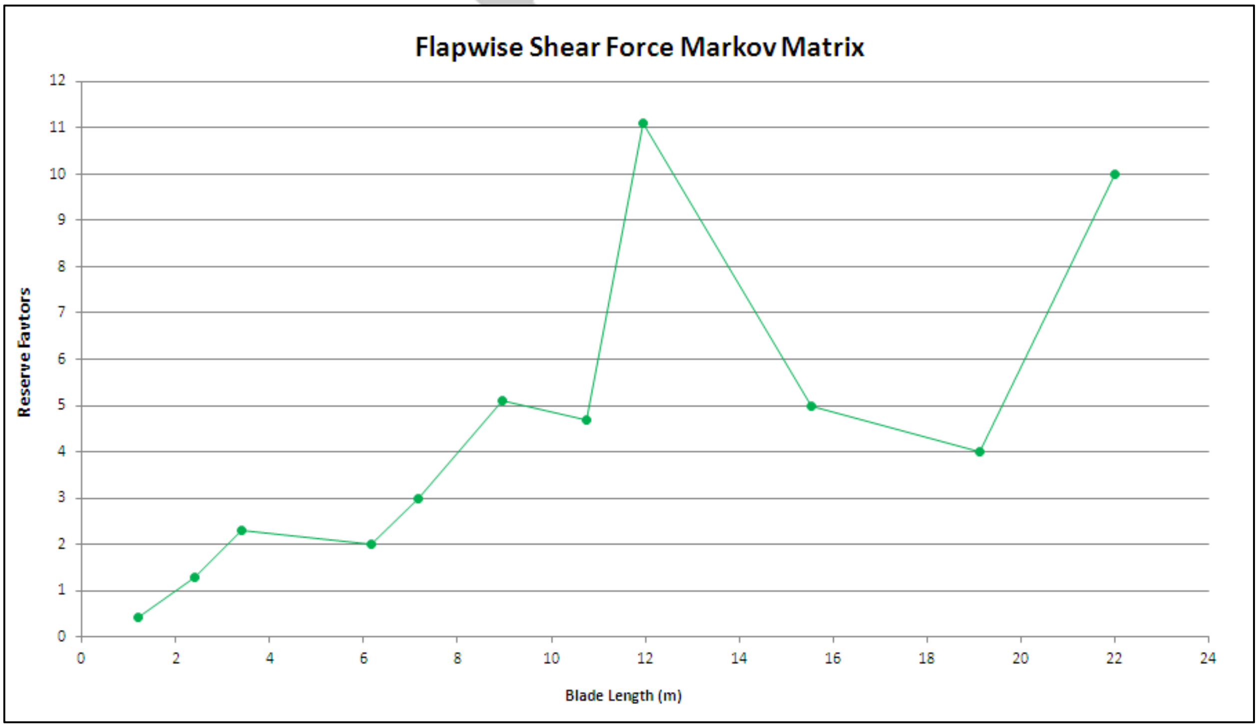


Figure 32 Flapwise Shear Force Markov Matrices Reserve Factors

A closer inspection of the trailing at web in the FE model at around Z = 1.2m shows a local stress concentration that occurs only over a few elements. It can be seen from Figure 33 that the strains over these elements are very high when compared to the strains seen by the rest of the web.

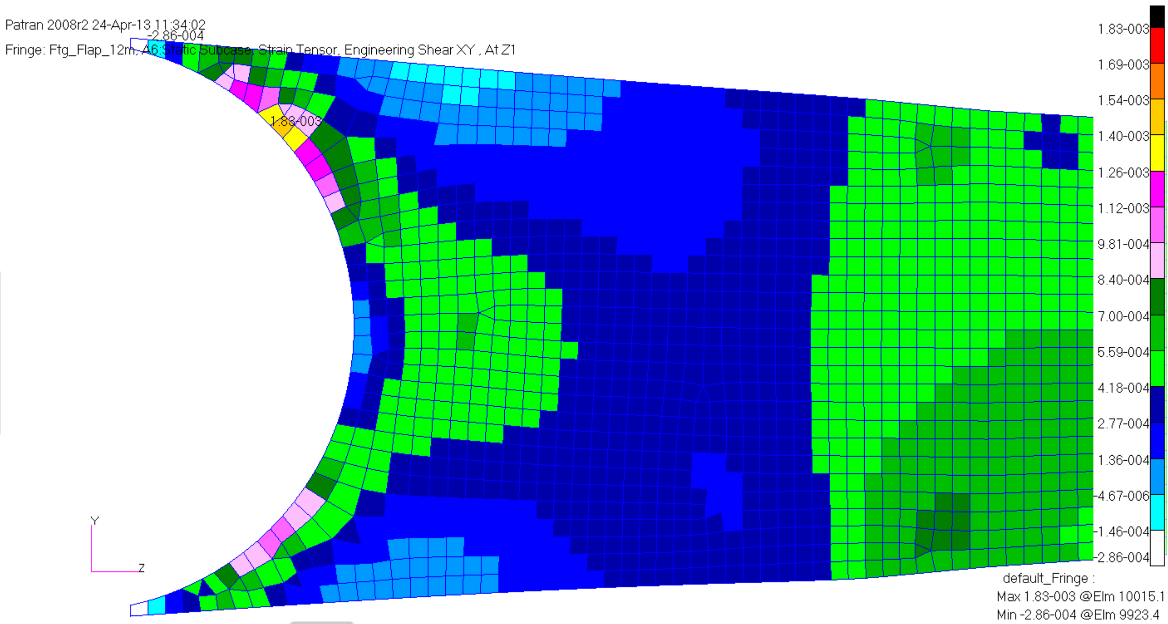


Figure 33 FE Plot of the Flapwise Strains – Trailing Edge Web

The point load of 10kN which was applied at the tip of the blade produces a Flapwise Bending Moment of 227.1kNm and a Flapwise Shear Force of 10kN at Z = 1.2m. The ratio between this bending moment and shear force is too large which creates strains on the webs that are not representative. This is evident when a comparison is made between Flapwise Bending Moment and Flapwise Shear Force at 1.2m for the blade's Damage Equivalent Loads (DEL).The ratio between the bending moment and shear force for the DELs is much lower that the ratio between the bending moment and shear force applied to the FE model used for the Markov Matrix analysis. In order to model the localised area of the web more realistically, a lower bending moment has to be applied at Z = 1.2m. This way the ratio of bending moment to shear force is more realistic and the shear webs should see a lower strain that represents reality.

The FE model was rerun with the point load of 10kN applied at Z = 12m on the blade. The shear force remains the same at 10kN but since a lower bending moment is being applied, the strains on the trailing edge web are lower as shown in Figure 34. Using these strains, the RF at Z = 1.2m was found to be 2.2 and acceptable. Even though the ratio of bending moment to shear for may not be accurate for the rest of the web in the original analysis conducted, the results of the analysis are considered to be conservative. Hence the rest of the trailing edge and leading edge webs have not been reanalysed for the correct ratio of bending moment to shear force.

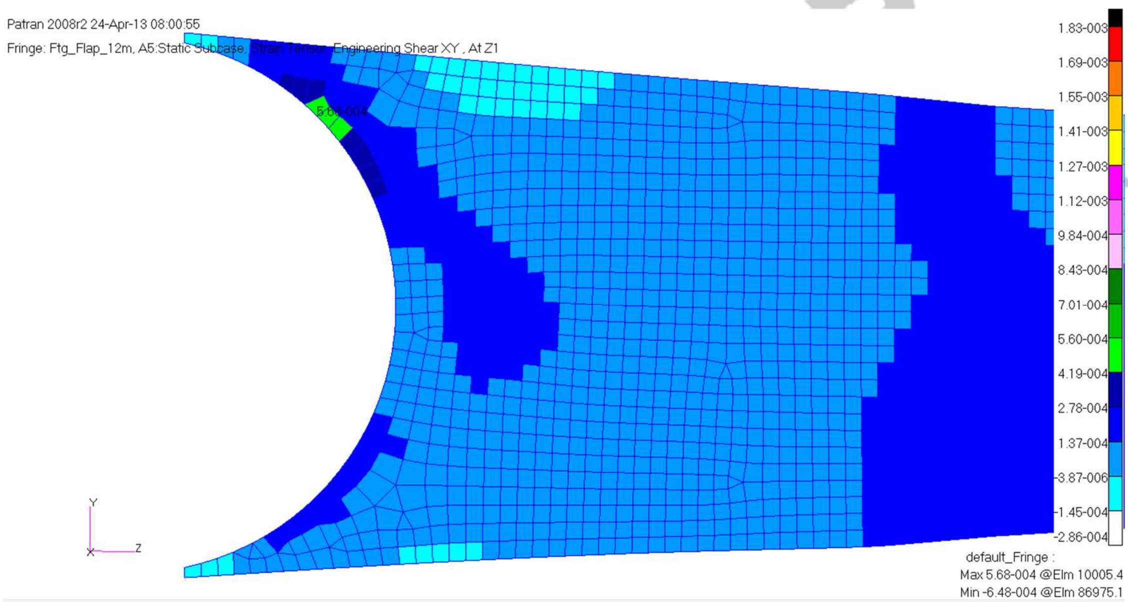


Figure 34 FE Plot of the Reduced Flapwise Strains – Trailing Edge Web

11.3.2 Edgewise

The blade RFs for the Edgewise Bending Moment Markov Matrix are shown in Table 28.

Z (m)	Leading Edge Shell	Trailing Edge Shell
0.00	11.4	10.7
0.30	13.8	16.0
1.20	**1.7**	**1.8**
2.39	5.4	4.5
3.39	7.4	5.2
6.17	7.3	3.9
7.17	6.9	4.0
8.96	7.2	5.2
10.76	7.9	5.1
11.95	7.8	5.2
15.54	10.6	7.3
19.12	17.3	18.0
22.00	40.0	54.2
23.66	96.3	167.6
Minimum RF	**1.7**	**1.8**

Table 28 Edgewise Bending Moment Markov Matrix Reserve Factors

Figure 35 shows that all blade RFs are above 1 and acceptable.

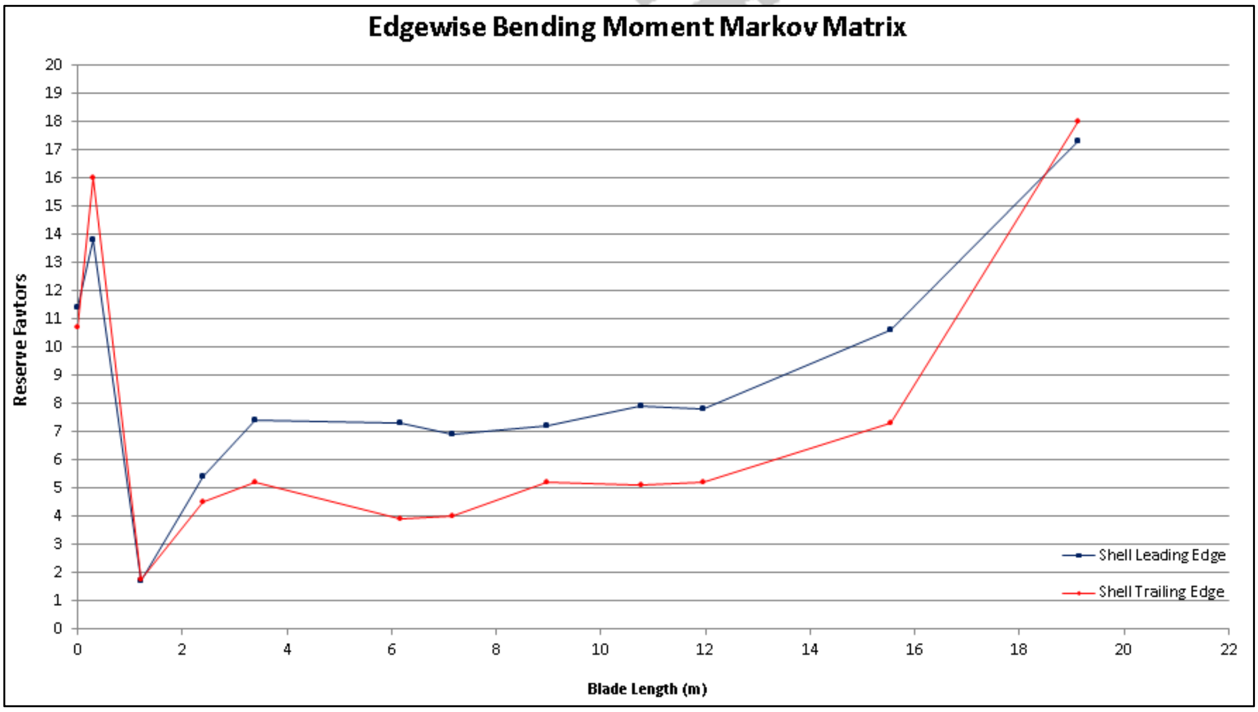


Figure 35 Blade Edgewise Markov Matrices Reserve Factors

11.3.3 Summary

Table 29 shows a summary of the minimum RFs from the Markov Matrix Fatigue analysis performed on the blade. The summary shows that all the RFs are above 1 and acceptable.

Loadcase	Wohler Coefficient (m)	Component	RF	Z (m)
Flapwise Bending Moment	14	Suction Side Spar Capping	2.9	15.5
		Pressure Side Spar Capping	3.2	15.5
	10	Shell Suction Side	3.9	15.5
		Shell Pressure Side	4.1	15.5
Flapwise Shear Force	10	Webs	1.3	2.4
Edgewise Bending Moment	10	Shell Leading Edge	1.7	1.2
		Shell Trailing edge	1.8	1.2

Table 29 Summary of Minimum RFs

12. Inter-Fibre Failure Analysis (GURIT)

12.1 Analysis Method

As specified in Paragraph 2, Section 5.5.3.1 of the GL 2010 (1), a 2D Puck inter-fibre failure analysis was conducted on the blade. The Puck analysis was conducted for all three inter-fibre failures modes A, B and C.

The blade strains required for the inter-fibre failure analysis were obtained from TSR's FE Model (2) for each of the following ULS loadcases:

- Positive Flapwise
- Negative Flapwise
- Positive Edgewise
- Negative Edgewise

The elements with the highest X strain, highest Y strain and highest XY strain under each of these four ULS loadcases were found for each zone of the blade structure. This method was used to identify the elements that could be critical for inter-fibre failure.

As specified in Paragaraph 1, Section 5.5.3.2.2 of GL 2010 (1), the inter-fibre failure analysis has to be performed with the characteristic loads. As the characteristic loads were unavailable, the strains obtained from the ULS loadcases as described above were then factored down by the Abnormal Load Partial Factor of 1.1, which is the lowest partial load factor applied to the calculated characteristic loads. This may be conservative in cases where the a partial load factor of 1.35 is applied.

The analysis was then performed for the critical elements using the Puck Failure Envelope which is described in the next section whilst the results are shown in Section 12.4.

12.2 Failure Envelope

When performing the inter-fibre failure analysis on the YE900 and XE600, it has been assumed that these multiaxial fabrics are made up of separate unidirectional plies at their respective orientations. The type of fibres and resin in the YE900 and XE600 are identical to a ply of UE1200. Hence, when analysing the separate unidirectional plies in a multiaxial fabric, the properties of the UE1200 are used. UC500 material properties were used for the inter-fibre failure analysis of the spar capping. The following properties were obtained from Gurit's in-house material test database and represent a good quality epoxy infused laminate. These properties should be validated by the blade builder if required.

The parameters shown in Table 30 and the safety factors shown in Section 6.3.4 were used to calculate the Puck Failure envelopes for both infused carbon and infused glass.

		Infused Glass UD	Infused Carbon UD
Mean Strength (MPa)	Transverse Tensile $R^{\perp}_{T}$	38	29
	Transverse Compressive $R^{\perp}_{c}$	127	95
	In Plane Shear $R^{\perp\parallel}$	38	29
Mean Modulus (MPa)	Transverse Tensile	8450	6350
	Transverse Compressive	8450	6350
	In Plane Shear	3190	3390
Inclination Parameters [Sect 5.5.3.1, 1]	$p^{\perp\parallel}_{t}$	0.30	0.30
	$p^{\perp\parallel}_{c}$	0.25	0.25

Table 30 Puck Analysis Parameters

The resulting Puck Failure envelopes with and without partial material safety factors applied (see section 6.3.4) for a single fibre direction of glass fibre epoxy composite are shown in Figure 36.

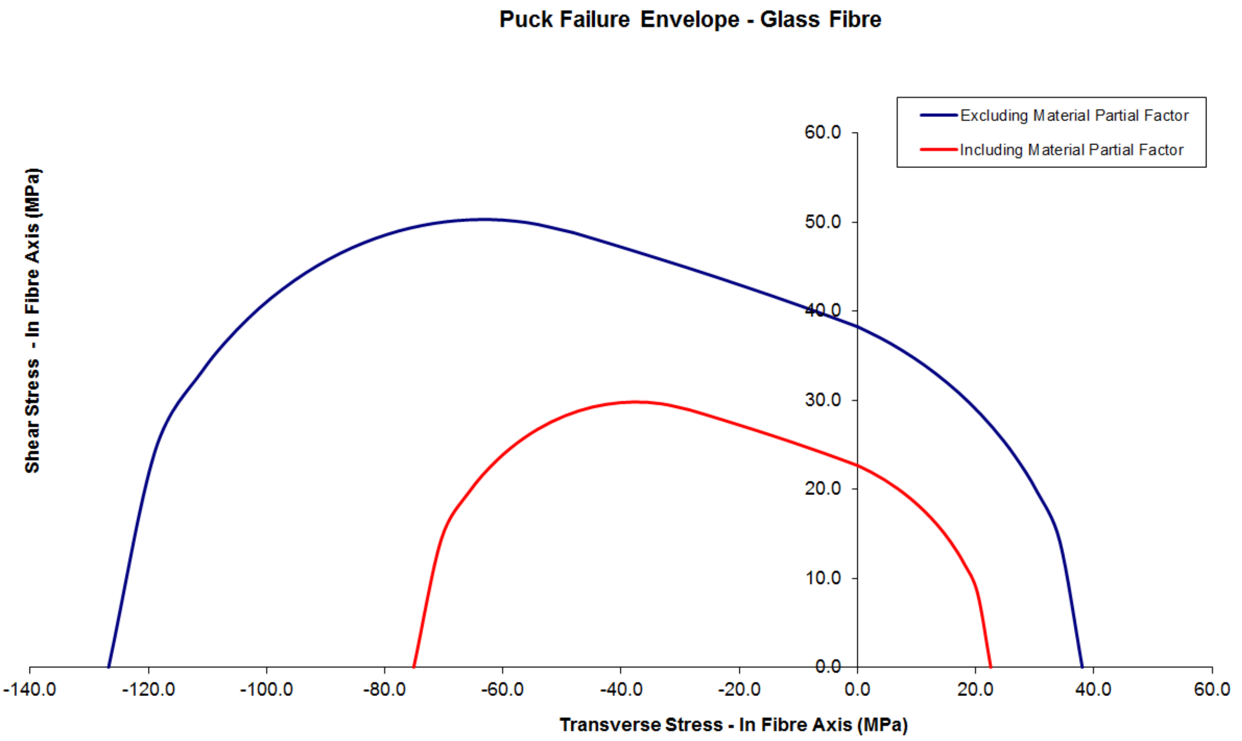


Figure 36 Puck Failure Envelope - Glass

The resulting Puck Failure envelopes with and without partial material safety factors applied (see section 6.3.4) for a single fibre direction of carbon-fibre epoxy composite are shown in Figure 37.

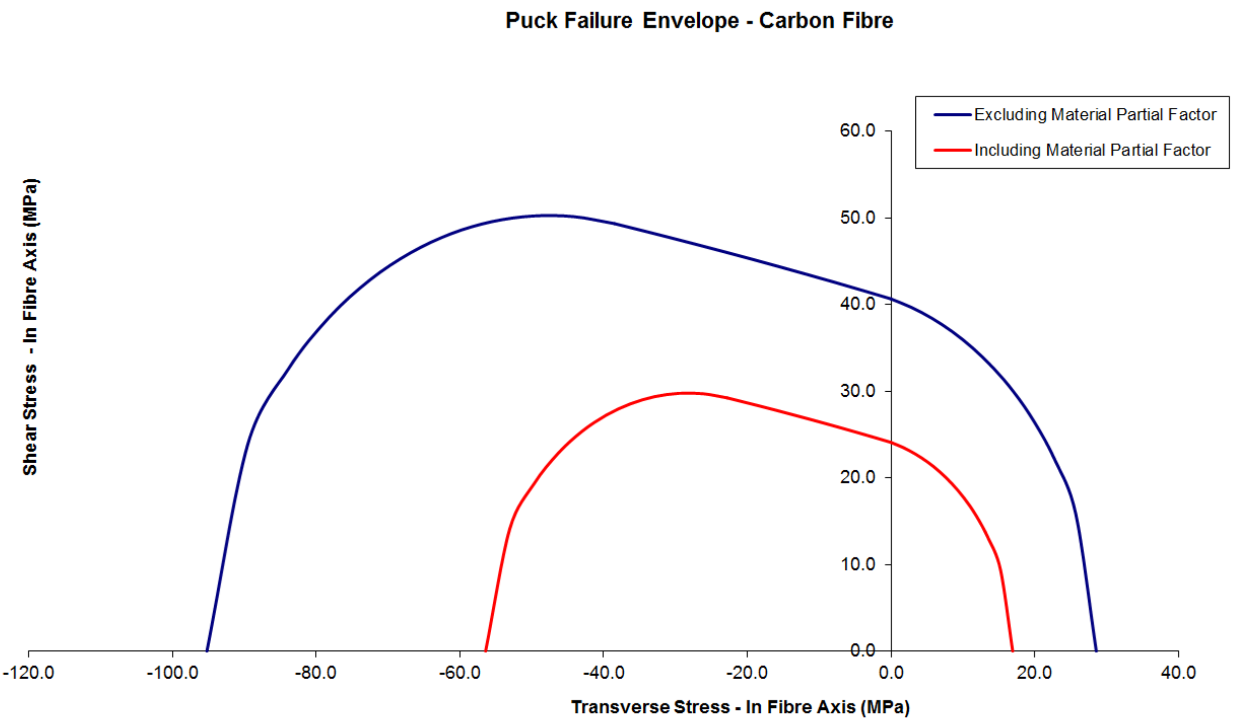


Figure 37 Puck Failure Envelope – Carbon

12.3 FE Model

As described in detail in Section 12.1, the strains for the inter-fibre failure analysis were obtained from the FE model for each of the ULS loadcases.

Peak longitudinal, transverse and shear strains were observed under the Positive Edgewise loadcase over a very localised area of the trailing edge panel at Z = 13.6m as shown in Figure 38. It was concluded that this unrealistic stress concentration was caused by the modelling of the adhesive solid elements having an abrupt change in the width of the TE bondline as shown in Figure 38. Hence these peak strains were ignored in the inter-fibre failure analysis performed.

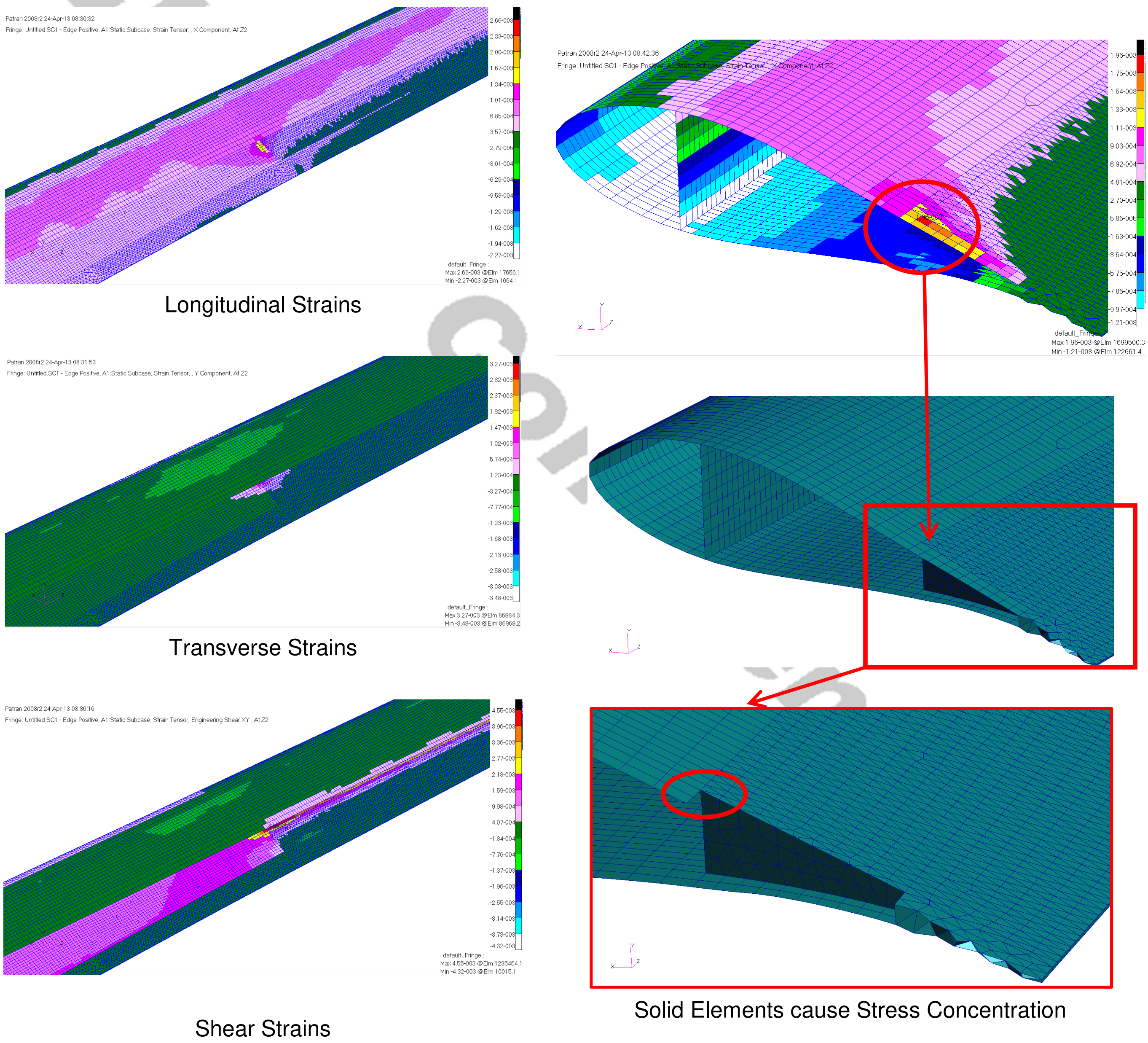


Figure 38 Stress Concentration in FE Model

12.4 Results

12.4.1 Glass Puck Failure Envelope

The inter-fibre failure RFs for the Positive Flapwise loadcase are shown in Table 31. All RFs are above 1 and acceptable.

Blade Zone		Strains			Stress		Results		
	Z (m)	X (%)	Y (%)	XY (%)	σ trans (Mpa)	τ12_fibre (Mpa)	RF	Fibre Angle (°)	Failure Mode
Leading Edge Shell	1.2	-0.17	0.13	0.00	-2.19	9.77	**2.45**	-45	B
Trailing Edge Shell	21.8	0.03	0.22	-0.10	19.25	-3.13	**1.15**	0	A
Shell in way of Capping Suction Side	23.3	-0.02	0.11	0.03	9.44	1.05	**2.37**	0	A
Shell in way of Capping Pressure Side	21.8	0.17	-0.04	0.12	10.59	-6.86	**1.70**	-45	A
Leading Edge Web	1.2	0.02	0.08	-0.14	10.01	-1.71	**2.21**	45	A
Trailing Edge Web	2.2	0.14	-0.20	0.09	-0.28	-10.92	**2.09**	-45	B

Table 31 Puck Analysis Results – Characteristic Positive Flapwise

The inter-fibre failure RFs for the Negative Flapwise loadcase are shown in Table 32. All RFs are above 1 and acceptable.

Blade Zone		Strains			Stress		Results		
	Z (m)	X (%)	Y (%)	XY (%)	σ trans (Mpa)	τ12_fibre (Mpa)	RF	Fibre Angle (°)	Failure Mode
Leading Edge Shell	1.2	0.11	-0.08	0.10	4.72	-6.30	**2.66**	-45	A
Trailing Edge Shell	13.6	0.12	0.04	0.23	16.29	-2.67	**1.36**	-45	A
Shell in way of Capping Suction Side	1.2	0.11	-0.03	-0.02	5.22	4.71	**3.01**	45	A
Shell in way of Capping Pressure Side	22.0	-0.01	0.15	-0.04	12.29	-1.16	**1.82**	0	A
Leading Edge Web	2.2	-0.07	0.16	0.03	12.09	1.00	**1.86**	0	A
Trailing Edge Web	2.2	-0.07	0.17	-0.04	12.82	-1.36	**1.74**	0	A

Table 32 Puck Analysis Results – Characteristic Negative Flapwise

The inter-fibre failure RFs for the Positive Edgewise loadcase are shown in Table 33. All RFs are above 1 and acceptable.

Blade Zone	Z (m)	Strains X (%)	Strains Y (%)	Strains XY (%)	Stress σ trans (Mpa)	Stress τ12_fibre (Mpa)	Results RF	Results Fibre Angle (°)	Results Failure Mode
Leading Edge Shell	1.2	-0.19	0.15	-0.03	-0.83	-10.76	**2.15**	45	B
Trailing Edge Shell	21.8	0.18	-0.05	-0.35	18.09	7.41	**1.12**	45	A
Shell in way of Capping Suction Side	21.8	0.17	-0.03	-0.17	12.81	6.47	**1.52**	45	A
Shell in way of Capping Pressure Side	23.6	0.01	0.11	0.07	9.81	2.11	**2.23**	0	A
Leading Edge Web	2.2	-0.09	0.13	0.04	9.04	1.33	**2.46**	0	A
Trailing Edge Web	9.5	0.09	-0.21	0.08	-4.04	-9.77	**2.57**	-45	B

Table 33 Puck Analysis Results – Characteristic Positive Edgewise

The inter-fibre failure RFs for the Negative Edgewise loadcase are shown in Table 34. All RFs are above 1 and acceptable.

Blade Zone	Z (m)	Strains X (%)	Strains Y (%)	Strains XY (%)	Stress σ trans (Mpa)	Stress τ12_fibre (Mpa)	Results RF	Results Fibre Angle (°)	Results Failure Mode
Leading Edge Shell	1.2	0.20	-0.10	0.03	6.05	-9.61	**1.84**	-45	A
Trailing Edge Shell	1.0	0.02	0.10	-0.09	9.55	-2.74	**2.23**	45	A
Shell in way of Capping Suction Side	1.4	-0.03	0.11	0.02	8.61	0.66	**2.61**	0	A
Shell in way of Capping Pressure Side	1.2	0.14	-0.04	-0.07	7.80	5.86	**2.18**	45	A
Leading Edge Web	2.2	0.08	-0.18	-0.01	-5.05	8.34	**3.16**	45	B
Trailing Edge Web	9.5	-0.09	0.21	-0.08	15.84	-2.46	**1.40**	0	A

Table 34 Puck Analysis Results – Characteristic Negative Edgewise

12.4.2 Carbon Puck Failure Envelope

The inter-fibre failure RFs for all four loadcase are shown in Table 35. All RFs are above 1 and acceptable.

Loadcase	Blade Spar Capping		Strains			Stress		Results		
		Z (m)	X (%)	Y (%)	XY (%)	σ trans (Mpa)	τ12_fibre (Mpa)	RF	Fibre Angle (°)	Failure Mode
Positive Flapwise	Suction Side	22.0	-0.02	0.11	0.03	6.9	1.1	2.42	0	A
	Pressure Side	1.2	0.17	-0.04	0.12	7.9	-7.3	1.74	-45	A
Negative Flapwise	Suction Side	1.2	0.11	-0.03	-0.02	4.0	5.0	3.03	45	A
	Pressure Side	22.0	-0.01	0.15	-0.04	9.1	-1.2	1.85	0	A
Positive Edgewise	Suction Side	1.2	0.17	-0.03	-0.17	9.5	6.9	1.56	45	A
	Pressure Side	23.6	0.01	0.11	0.07	7.3	2.2	2.25	0	A
Negative Edgewise	Suction Side	1.4	-0.03	0.11	0.02	6.3	0.7	2.69	0	A
	Pressure Side	1.2	0.14	-0.04	-0.07	5.9	6.2	2.22	45	A

Table 35 Puck Analysis Results – Spar Capping

13. Stability Analysis (TSR)

Stability is assessed by a linear buckling analysis. The applied load conditions are extracted from the load envelope as reported in Section 5.2. The safety factors are applied to materials as defined in GL2010 (1). The stability verification is satisfied if eigenvalues are bigger than 1.

13.1 Buckling Modes and Buckling Load Factor

The first load case exhibits a minimum eigenvalue very slightly lower than 1, and it is approximated to the unit value. The most critical buckling eigenvalues are reported in Table 36, while the corresponding modes are represented from Figure 39 to Figure 42.

Load condition	***Buckling analysis minimum eigenvalue***
Max Edgewise Bending Moment	*0.998=1.0*
Min Edgewise Bending Moment	*1.51*
Max Flapwise Bending Moment	*1.40*
Min Flapwise Bending Moment	*1.01*

Table 36 Lowest buckling eigenvalues for each load condition

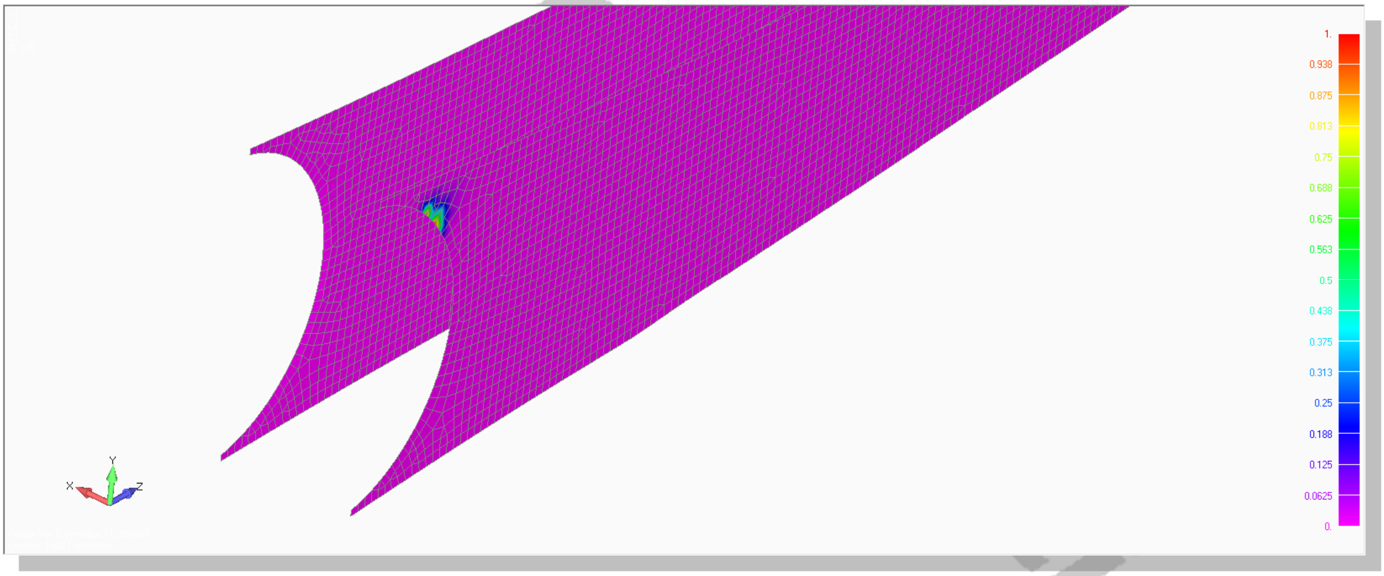


Figure 39 Buckling modes - Max Edgewise Bending Moment – Trailing Edge shear web start

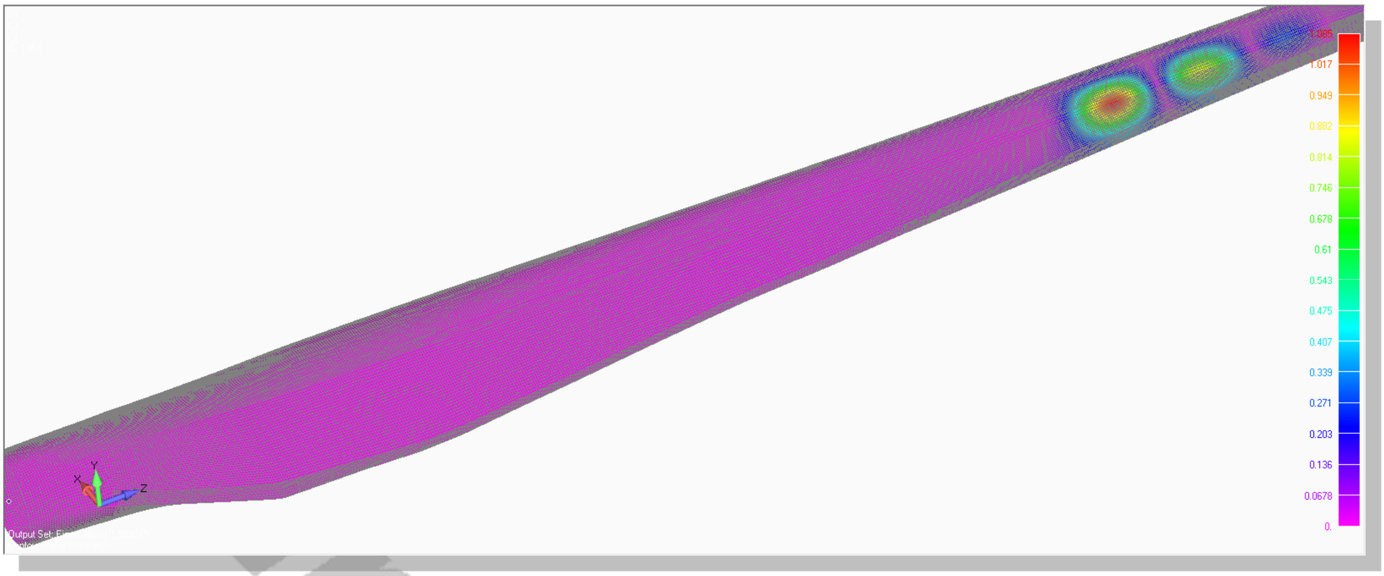


Figure 40 Buckling modes - Min Edgewise Bending Moment - Blade mid span, suction side

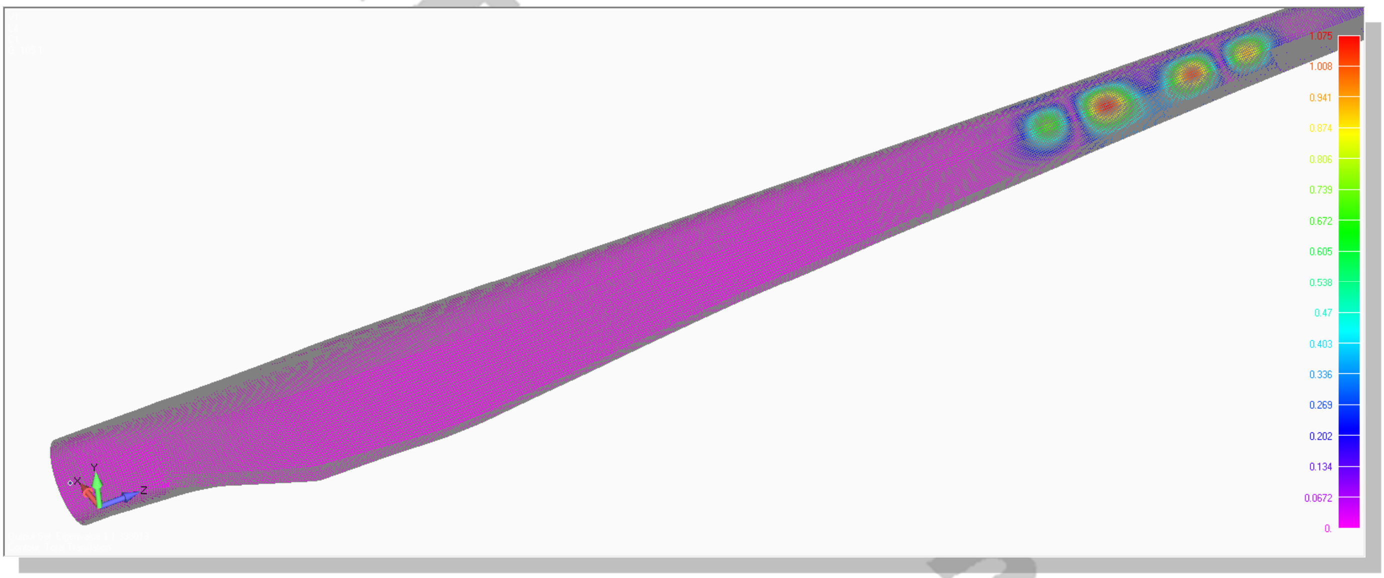


Figure 41 Buckling modes - Max Flapwise Bending Moment – Blade mid span, suction side

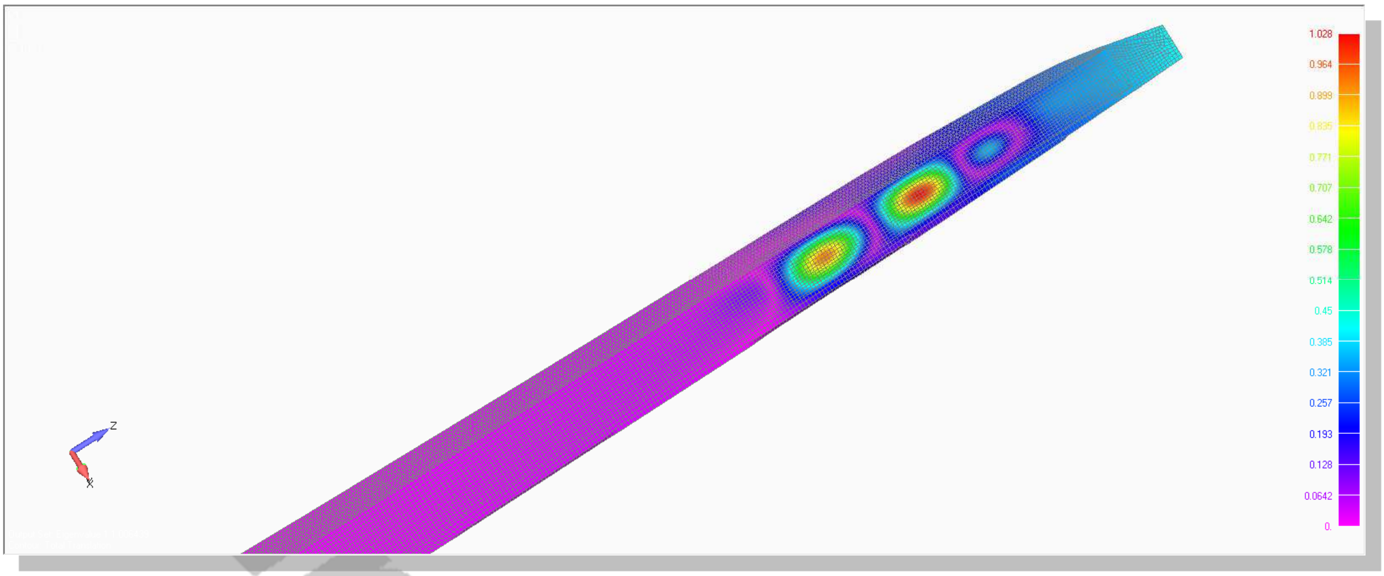


Figure 42 Buckling modes - Min Flapwise Bending Moment – Blade tip, pressure side

13.2 Mesh Verification

In order to verify the convergence of the mesh, GL 2010 (1) Section 5.5.3.2.3 Paragraph 4 is applied. The number of shell elements is more than doubled and the other elements (tetrahedra and concentrated masses), are consequently updated. Table 37 reports the number elements of the refined model, compared to the original one. Table 38 reports the percent differences for the two lowest eigenvalues, differences which are very small.

Element type	*Number*
CTRIA3 & CQUAD4	*319499*
CTETRA	*215531*
CONM2	*98230*

Table 37 Number of finite element model for buckling convergence analysis

Original model eigenvalue	*Refined model eigenvalue*	*Percent difference*
0.998	*0.992*	*0.6%*
1.01	*1.02*	*0.9%*

Table 38 Variation of buckling eigenvalues for convergence analysis

14. Tip Deflection Analysis (TSR)

With a rotor diameter of 49m, a rotor pre-cone angle of 3deg and a nacelle up-tilt of 5deg, the blade to tower clearance computed in an unloaded configuration is 5.3747m. The max allowable blade tip deflection is therefore 3.7623m.

The max tip deflection estimated in all considered DLCs is 3.29 m (from DLC6.2, yaw misalignment -30deg).

15. Natural Frequency (TSR)

The first natural frequencies of the blade computed with a beam model (i.e. from the aeroelastic model) are summarized in the following table.

	@ 0 rpm	@ 28.5 rpm
	[Hz]	[Hz]
flapwise	1,34	1,51
edgewise	2,45	2,47
flapwise	3,75	3,94
flapwise	7,23	7,42
edgewise	7,65	7,71

Table 39 Natural frequencies of the blade.

The complete Campbell diagram (i.e the coupled frequencies) are reported in the following figure.

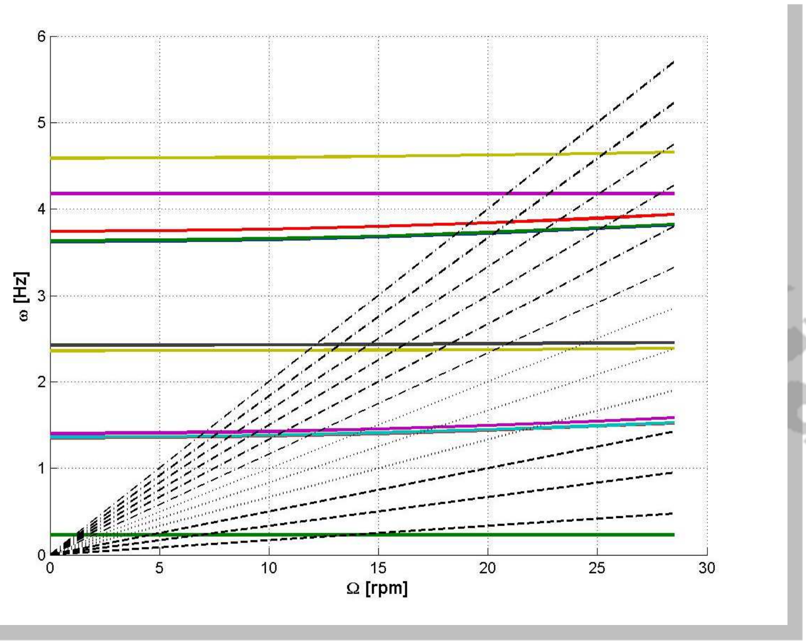


Figure 43 Campbell diagram.

16. Mass Tolerance and Balancing (GURIT)

16.1 Blade Balancing

The method for balancing the blades is shown in Figure 44 as specified by ETA. The rotor is balanced by ensuring that the maximum difference between $P_{Blade\ 1}$, $P_{Blade\ 2}$, and $P_{Blade\ 3}$ is not more than 2.5kg.

Figure 44 ETA Blade Balancing Specification

In order to balance the rotor to meet the ETA specification, a balancing chamber was designed as shown in Blade Shell Laminate drawing (5). One balancing chamber is located between Z = 15m and Z = 17m which can be filled with the required amount of ballast to meet the specification. The maximum permissible ballast weight of 31kg was calculated on the agreed assumption a 2% variation in total blade weight.

17. Bonding Calculations (GURIT)

17.1 Leading Edge and Trailing Edge

The shear flows on the leading edge and trailing edge were obtained from the FE model. These shear flows were used to analyse both the adhesive and the bonding plies (overlaminate bonding) in the leading and trailing edge joint as shown in Figure 45

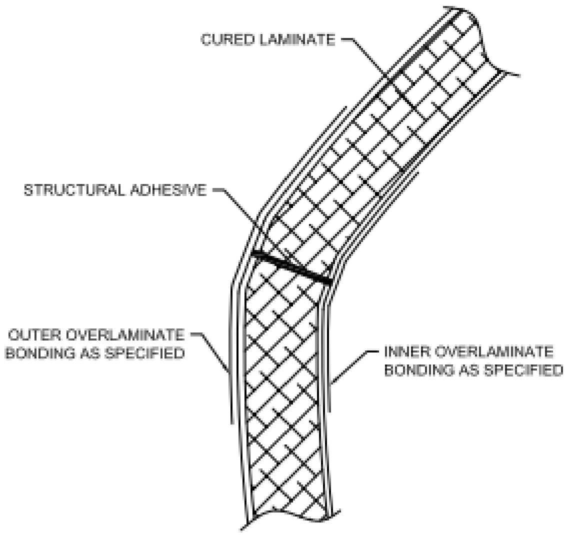


Figure 45 Typical Bonding Plies

The joints were designed to ensure the shear stresses remained below the allowable shear stresses of the bonding plies and adhesive as detailed in Section 6.4 and Section 6.7. Table 40 shows the minimum Reserve Factor (RF) of the bonding flange adhesive joint found along the length of the blade. All RFs are above 1 and is acceptable.

		ULS		FLS	
		Min RF	Z (m)	Min RF	Z (m)
Leading Edge	Adhesive Joint	4.7	22.0	2.7	10.0
	Bonding Plies	3.4	0.6	3.1	4.0
Trailing Edge	Adhesive Joint	12.0	3.0	7.6	3.0
	Bonding Plies	1.8	1.0	1.4	1.0

Table 40 Leading and Trailing Edge Joint Reserve Factors

17.2 Shear Webs

The webs are bonded to the suction side and pressure side shell with bonding flanges as shown in Figure 46.

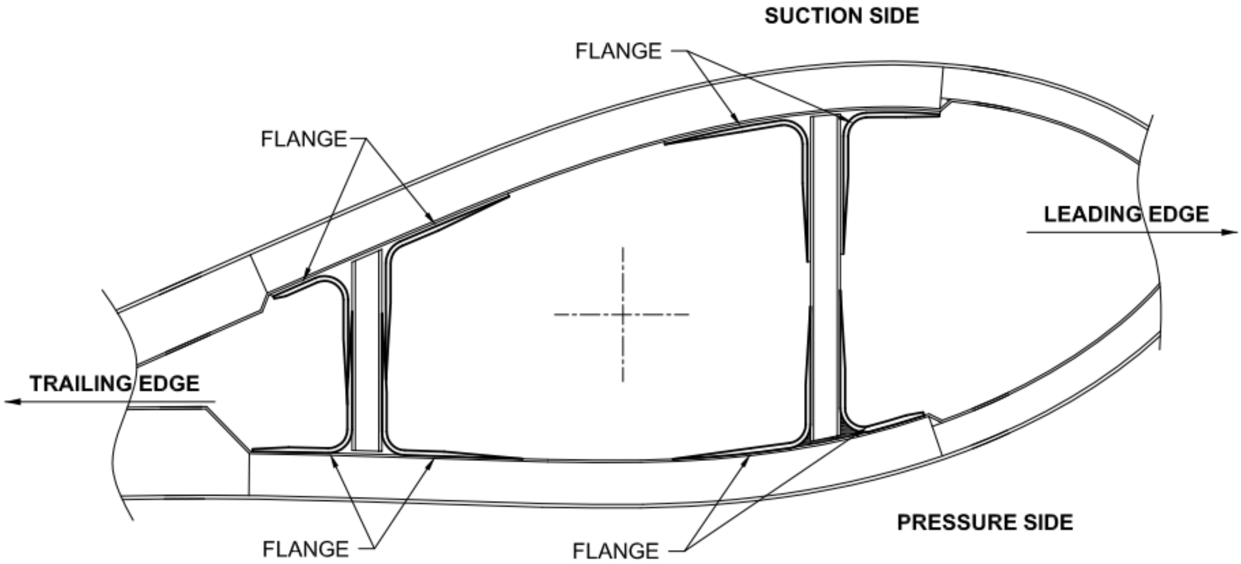


Figure 46 Shear Web Bonding Flanges

The bonding flanges were designed to transfer the shear load from the webs into the shells. The laminate for each flange has the same number of plies as each skin in the web in order to transfer these loads. Since the bonding flange laminate matches the web laminate, the bonding flange should have sufficient strength under the ULS and FLS loadcases the webs have been designed for.

These bonding flanges are premade and bonded to the webs and the shells using an adhesive as specified in Section 6.7. Hence, the shear load is transferred from the web to the shell via this adhesive joint. Based on the width of the bonding flange as specified in Blade Shearweb Laminate drawing (6), the shear stress in this bonded joint was analysed. It was ensured that the stresses in the bonded flange joint were lower than the adhesive design allowable shear strength specified in Section 6.7.

Table 41 shows the minimum Reserve Factor (RF) of the bonding flange adhesive joint found along the length of the blade. All RFs are above 1 and is acceptable.

	Minimum Reserve Factors	
	ULS	FLS
Leading Edge Web	2.0	1.3
Trailing Edge Web	2.7	1.4

Table 41 Bonding Flange Joint Reserve Factors

18. Analysis of Bolted Root Connection (GURIT)

This section details the methods used in the design and analysis of the bolted connection at the blade root which includes the bolts and the composite parts.

18.1 Analysis Method

A T-Bolt joint was chosen for attaching the blade to the pitch bearing. Since the blade is to be mounted onto an existing pitch bearing the parameters shown in Table 42 were fixed:

Parameter	Value
Pitch Circle Diameter (PCD) (mm)	920
Number of Bolts (n)	60
Thread size	M20

Table 42 Root Geometry

The existing bolting pattern was designed for metal inserts adhesively bonded into the composite laminate which gives a close spacing between adjacent bolts. To ensure there is sufficient composite laminate between the barrel nuts a “double row T-bolt” configuration as shown in Figure 47 (see (7)) is required.

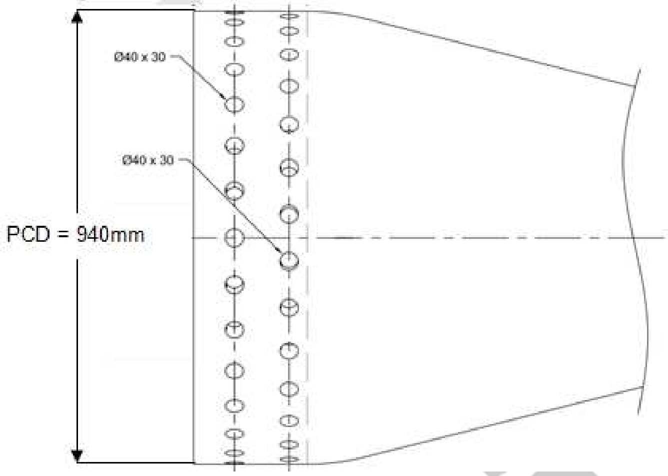


Figure 47 Double Row T-bolt Root Joint

Figure 48 shows a cross section through the root in way of the bolts.

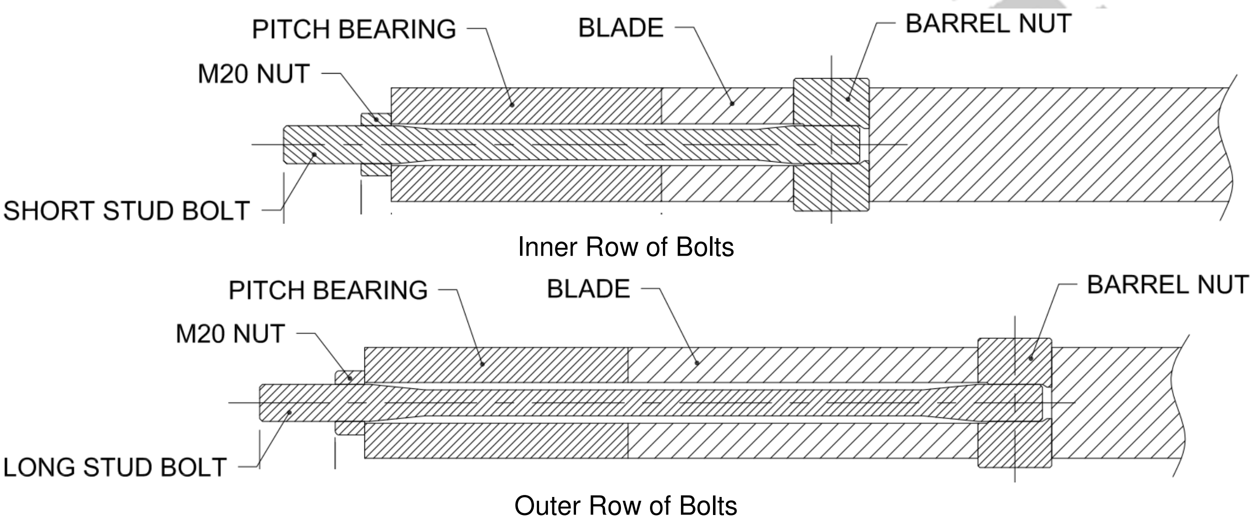


Figure 48 Cross Section in Way of Bolts

In order to validate the design of this double row T-bolt configuration, Finite Element Analysis (FEA) was conducted on a segment of a blade root. The results obtained from the FE model were then used to perform bolting calculations as specified in VDI 2230 (8).

18.1.1 Root Joint FE Model

The purpose of the FE model was to investigate two effects:

- The stress concentration factor (SCF) in the composite laminate around the barrel nut holes
- The proportion of load that is carried by the bolt (Φ) in a double row T-bolt configuration.

A 6° segment of the blade root joint was modelled and meshed with 59846 first order tetrahedral solid elements with an element length of 5mm as shown in Figure 49. To simulate the behaviour of the barrel nuts against the surface of the composite without conducting a contact analysis, a 90° segment of the inboard nodes of the barrel nuts were equivalenced with inboard nodes of the composite. A 90° segment of the outboard nodes of the barrel nuts remained unequivalenced with outboard nodes of the composite.

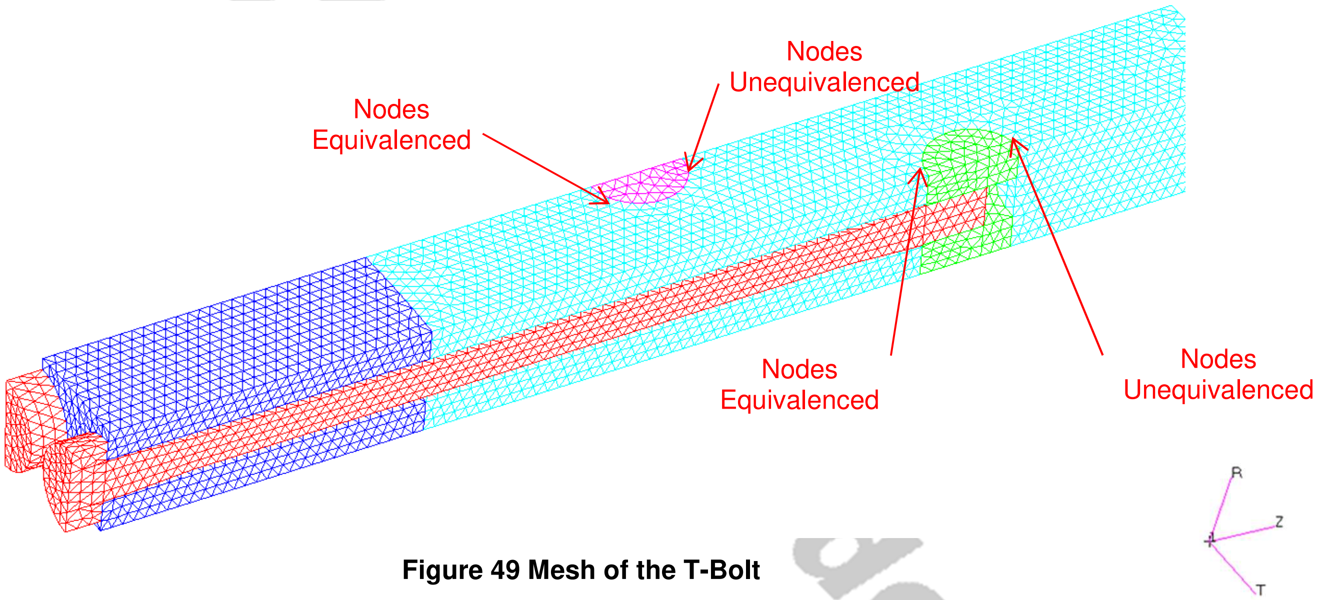


Figure 49 Mesh of the T-Bolt

The root laminate consisted of both YE900 and UC500, where 1 ply of UC500 was interleaved for every 3 plies of YE900. This increased the longitudinal stiffness of the composite part of the root which reduced the proportion of applied load carried by the bolt.

To investigate the stress concentration caused by the holes in the laminate, early in the design phase the FE model was run without the bolts and the barrel nuts to isolate the effect of the SCF from the effect of Φ. The ULS load per bolt segment of 88kN was applied to the 50mm thick laminate for the model investigating the SCF, this being the parameters of the blade root at that point in the design phase. The calculated SCF is independent of the applied load.

Once the SCF was known, the FE model was run with the bolts and the barrel nuts to investigate the effect of Φ. Figure 50 shows the boundary conditions and loads that were applied to the FE model. The ULS load per bolt segment of 105.2kN was applied to the 60mm thick laminate for the model investigating the effect of Φ. Once again the calculated value of Φ is independent of the applied load but does depend on the laminate thickness which is why the laminate thickness was increased to 60mm.

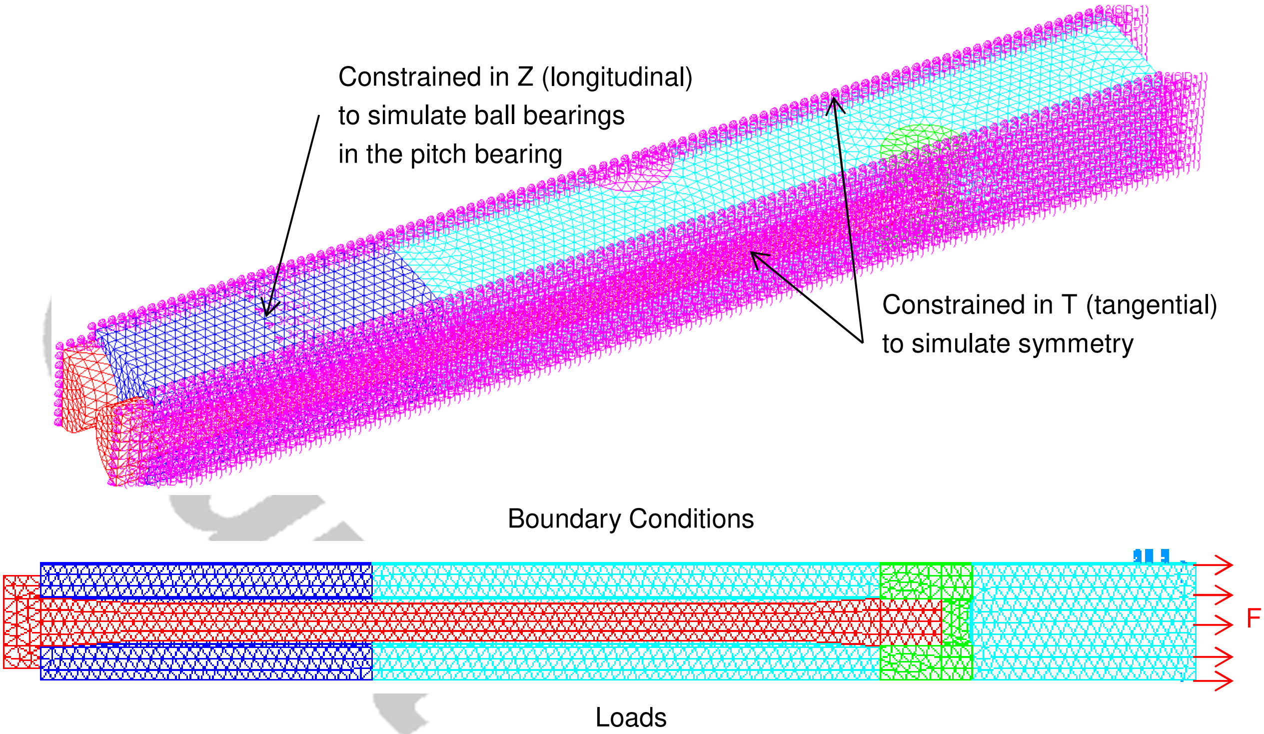


Figure 50 Boundary Conditions & Loads Applied

* Length given between closest nut faces.

Table 43 shows a summary of the parameters that were used for the FE models:

	SCF Model	Φ Model
Applied Load (kN)	88	105.2
Material	7 x YE900: 2 x UC450	7 x YE900: 2 x UC450
Laminate Thickness (mm)	50	60
Laminate Longitudinal Stiffness (MPa)	38960	38960
10.9 Steel Stiffness (MPa)	-	205 000
Length of Pitch Bearing (mm)	143	143
Bolt Thread Diameter (mm)	-	20
Barrel Nut Diameter (mm)	-	40
Inner Bolt Length* (mm)	-	213
Inner Bolt Necked Diameter (mm)	-	16
Outer Bolt Length* (mm)	-	332
Outer Bolt Necked Diameter (mm)	-	14

* Length given between closest nut faces.

Table 43 Root FE Parameters

18.1.2 Bolting Calculations

Bolting calculations were performed as specified in VDI 2230 (8) and the following parameters shown in Table 44 and Table 45 were used in the calculations.

The fatigue strength of the bolts was assessed based on the threaded area of the bolts and the allowable strength calculated using DNV-RP-C203 (9).

The bolt segment load was calculated using the equation below:

$$Bolt\ segment\ load = \frac{4.M}{N.PCD}$$

where M is the applied bending moment, N the number of bolts and PCD the bolt PCD. This theoretical load was increased by a factor of 1.33, which was found from the TSR model to be the deviation of the FE calculated bolt loads when compared to the theoretical load calculated with the above equation.

Parameter		ULS Analysis	
		Long Bolt	Short Bolt
Bolt Grade		10.9	10.9
Bolt Modulus (MPa)		205000	205000
Bolt Yield Strength (MPa)		940	940
Bolt Necked Diameter (mm)		14	16
Fraction of Applied Load Carried by Bolt (ϕ_{FE})		18.2%	10.7%
Root Bending Moment (kNm)		847	847
Bolt Load due to Applied Load (kN)		14.9	8.7
Factor of safety on gap opening		1.05	1.05
Preload loss factor due to relaxation		20%	20%
Scatter of preload		10%	10%
Tightening factor		1.22	1.22
Hydraulic tensioner load transfer factor		1.10	1.10
Bolt Preload kN	Minimum	88	96
	Nominal	97	106
	Maximum	107	117

Table 44 Root Bolting Calculation Parameters – ULS

Parameter	FLS Analysis	
	Long Bolt	Short Bolt
Bolt Diameter (mm)	20	20
Bolt Design Life (Years)	20	20
Wohler Coefficient(m)	5	5
Number of cycles (N)	1×10^7	1×10^7
Allowable nominal bolt stress amplitude (MPa)	18.4	18.4
Fraction of Applied Load Carried by Bolt (Φ_{FE})	18.2	10.7
Applied Root Bending Moment (kNm)	210	210
Applied Fatigue Stress Amplitude (MPa)	15	8.8

Table 45 Root Bolting Calculation Parameters - FLS

18.1.3 Composite Strength Calculations

Table 46 shows the parameters used in the calculation of the root laminate.

	Parameter	ULS Analysis	FLS Analysis
Laminate	Laminate Material	3 x YE900: 1 xUC500	3 x YE900: 1 xUC500
	Laminate Thickness (mm)	60	60
	Composite FE SCF between barrel nuts	1.87	1.87
	Laminate Longitudinal Modulus (MPa)	40810	40810
	Allowable Bearing Strength (MPa)	100	27
Loads	Root Bending Moment (kNm)	847	210
	Design Life (years)	-	20
	Number of Cycles (N)	-	1×10^7
	Wohler Coefficient (m)	-	10

Table 46 Root Laminate Calculation Parameters

18.2 Results

18.2.1 Root Joint FE Model

A FE plot of the stresses on the model that was run for the SCF study is shown in Figure 51. As expected the peak stress occurs on the inner hole where there is the least amount of material to take the load.

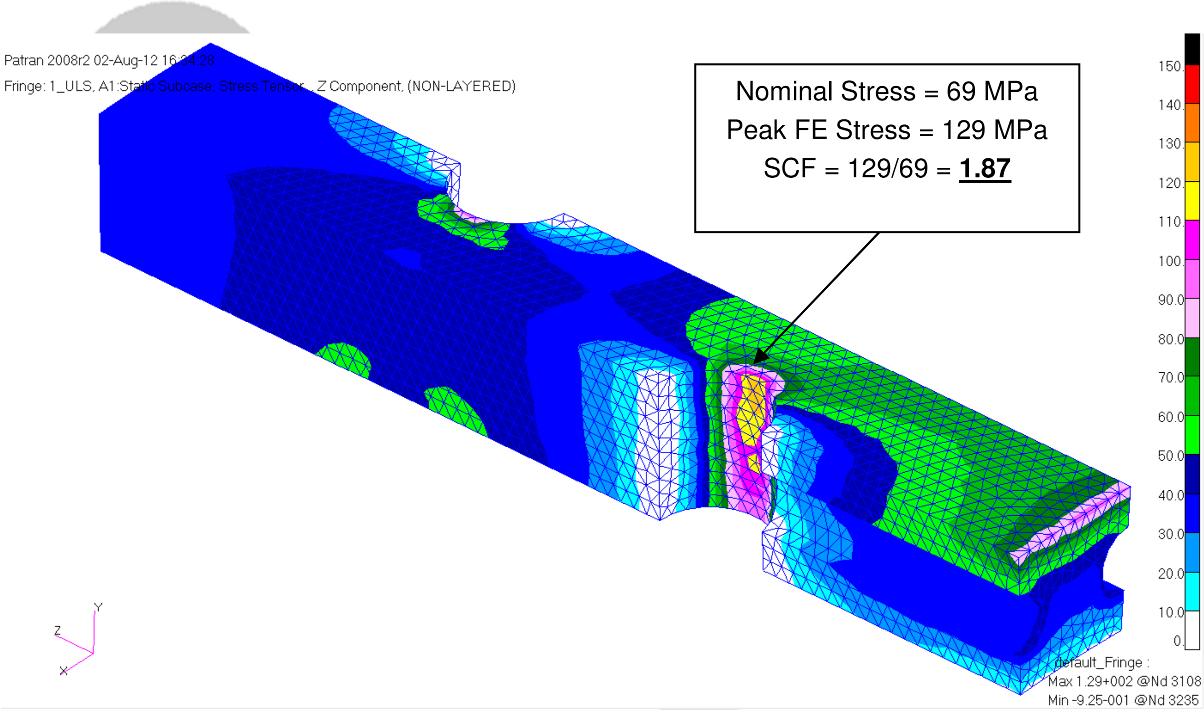


Figure 51 FE Plot of the Peak Stress in Composite Part

A FE plot of the stresses on the model to obtain Φ is shown in Figure 52.

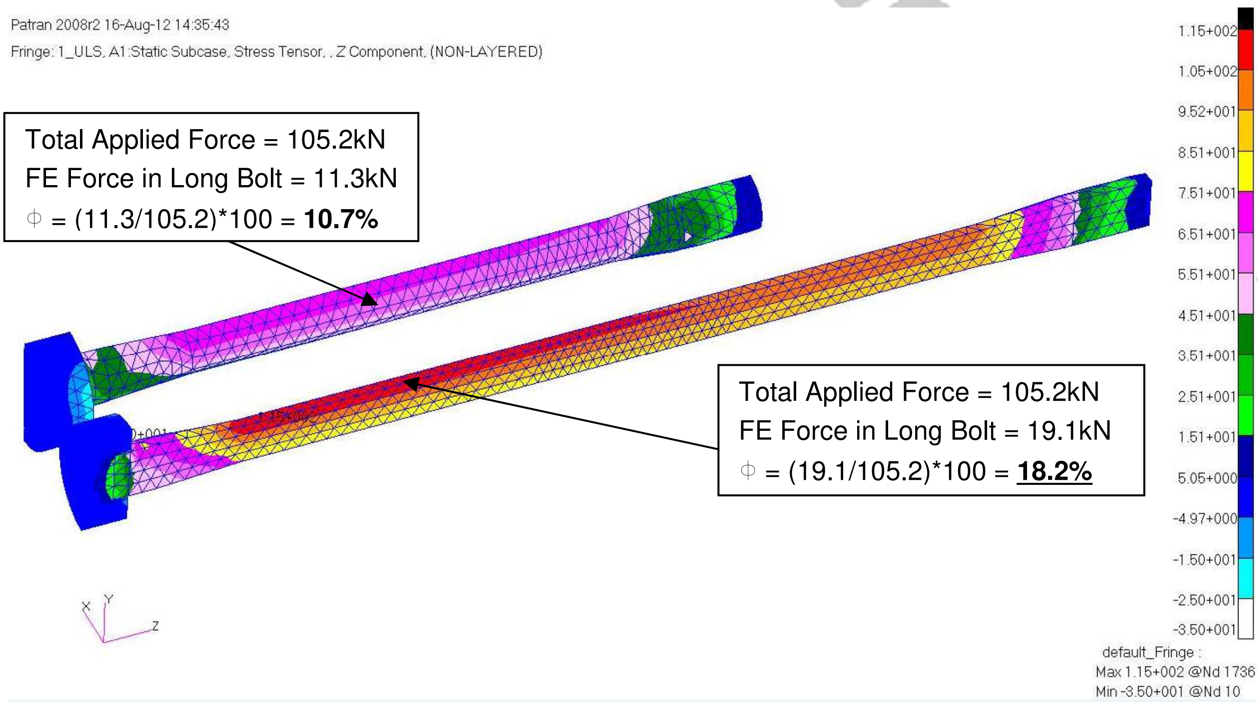


Figure 52 FE Plot of Stresses in Bolts

18.2.2 Bolting Calculations

Table 47 shows the reserve factors for the bolts. All Reserve Factors are above 1 which is acceptable.

Loadcase	Failure Mode	Reserve Factors	
		Long Bolt	Short Bolt
ULS	On Yield at ULS Load	1.2	1.5
	On Yield at Nominal Tightening Load	1.3	1.5
FLS	Fatigue of Threads	1.2	2.1

Table 47 Root Bolting Reserve Factors

18.2.3 Composite Calculations

Table 48 shows the reserve factors for the composite root analysed. All Reserve Factors are above 1 which is acceptable.

Loadcase	Location	Failure Mode	Reserve Factors
ULS	Between Barrel Nuts	Tensile-Fibre	9.6
		Tensile-Matrix	5.8
		Compressive	1.3
	Barrel Nut Hole	Bearing	1.6
Installation	Barrel Nut Hole	Bearing	1.9
FLS	Between Barrel Nuts	Fibre	2.5
	Barrel Nut Hole	Bearing	14.7
Minimum RF			**1.3**

Table 48 Root Composite Reserve Factors

18.3 Discussion

The root laminate analysed had a 1 ply of UD500 for every 3 plies of YE900. During the production trials, the cured ply thickness achieved were lower than the cured ply thickness assumed in the analysis. Since the thickness of the blade root could not be modified, the laminate had to be modified to achieve a root with a final thickness of 60mm. Hence the as built laminate as specified in Blade Shell Laminate drawing (5) has 1 ply of UD500 for every 4 plies of YE900.

Table 49 shows the comparison of the material properties that were used for the root analysis with the material properties of the as built root. The modification to the laminate has meant that the as built root is stiffer in the longitudinal direction than the root laminate that has been analysed.

Material	Property	Analysis	As Built
YE900	Fibre Volume Fraction (%)	0.46	0.52
	Cured Ply Thickness (mm)	0.74	0.66
	Longitudinal Tensile Modulus (MPa)	22780	25541
	Longitudinal Compressive Modulus (MPa)	22780	25541
UC500	Fibre Volume Fraction (%)	0.48	0.6
	Cured Ply Thickness (mm)	0.58	0.46
	Longitudinal Tensile Modulus (MPa)	112110	141040
	Longitudinal Compressive Modulus (MPa)	107540	135291
Root Laminate	1 x UC500: 3 x YE900 Longitudinal Tensile Modulus (MPa)	40810	-
	1 x UC500: 4 x YE900 Longitudinal Tensile Modulus (MPa)	-	42590

Table 49 Root Material Properties Comparison

Since the root has been analysed with the lower longitudinal tensile modulus, it can be said that the result presented in this report are still valid and more conservative than the as built root laminate.

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19. Root - Spar Capping Joint (GURIT)

19.1 Analysis Method

The root design as discussed in Section 0 has carbon unidirectional plies interleaved with the glass triaxial plies to increase the root longitudinal stiffness. For ease of manufacture and to avoid the carbon plies starting and stopping abruptly, the carbon plies in the blade root are continuous into the spar capping. Hence, as shown in GU4507-1002 E Blade Shell Laminate and in Figure 53, 18 plies in the spar cap run all the way to Z = 0.

An idealised transition between the spar capping material (UC500/XE600) and the root material (YE900/UC500) is shown in Figure 53 and the transition has been modelled as a scarf joint. The method used to analyse the scarf joint is detailed in Analysis and Design of Composite Scarf Joints (10). This approach is conservative as it assumes all the load is transferred through the resin joint between the blade root and spar capping and does not take into account the secondary load path via the blade inner and outer skins nor the continuous capping plies that extend to the blade root.

The scarf joint was designed to ensure that the shear stresses were lower than the allowable shear strength. Since the spar capping and root were infused together, the allowable shear strength is the allowable interlaminar shear strength (ILSS) of the infusion resin (Prime 20 which is similar to Prime 27 which was used to manufacture the blades).

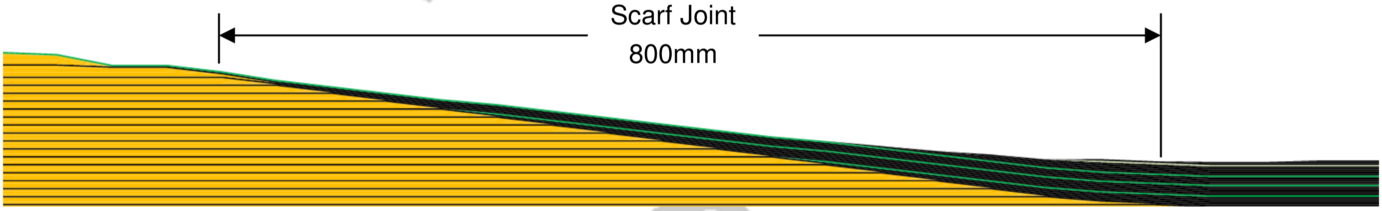

Figure 53 Root - Spar Capping Joint (Not To Scale)

Table 50 shows the inputs that were used to design the scarf joint.

	Root	Spar Capping	Resin
Material	3 x YE900: 1 xUC500	6 xUC500: 1 x XE600	Prime 20
Longitudinal Tensile Modulus (MPa)	38960	97265	-
Laminate Thickness at Ends of Joint (mm)	42	15	-
ULS Design Allowable ILSS incl Material Factor (MPa)	-	-	14.3
FLS Design Allowable ILSS incl Material Factor (MPa)	-	-	1.9

Table 50: Root- Spar Capping Analysis Inputs

Table 51 shows the joint peak axial load intensity which are calculated from the spar capping strains obtained from the FE model (2).

	ULS	FLS
Peak Spar Capping Strain Z = 1.2m (%)	0.2	0.05
Peak Axial Load Intensity (N/mm)	2903	683

Table 51: Root- Spar Capping Load Intensity

19.2 Results

The joint shear stresses for both the ULS and FLS loadcases are shown in Figure 54 and Figure 55. The joint shear stresses are fairly even and well below the allowable shear strength of the joint.

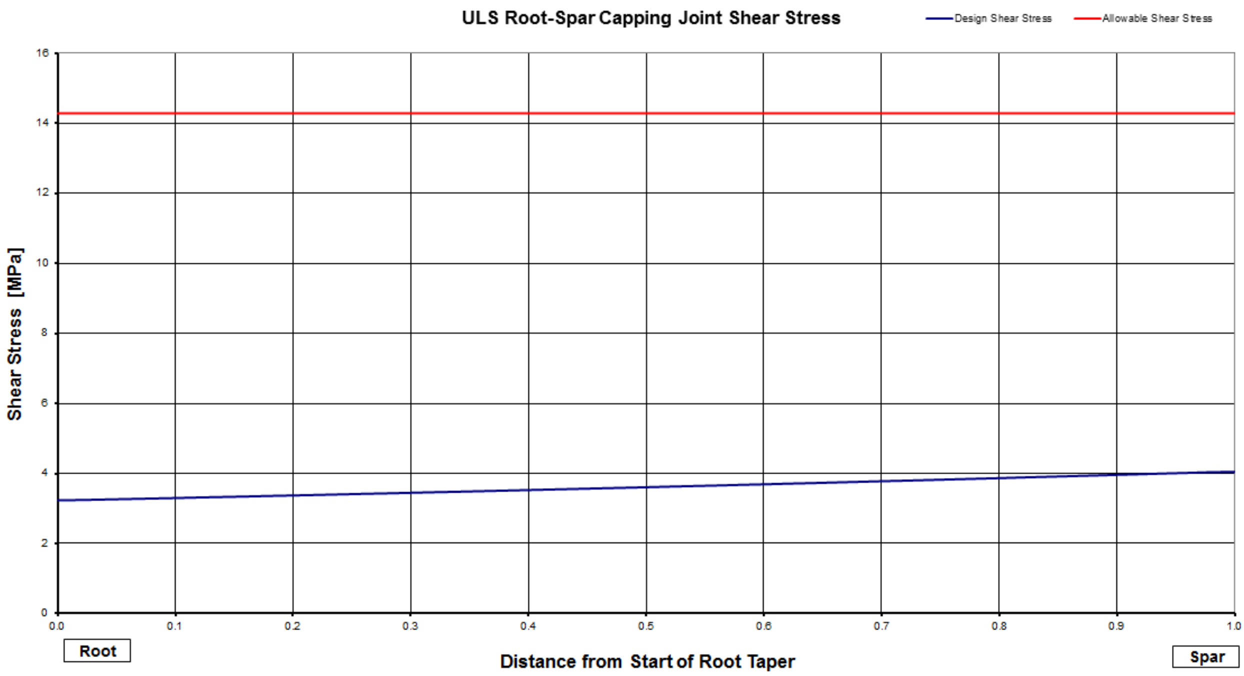

Figure 54 Scarf Joint Shear Stress - ULS

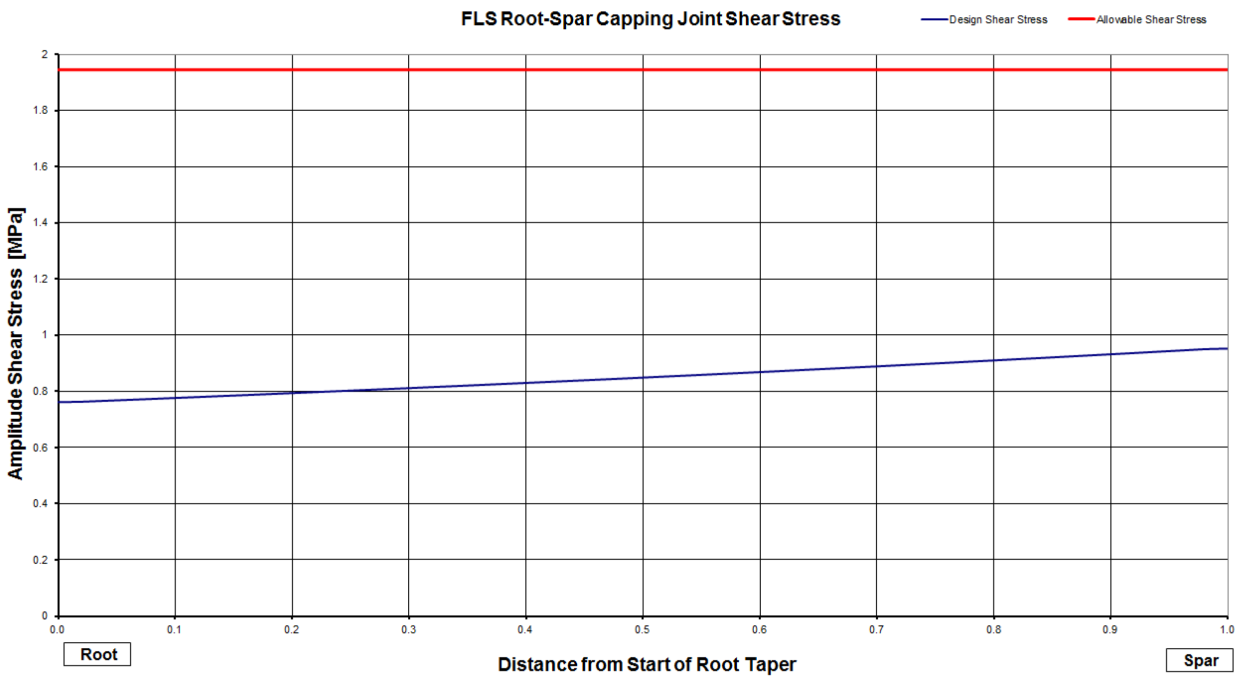

Figure 55 Scarf Joint Shear Stress – FLS

Table 52 shows the joint minimum Reserve Factors which are all above 1 and acceptable.

	ULS	FLS
Maximum Shear Stress (MPa)	4.1	1.0
Allowable Shear Strength (MPa)	14.3	1.9
Reserve Factor	3.5	1.9

Table 52 Scarf Joint Reserve Factor

20. Conclusions

Strength and stability analyses have been performed on the ETA 24m blade for the purpose of certification of the structural design of the blade to IEC61400-1 ed2 Wind turbine generator systems. These analyses were performed, where applicable, with reference to the Germanischer Lloyd Guideline for the Certification of Wind Turbines 2010 (1).

The analyses performed on the blade are summarised below:

- Ultimate strength analyses were performed for static strength by FEA.

- Fatigue strength analyses were performed by the use of FEA and Markov Matrices.

- Separate analyses, based on FEA are presented for:
    - Inter-Fibre Failure
    - Stability
    - Natural Frequencies
    - Maximum Tip Deflection
    - Joint Design

Together with structural component and full scale blade testing, the analytical results presented in this document should demonstrate sufficient margin of safety for the structure.

21. References

1. *Guideline for Certification of Wind Turbine Blades.* 2010. Germanischer Lloyd.
2. *TSR FE Model ver27032013.*
3. *Complex stress state effect on fatigue life of GPR laminates. Part II, theoretical formulation.* **Philippidis, T.P. and Vassilopoulos, A., P.** s.l. : International Journal of fatigue, 24, 2002, pp. 825-830.
4. **TSR.** *ETA4X_GL_ver1.0_27032013.xlsx .*
5. GU4507-1002 E Blade Shell Laminate.
6. GU4507-1003 B Blade Shearweb Laminate.
7. GU4507-2001 B M20 Barrel Nut and Stud Bolt.
8. *Systematic calculation of high duty bolted joints, joints with one cylindrical bolt.* February 2003. VDI 2230.
9. **DNV.** *Fatigue Design of Offshore Steel Structures.* April 2010. DNV-RP-C203.
10. *Analysis and Design of Composites Scarf Joints.* **Yan, S, Wu, D.** Newark, Delaware; USA : Computer Aided Design in Composite Material Technology. III, 13-15 May 1992.

Appendix A - Mass and Stiffness Distributions (TSR)

The mass and stiffness distributions of the blade are reported in the following tables.

All properties refer to a Reference System with axes parallel to the principal ones and centred in the pitch axis (see Fig. Figure 56 - Local Reference System for Mass and Stiffness distributions.

This reference system is rotated with respect to the local chord by the angle $\Delta\Theta$. The angle Θ defines the geometric (i.e. aerodynamic) twist, while the angle $\Theta+\Delta\Theta$ the structural twist.

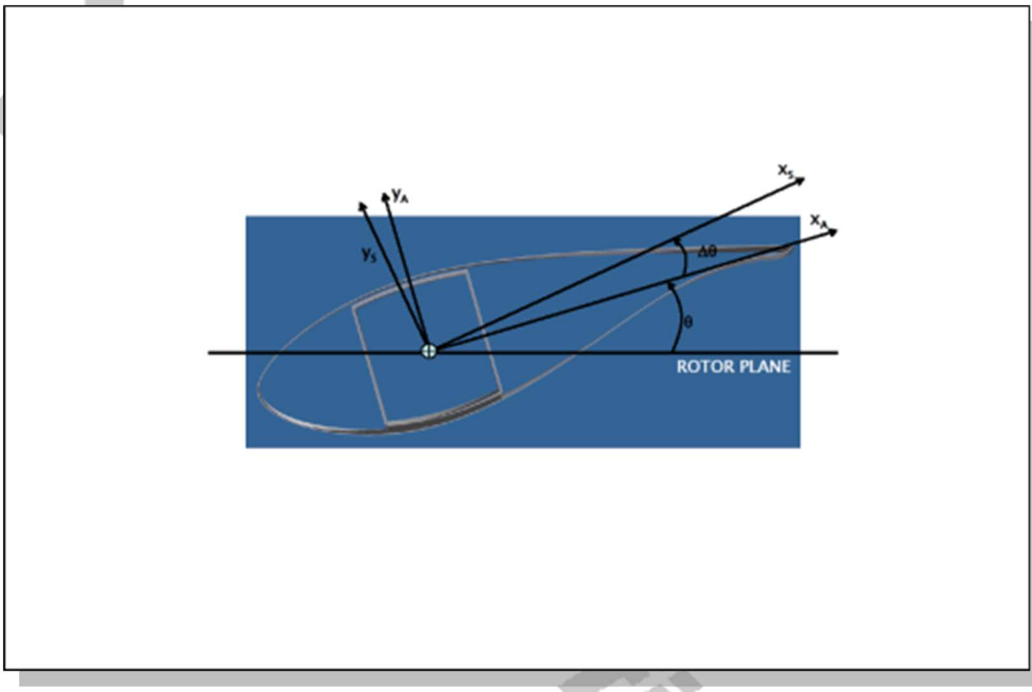

Figure 56 - Local Reference System for Mass and Stiffness distributions.

Eta	Radius [m]	Structural Mass [Kg/m]	Non-Structural Mass [Kg/m]	Jpolar [kgm^2/m]	CenterOfMass Xs [mm]	CenterOfMass Ys [mm]
0,00	0,00	308,0	7,0	65,15	-0,01927	0,07796
0,01	0,30	308,0	8,2	65,15	-0,01927	0,07796
0,03	0,69	213,2	9,5	49,75	-32,91	0,7951
0,05	1,10	91,2	11,7	22,68	-68,59	0,009939
0,05	1,20	62,0	12,3	14,14	-56,21	-1,429
0,09	2,20	73,8	24,6	21,03	-161	-11,03
0,10	2,39	74,0	26,1	20,95	-161,5	-9,736
0,13	3,05	76,2	26,9	19,76	-151,4	-1,989
0,14	3,39	75,6	27,3	18,90	-153,8	8,793
0,15	3,66	77,2	27,4	18,98	-152,2	16,06
0,17	4,09	74,7	27,0	16,98	-147,8	25,32
0,20	4,71	71,4	25,6	13,95	-127,8	29,17
0,22	5,35	64,5	24,3	10,55	-104,7	33,63

0,26	6,17	56,1	22,6	7,13	-80,52	37,11
0,28	6,75	54,3	21,6	5,77	-67,77	35,65
0,30	7,17	52,2	20,9	4,81	-56,67	34,05
0,31	7,33	51,5	20,7	4,53	-53,69	33,44
0,34	8,21	48,2	19,9	3,44	-44,55	30,08
0,37	8,89	45,5	19,2	2,68	-35,72	27,45
0,38	8,96	45,3	19,1	2,62	-35,16	27,23
0,41	9,79	40,7	17,8	1,95	-27,94	25,04
0,44	10,46	37,1	16,9	1,55	-23,68	23,74
0,45	10,76	34,3	16,4	1,33	-20,86	23,16
0,48	11,55	32,7	13,0	1,09	-18,24	21,65
0,50	11,95	32,0	11,5	0,99	-17,54	20,93
0,52	12,38	31,2	11,1	0,89	-16,9	20,19
0,55	13,04	29,4	10,6	0,76	-17,78	20,04
0,57	13,60	27,7	10,2	0,66	-20,41	19,65
0,60	14,30	26,1	9,8	0,57	-21,36	19,1
0,64	15,39	23,7	9,2	0,45	-24,29	19,21
0,65	15,54	22,1	9,1	0,41	-25,43	19,14
0,67	15,93	21,0	9,0	0,37	-25,6	18,62
0,70	16,73	18,9	8,8	0,30	-25,65	17,97
0,72	17,23	17,8	8,7	0,26	-25,95	18,01
0,74	17,77	16,1	8,6	0,22	-26,8	17,57
0,76	18,28	15,2	8,5	0,20	-26,96	16,87
0,79	18,80	13,7	8,4	0,17	-27,12	16,1
0,80	19,11	13,4	8,3	0,15	-26,95	15,71
0,80	19,12	12,5	8,3	0,14	-26,44	15,87
0,81	19,38	11,8	7,8	0,11	-23,36	15,92
0,83	19,72	11,1	7,1	0,10	-23,62	15,46
0,84	20,05	10,3	6,6	0,09	-24,17	15,05
0,85	20,37	9,6	6,0	0,08	-24,51	14,67
0,87	20,84	8,8	5,3	0,07	-25,25	14,14
0,89	21,29	7,7	4,7	0,06	-26,24	13,64
0,91	21,79	7,0	4,0	0,05	-27,04	13,19
0,92	22,00	6,5	3,7	0,05	-27,84	12,98
0,93	22,29	5,9	3,7	0,04	-29,06	12,71
0,94	22,56	5,0	3,6	0,04	-31,01	12,28
0,96	22,82	4,4	3,5	0,03	-32,27	11,66
0,98	23,35	2,5	3,0	0,02	-36,18	9,434
0,98	23,48	2,3	2,8	0,01	-33,68	8,772
0,99	23,58	1,8	2,6	0,01	-28,17	7,804
0,99	23,66	1,6	2,4	0,01	-22,04	7,158
1,00	23,90	0,9	1,7	0,00	3,439	5,013

Table 53 - Mass distributions.

Eta	Radius	EA	E11	E22	GJ	Δθ
-	[m]	[N]	[Nm^2]	[Nm^2]	[Nm^2]	deg
0,00	0,00	4,08E+09	4,32E+08	4,32E+08	2,29E+08	80,38
0,01	0,30	4,08E+09	4,32E+08	4,32E+08	2,29E+08	80,38
0,03	0,69	3,86E+09	4,06E+08	4,76E+08	1,65E+08	-84,35
0,05	1,10	2,74E+09	2,12E+08	3,79E+08	6,25E+07	-86,23
0,05	1,20	2,31E+09	1,30E+08	3,38E+08	3,41E+07	-87,44
0,09	2,20	2,63E+09	2,45E+08	2,86E+08	2,95E+07	-72,13
0,10	2,39	2,63E+09	2,45E+08	2,64E+08	2,76E+07	-44,45
0,13	3,05	2,71E+09	2,01E+08	2,52E+08	2,25E+07	-2,21
0,14	3,39	2,74E+09	1,76E+08	2,49E+08	1,97E+07	1,25
0,15	3,66	2,73E+09	1,56E+08	2,53E+08	1,83E+07	2,13
0,17	4,09	2,68E+09	1,25E+08	2,34E+08	1,49E+07	3,01
0,20	4,71	2,61E+09	9,40E+07	1,99E+08	1,14E+07	3,62
0,22	5,35	2,49E+09	6,89E+07	1,57E+08	7,88E+06	3,97
0,26	6,17	2,35E+09	4,65E+07	1,15E+08	4,89E+06	4,04
0,28	6,75	2,30E+09	3,60E+07	9,72E+07	3,93E+06	3,60
0,30	7,17	2,25E+09	3,05E+07	8,44E+07	3,35E+06	3,32
0,31	7,33	2,30E+09	2,94E+07	8,18E+07	3,17E+06	3,27
0,34	8,21	2,21E+09	2,15E+07	6,68E+07	2,35E+06	2,57
0,37	8,89	2,15E+09	1,62E+07	5,62E+07	1,80E+06	1,90
0,38	8,96	2,14E+09	1,58E+07	5,53E+07	1,76E+06	1,85
0,41	9,79	2,04E+09	1,23E+07	4,53E+07	1,28E+06	1,62
0,44	10,46	1,95E+09	1,05E+07	3,91E+07	9,94E+05	1,58
0,45	10,76	1,85E+09	9,46E+06	3,50E+07	8,09E+05	1,68
0,48	11,55	1,79E+09	7,54E+06	3,05E+07	6,49E+05	1,23
0,50	11,95	1,71E+09	6,59E+06	2,79E+07	5,77E+05	1,04
0,52	12,38	1,68E+09	5,84E+06	2,60E+07	5,18E+05	0,84
0,55	13,04	1,58E+09	4,43E+06	2,30E+07	4,12E+05	0,47
0,57	13,60	1,54E+09	3,76E+06	2,10E+07	3,49E+05	0,34
0,60	14,30	1,45E+09	3,04E+06	1,85E+07	2,92E+05	0,16
0,64	15,39	1,37E+09	2,06E+06	1,55E+07	2,00E+05	-0,08
0,65	15,54	1,27E+09	1,89E+06	1,41E+07	1,82E+05	0,01
0,67	15,93	1,20E+09	1,65E+06	1,29E+07	1,63E+05	-0,03
0,70	16,73	1,08E+09	1,22E+06	1,05E+07	1,26E+05	-0,11
0,72	17,23	1,01E+09	9,83E+05	9,36E+06	1,06E+05	-0,14
0,74	17,77	9,01E+08	7,89E+05	7,93E+06	8,86E+04	-0,12
0,76	18,28	8,39E+08	6,70E+05	6,97E+06	7,72E+04	-0,12
0,79	18,80	7,42E+08	5,45E+05	5,83E+06	6,65E+04	-0,08
0,80	19,11	7,28E+08	4,98E+05	5,49E+06	6,08E+04	-0,08
0,80	19,12	6,87E+08	4,79E+05	5,09E+06	5,48E+04	-0,02
0,81	19,38	6,70E+08	4,42E+05	4,62E+06	4,47E+04	-0,05
0,83	19,72	6,23E+08	3,88E+05	4,13E+06	4,04E+04	-0,01
0,84	20,05	5,76E+08	3,41E+05	3,68E+06	3,61E+04	0,04
0,85	20,37	5,31E+08	3,01E+05	3,27E+06	3,30E+04	0,09
0,87	20,84	4,83E+08	2,55E+05	2,81E+06	2,85E+04	0,15

0,89	21,29	4,06E+08	2,06E+05	2,25E+06	2,47E+04	0,25
0,91	21,79	3,62E+08	1,74E+05	1,90E+06	2,18E+04	0,31
0,92	22,00	3,27E+08	1,56E+05	1,68E+06	2,03E+04	0,36
0,93	22,29	2,57E+07	1,11E+04	3,02E+05	1,27E+04	0,22
0,94	22,56	2,52E+07	1,04E+04	2,83E+05	1,19E+04	0,22
0,96	22,82	2,42E+07	9,17E+03	2,51E+05	1,05E+04	0,22
0,98	23,35	2,10E+07	5,96E+03	1,64E+05	6,83E+03	0,23
0,98	23,48	1,95E+07	4,80E+03	1,31E+05	5,49E+03	0,19
0,99	23,58	1,76E+07	3,60E+03	9,72E+04	4,10E+03	0,12
0,99	23,66	1,61E+07	2,80E+03	7,46E+04	3,18E+03	0,06
1,00	23,90	1,10E+07	9,45E+02	2,39E+04	1,05E+03	-0,20

Table 54 - Stiffness distributions.

Appendix B –Load Cases (TSR)

The following tables report the Envelope Matrices for different sections along the blade span.

	Envelope @ Station 1 - Eta = 0 - SAFETY FACTORS ALREADY APPLIED.							0	m				
	Fx	Fy	Fxy	Fz	Mx	My	Mxy	Mz		Blade Nb	DLC	Time	Safety Fac
	N	N	N	N	Nm	Nm	Nm	Nm		-	-	sec	-
Loads @ max Fx	86786	17183	88470	32102	-167917	687079	707300	-18987		Blade 1	DLC62_ID_T_YMdeg-90	79,00	1,1
Loads @ min Fx	-80859	-14670	82179	-3705	175598	-626409	650556	14576		Blade 1	DLC62_ID_T_YMdeg60	79,20	1,1
Loads @ max Fy	34075	43397	55176	188064	-396736	451603	601120	5577		Blade 2	DLC15_vne	40,20	1,35
Loads @ min Fy	-9394	-42304	43334	171705	406931	-181788	445690	1804		Blade 3	DLC15_vnb	43,50	1,35
Loads @ max Fxy	86786	17183	88470	32102	-167917	687079	707300	-18987		Blade 1	DLC62_ID_T_YMdeg-90	79,00	1,1
Loads @ min Fxy	52	80	96	-9438	-16230	21467	26912	-4966		Blade 2	DLC62_ID_T_YMdeg-120	81,40	1,1
Loads @ max Fz	22493	5087	23061	283355	24226	14214	28088	-3845		Blade 1	DLC15_vnf	41,80	1,35
Loads @ min Fz	51904	6280	52283	-41061	-86668	482895	490611	-20053		Blade 1	DLC62_ID_T_YMdeg-120	117,80	1,1
Loads @ max Mx	-12261	-41442	43218	213012	445151	-255064	513047	1714		Blade 1	DLC15_vnb	43,10	1,35
Loads @ min Mx	35102	43154	55627	192717	-402444	441428	597344	5560		Blade 2	DLC15_vnc	40,10	1,35
Loads @ max My	76806	5304	76989	143556	-129638	846958	260469	-1800		Blade 1	DLC16_vna	42,30	1,35
Loads @ min My	-74695	-19832	77283	-8000	236563	-648250	690066	28598		Blade 1	DLC62_ID_T_YMdeg120	79,00	1,1
Loads @ max Mxy	76806	5304	76989	143556	-129638	846958	856822	-1800		Blade 1	DLC16_vna	42,30	1,35
Loads @ min Mxy	-3084	-1862	268	-9318	217	-157	268	-3839		Blade 2	DLC62_ID_T_YMdeg-120	103,60	1,1
Loads @ max Mz	-74695	-19832	77283	-8000	236563	-648250	690066	28598		Blade 1	DLC62_ID_T_YMdeg120	79,00	1,1
Loads @ min Mz	62320	12679	63597	14813	-132552	493839	511319	-27677		Blade 2	DLC62_ID_T_YMdeg150	87,80	1,1

	Envelope @ Station 3 - Eta = 0.05 - SAFETY FACTORS ALREADY APPLIED.							1,195	m				
	Fx	Fy	Fxy	Fz	Mx	My	Mxy	Mz		Blade Nb	DLC	Time	Safety Fac
	N	N	N	N	Nm	Nm	Nm	Nm		-	-	sec	-
Loads @ max Fx	82786	15689	84260	33736	-144928	586058	603711	-18485		Blade 1	DLC62_ID_T_YMdeg-90	79,00	1,1
Loads @ min Fx	-77030	-14896	78457	-1521	154691	-532350	554369	14222		Blade 1	DLC62_ID_T_YMdeg60	79,20	1,1
Loads @ max Fy	34858	38596	52007	183671	-344445	411907	536945	5576		Blade 2	DLC15_vne	40,20	1,35
Loads @ min Fy	-14225	-37031	39670	204644	394237	-240974	462051	1808		Blade 1	DLC15_vnf	43,10	1,35
Loads @ max Fxy	82786	15689	84260	33736	-144928	586058	603711	-18485		Blade 1	DLC62_ID_T_YMdeg-90	79,00	1,1
Loads @ min Fxy	17	80	82	-3780	-11753	11671	16563	-3884		Blade 2	DLC62_ID_T_YMdeg-120	83,20	1,1
Loads @ max Fz	18903	3834	19288	272697	29010	-10204	30753	-3753		Blade 1	DLC15_vnf	41,80	1,35
Loads @ min Fz	46263	6627	46736	-37526	-74749	397711	404674	-16975		Blade 1	DLC62_ID_T_YMdeg-120	117,60	1,1
Loads @ max Mx	-13946	-37007	39547	204608	395116	-240997	462813	1754		Blade 1	DLC15_vnb	43,10	1,35
Loads @ min Mx	35631	38369	52362	187561	-350472	400700	532345	5567		Blade 2	DLC15_vnc	40,10	1,35
Loads @ max My	74128	7377	74494	139620	-117938	757509	233607	-1687		Blade 1	DLC16_vna	42,30	1,35
Loads @ min My	-72214	-18209	74474	-5623	210169	-561122	599190	28033		Blade 1	DLC62_ID_T_YMdeg120	79,00	1,1
Loads @ max Mxy	74128	7377	74494	139620	-117938	757509	766635	-1687		Blade 1	DLC16_vna	42,30	1,35
Loads @ min Mxy	7141	709	627	-3381	548	-306	627	-10447		Blade 1	DLC62_ID_T_YMdeg-150	107,80	1,1
Loads @ max Mz	-72214	-18209	74474	-5623	210169	-561122	599190	28033		Blade 1	DLC62_ID_T_YMdeg120	79,00	1,1
Loads @ min Mz	60692	13327	62138	12176	-114635	420349	435700	-27035		Blade 2	DLC62_ID_T_YMdeg150	87,80	1,1

	Envelope @ Station 5 - Eta = 0.1419 - SAFETY FACTORS ALREADY APPLIED.							3,39141	m				
	Fx	Fy	Fxy	Fz	Mx	My	Mxy	Mz		Blade Nb	DLC	Time	Safety Fac
	N	N	N	N	Nm	Nm	Nm	Nm		-	-	sec	-
Loads @ max Fx	70585	4617	70736	140979	-63058	601191	604489	-708		Blade 1	DLC16_vna	42,40	1,35
Loads @ min Fx	-61571	-12216	62771	18639	116307	-412962	429027	14233		Blade 1	DLC62_ID_T_YMdeg90	53,20	1,1
Loads @ max Fy	37308	31156	48606	171832	-238412	356929	429230	5787		Blade 2	DLC15_vne	40,20	1,35
Loads @ min Fy	-18641	-32232	37235	192272	298953	-234316	379838	2053		Blade 1	DLC15_vnb	43,10	1,35
Loads @ max Fxy	70585	4617	70736	140979	-63058	601191	604489	-708		Blade 1	DLC16_vna	42,40	1,35
Loads @ min Fxy	-54	10	55	6579	8723	-37041	38055	-2773		Blade 1	DLC62_ID_T_YMdeg-180	45,60	1,1
Loads @ max Fz	12188	2254	12395	254766	30729	-47352	56449	-2937		Blade 1	DLC15_vnf	41,80	1,35
Loads @ min Fz	41944	3846	42120	-30334	-34618	322574	324426	-14202		Blade 1	DLC62_ID_T_YMdeg-120	117,80	1,1
Loads @ max Mx	-18641	-32232	37235	192272	298953	-234316	379838	2053		Blade 1	DLC15_vnb	43,10	1,35
Loads @ min Mx	31143	30001	43243	158527	-253690	273126	372768	5523		Blade 3	DLC15_vn+2c	39,80	1,35
Loads @ max My	69901	2912	69962	130750	-51560	606050	187334	-1233		Blade 1	DLC16_vna	42,30	1,35
Loads @ min My	-56633	-12665	58032	3147	139112	-436332	457971	17440		Blade 1	DLC62_ID_T_YMdeg120	21,80	1,1
Loads @ max Mxy	69901	2912	69962	130750	-51560	606050	608239	-1233		Blade 1	DLC16_vna	42,30	1,35
Loads @ min Mxy	10078	2220	306	7947	253	-173	306	-4281		Blade 3	DLC62_ID_T_YMdeg-180	50,00	1,1
Loads @ max Mz	-40781	-12669	42704	-14503	161390	-366676	400622	20790		Blade 3	DLC62_ID_T_YMdeg150	93,60	1,1
Loads @ min Mz	48223	8693	49000	9364	-61535	307713	313805	-18861		Blade 2	DLC62_ID_T_YMdeg150	87,80	1,1

	Envelope @ Station 7 - Eta = 0.3 - SAFETY FACTORS ALREADY APPLIED.							7,17 m				
	Fx	Fy	Fxy	Fz	Mx	My	Mxy	Mz	Blade Nb	DLC	Time	Safety Fac
	N	N	N	N	Nm	Nm	Nm	Nm	-	-	sec	-
Loads @ max Fx	56626	-2415	56677	111065	4756	357712	357743	-7	Blade 1	DLC16_vna	42,40	1,35
Loads @ min Fx	-40621	-5687	41018	1369	48541	-254787	259370	8835	Blade 1	DLC62_ID_T_YMdeg120	94,80	1,1
Loads @ max Fy	29142	18520	34529	129511	-129531	182886	224110	4614	Blade 3	DLC15_vn+2c	39,80	1,35
Loads @ min Fy	-22949	-22111	31867	146760	156036	-182670	240240	1801	Blade 1	DLC15_vnb	43,10	1,35
Loads @ max Fxy	56626	-2415	56677	111065	4756	357712	357743	-7	Blade 1	DLC16_vna	42,40	1,35
Loads @ min Fxy	6	24	25	19724	6417	-13274	14743	-795	Blade 1	DLC15_voc	45,10	1,35
Loads @ max Fz	15433	11976	19535	202066	-57747	26911	63710	-1373	Blade 2	DLC15_vnf	41,60	1,35
Loads @ min Fz	25204	10	25204	-17324	5606	193248	193329	-6266	Blade 1	DLC62_ID_T_YMdeg-120	117,60	1,1
Loads @ max Mx	-22949	-22111	31867	146760	156036	-182670	240240	1801	Blade 1	DLC15_vnb	43,10	1,35
Loads @ min Mx	29142	18520	34529	129511	-129531	182886	224110	4614	Blade 3	DLC15_vn+2c	39,80	1,35
Loads @ max My	56243	-3604	56359	103369	11649	363240	114353	-373	Blade 1	DLC16_vna	42,30	1,35
Loads @ min My	-39696	-5756	40111	8	53218	-266890	272144	8472	Blade 1	DLC62_ID_T_YMdeg120	21,80	1,1
Loads @ max Mxy	56243	-3604	56359	103369	11649	363240	363427	-373	Blade 1	DLC16_vna	42,30	1,35
Loads @ min Mxy	2029	387	263	-1090	-170	201	263	2166	Blade 3	DLC62_ID_T_YMdeg-180	41,80	1,1
Loads @ max Mz	-32044	-7561	32924	-13237	76993	-244441	256280	11825	Blade 3	DLC62_ID_T_YMdeg150	93,60	1,1
Loads @ min Mz	28640	441	28644	-6403	5213	205503	205569	-8384	Blade 2	DLC62_ID_T_YMdeg-150	80,40	1,1

	Envelope @ Station 9 - Eta = 0.45 - SAFETY FACTORS ALREADY APPLIED.							10,755 m				
	Fx	Fy	Fxy	Fz	Mx	My	Mxy	Mz	Blade Nb	DLC	Time	Safety Fac
	N	N	N	N	Nm	Nm	Nm	Nm	-	-	sec	-
Loads @ max Fx	39710	-3707	39883	67772	11802	192728	193089	106	Blade 1	DLC16_vna	42,30	1,35
Loads @ min Fx	-27715	-3902	27988	-265	30349	-148635	151702	4719	Blade 1	DLC62_ID_T_YMdeg120	80,40	1,1
Loads @ max Fy	14369	11862	18632	101755	-69142	41922	80858	668	Blade 3	DLC15_voc	39,80	1,35
Loads @ min Fy	-20178	-14066	24597	105086	79501	-111595	137018	996	Blade 1	DLC15_vnb	43,10	1,35
Loads @ max Fxy	39710	-3707	39883	67772	11802	192728	193089	106	Blade 1	DLC16_vna	42,30	1,35
Loads @ min Fxy	8	5	9	31995	3368	-10466	10995	-197	Blade 1	DLC15_vnf	45,60	1,35
Loads @ max Fz	5847	6588	8808	141819	-27255	-6614	28046	-1225	Blade 2	DLC15_vnf	41,60	1,35
Loads @ min Fz	11376	-182	11377	-12112	2711	65831	65887	-2479	Blade 3	DLC62_ID_T_YMdeg-120	21,80	1,1
Loads @ max Mx	-20178	-14066	24597	105086	79501	-111595	137018	996	Blade 1	DLC15_vnb	43,10	1,35
Loads @ min Mx	21649	11759	24636	89030	-69795	98837	120996	2745	Blade 3	DLC15_vn+2c	39,80	1,35
Loads @ max My	37300	-3199	37437	60964	12883	193445	95868	-32	Blade 2	DLC15_vn-2e	40,20	1,35
Loads @ min My	-25663	-7832	26832	41470	51043	-155034	163221	-246	Blade 3	DLC13_vob	46,50	1,35
Loads @ max Mxy	37300	-3199	37437	60964	12883	193445	193874	-32	Blade 2	DLC15_vn-2e	40,20	1,35
Loads @ min Mxy	398	136	18	-319	-18	-4	18	1311	Blade 3	DLC62_ID_T_YMdeg150	26,40	1,1
Loads @ max Mz	-24741	-4830	25208	-6781	40588	-148731	154170	6598	Blade 3	DLC62_ID_T_YMdeg150	93,60	1,1
Loads @ min Mz	20282	-1297	20323	-5319	11784	118211	118797	-4461	Blade 2	DLC62_ID_T_YMdeg-150	80,60	1,1

	Envelope @ Station 11 - Eta = 0.65 - SAFETY FACTORS ALREADY APPLIED.							15,535				
	Fx	Fy	Fxy	Fz	Mx	My	Mxy	Mz	Blade Nb	DLC	Time	Safety Fac
	N	N	N	N	Nm	Nm	Nm	Nm	-	-	sec	-
Loads @ max Fx	18764	-721	18778	33733	1676	60931	60954	359	Blade 2	DLC15_vn-2c	40,10	1,35
Loads @ min Fx	-15288	-3911	15780	25622	15689	-58618	60681	-637	Blade 3	DLC13_vob	46,50	1,35
Loads @ max Fy	3593	7276	8114	52886	-23607	4588	24049	-264	Blade 3	DLC15_voc	39,80	1,35
Loads @ min Fy	-11326	-7108	13372	59002	24746	-38472	45743	-53	Blade 1	DLC15_vnb	43,10	1,35
Loads @ max Fxy	18734	-1502	18794	34530	5139	61511	61725	208	Blade 2	DLC15_vn-2e	40,20	1,35
Loads @ min Fxy	-5	2	6	3740	146	-684	700	-11	Blade 2	DLC15_vn+2c	48,10	1,35
Loads @ max Fz	-6396	-812	6447	75783	6648	-30020	30748	-916	Blade 1	DLC15_vnf	41,80	1,35
Loads @ min Fz	5821	-197	5824	-7868	887	23345	23362	-840	Blade 3	DLC62_ID_T_YMdeg-120	22,20	1,1
Loads @ max Mx	-11559	-7030	13529	60489	24791	-41118	48014	-341	Blade 1	DLC15_vnf	43,00	1,35
Loads @ min Mx	6092	7138	9384	41190	-24671	15529	29151	378	Blade 3	DLC15_vof	39,80	1,35
Loads @ max My	18734	-1502	18794	34530	5139	61511	32280	208	Blade 2	DLC15_vn-2e	40,20	1,35
Loads @ min My	-14728	-3676	15180	29462	15739	-59489	61536	-737	Blade 1	DLC13_vob	45,85	1,35
Loads @ max Mxy	17150	-5507	18013	20197	19353	61383	64362	-706	Blade 2	DLC16_vn-2a	42,80	1,35
Loads @ min Mxy	2229	376	41	35635	18	36	41	-980	Blade 3	DLC13_vn-2b	41,65	1,35
Loads @ max Mz	-13808	-2099	13967	-17	10875	-53293	54391	2316	Blade 3	DLC62_ID_T_YMdeg150	93,80	1,1
Loads @ min Mz	-5271	627	5309	66666	464	-25989	25994	-2272	Blade 1	DLC15_vnf	42,50	1,35

	Envelope @ Station 12 - Eta = 0.8 - SAFETY FACTORS ALREADY APPLIED.							19,12					
	Fx	Fy	Fxy	Fz	Mx	My	Mxy	Mz		Blade Nb	DLC	Time	Safety Fac
	N	N	N	N	Nm	Nm	Nm	Nm		-	-	sec	-
Loads @ max Fx	8729	-2233	9010	1657	4707	18436	19027	-60		Blade 1	DLC62_ID_T_YMdeg-30	119,80	1,1
Loads @ min Fx	-8544	-1782	8728	10545	4233	-18906	19374	-589		Blade 1	DLC13_vob	45,85	1,35
Loads @ max Fy	1965	3348	3882	17541	-5878	2957	6580	-48		Blade 3	DLC15_vof	39,80	1,35
Loads @ min Fy	-5619	-2911	6328	24184	5681	-10937	12325	-478		Blade 1	DLC15_vnf	43,00	1,35
Loads @ max Fxy	8729	-2233	9010	1657	4707	18436	19027	-60		Blade 1	DLC62_ID_T_YMdeg-30	119,80	1,1
Loads @ min Fxy	-4	-3	5	207	35	-593	594	180		Blade 1	DLC62_ID_T_YMdeg150	55,40	1,1
Loads @ max Fz	-1809	1161	2150	31211	-1013	-4951	5054	-292		Blade 2	DLC15_vnf	41,70	1,35
Loads @ min Fz	-5923	131	5925	-2905	336	-13199	13203	471		Blade 3	DLC62_ID_T_YMdeg-120	119,80	1,1
Loads @ max Mx	-5657	-2873	6345	22644	5727	-11136	12522	-415		Blade 2	DLC15_vnd	42,50	1,35
Loads @ min Mx	1965	3348	3882	17541	-5878	2957	6580	-48		Blade 3	DLC15_vof	39,80	1,35
Loads @ max My	8729	-2233	9010	1657	4707	18436	4660	-60		Blade 1	DLC62_ID_T_YMdeg-30	119,80	1,1
Loads @ min My	-8531	-1688	8697	10215	4179	-19252	19701	-688		Blade 1	DLC13_vob	45,80	1,35
Loads @ max Mxy	-8531	-1688	8697	10215	4179	-19252	19701	-688		Blade 1	DLC13_vob	45,80	1,35
Loads @ min Mxy	262	-29	1	472	0	0	1	18		Blade 3	DLC62_ID_T_YMdeg-30	33,60	1,1
Loads @ max Mz	-7664	-527	7682	-354	1769	-16441	16536	844		Blade 3	DLC62_ID_T_YMdeg150	93,80	1,1
Loads @ min Mz	-590	319	670	14295	482	-2409	2456	-1475		Blade 3	DLC11_21a	65,80	1,35

	Envelope @ Station 13 - Eta = 0.9205 - SAFETY FACTORS ALREADY APPLIED.							21,99995					
	Fx	Fy	Fxy	Fz	Mx	My	Mxy	Mz		Blade Nb	DLC	Time	Safety Fac
	N	N	N	N	Nm	Nm	Nm	Nm		-	-	sec	-
Loads @ max Fx	2893	-676	2971	-207	564	2476	2540	33		Blade 1	DLC62_ID_T_YMdeg-30	119,80	1,1
Loads @ min Fx	-3286	-663	3353	3438	666	-2906	2981	-222		Blade 2	DLC13_vob	45,20	1,35
Loads @ max Fy	512	903	1038	4997	-628	102	636	-51		Blade 3	DLC15_vof	39,80	1,35
Loads @ min Fy	-1672	-841	1872	4540	923	-1532	1789	-419		Blade 3	DLC11_23a	89,30	1,35
Loads @ max Fxy	-3286	-663	3353	3438	666	-2906	2981	-222		Blade 2	DLC13_vob	45,20	1,35
Loads @ min Fxy	2	1	2	-4	1	-13	14	25		Blade 2	DLC62_ID_T_YMdeg120	117,00	1,1
Loads @ max Fz	-1089	236	1114	8862	65	-399	404	-73		Blade 2	DLC15_vnf	41,70	1,35
Loads @ min Fz	1206	3	1206	-1080	30	1047	1047	-114		Blade 3	DLC62_ID_T_YMdeg-120	22,20	1,1
Loads @ max Mx	-1672	-841	1872	4540	923	-1532	1789	-419		Blade 3	DLC11_23a	89,30	1,35
Loads @ min Mx	512	903	1038	4997	-628	102	636	-51		Blade 3	DLC15_vof	39,80	1,35
Loads @ max My	2893	-676	2971	-207	564	2476	705	33		Blade 1	DLC62_ID_T_YMdeg-30	119,80	1,1
Loads @ min My	-3262	-673	3331	3606	691	-2925	3005	-270		Blade 3	DLC13_vob	44,45	1,35
Loads @ max Mxy	-3252	-697	3326	3823	714	-2922	3008	-267		Blade 1	DLC13_vob	43,80	1,35
Loads @ min Mxy	11	1	1	14	0	0	1	2		Blade 2	DLC62_ID_T_YMdeg90	76,60	1,1
Loads @ max Mz	-1191	176	1204	5162	-184	-1286	1299	241		Blade 2	DLC11_23a	66,00	1,35
Loads @ min Mz	-541	-21	541	3933	272	-488	559	-493		Blade 3	DLC11_21a	65,80	1,35