NREL
NATIONAL RENEWABLE ENERGY LABORATORY






Gearbox Reliability Collaborative (GRC) Description and Loading

F. Oyague

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5000-47773
November 2011

Contract No. DE-AC36-08GO28308

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Gearbox Reliability Collaborative (GRC) Description and Loading

F. Oyague

Prepared under Task No. WE10.1131

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5000-47773
November 2011

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

CLC	Calibration load case
CRB	Cylindrical roller bearing
DGBB	Deep groove ball bearing
DLC	Design load case
ECD	Extreme coherent gust
ETM	Extreme turbulent model
EWM	Extreme wind speed model
EWS	Extreme wind sheer
fcCRB	Full Complement Cylindrical roller bearing
GPa	Gigapascal
HS	High Speed
HS-SH	High Speed Shaft
IMS	Intermediate Speed
IMS-SH	Intermediate Speed Shaft
INP-SH	Rotor shaft or main shaft
LS	Low Speed
LS-SH	Low Speed Shaft
NTM	Normal turbulence model
NWP	Normal wind profile model
PL	Planet
PLC	Planet carrier
SRB	Spherical roller bearing
ST	Stage
TRB	Tapered roller bearing
Vave	Annual average wind speed at hub height
Vhub	wind speed at hub height averaged over ten minutes
Vin	cut–in wind speed
Vout	cut–out wind speed
Vr	Rated wind speed
Vref	Reference wind speed averaged over ten minutes

Executive Summary

This document describes simulated turbine load cases in accordance with the IEC 61400-1 Ed.3 standard, which is representative of the typical wind turbine design process. The information presented herein is intended to provide a broad understanding of the Gearbox Reliability Collaborative 750kW drivetrain and turbine configuration. In addition, fatigue and ultimate strength drivetrain loads resulting from simulations are presented. This information provides the basis for the analytical work of the Gearbox Reliability Collaborative effort.

Introduction

The National Wind Technology Center (NWTC), at the National Renewable Energy Laboratory (NREL), has embarked on the task of revealing the causes and loading conditions that result in the premature failure of wind turbine gearboxes.

The NWTC approaches the problem by bringing together the different parties involved in the gearbox design process, with the common goal of the improvement of the lifetime of gearboxes. It achieves this with the Gearbox Reliability Collaborative (GRC).

The GRC seeks to achieve its goal by exploring three avenues of research. These include drivetrain numerical analysis and modeling, full-scale dynamometer testing, and field testing. These different branches will be iteratively correlated to arrive at a comprehensive understating of the loading conditions and internal behavior that potentially could be the culprit of the premature failures.

Numerical analysis plays a key role in the design process of the gearboxes. To better understand the implementation and capabilities of the analytical tools currently available in the industry, the GRC has initiated an *Analysis Round Robin.* The round robin explores various analytical approaches to gain insight into the validity and level of fidelity in the design practice. The analysis is based on modeling techniques that range from simple torsional models to models that account for gear tooth contact and gear tooth load distribution, as well as bearing compliances and roller load distribution.

The gearbox description and loading conditions presented here serve as the basis for the previously mentioned analytical evaluation. In addition, this report gives the reader a broad understanding of the drivetrain and gearbox operation. Detailed information of the gearing and other components is not in the public domain at this point. However, it will be released to the public as the project proceeds.

Turbine Technical Description

General Description of the Wind Turbine

Type	3 Blade upwind
Power rating	750 kW
Rotor diameter	48.2 m
Rated generator speed	22/15 rpm
Power regulation	Stall
Aerodynamic Brake	Pitchable tips
Nacelle Lay out	Three point suspension drivetrain with a low speed shaft, external main bearing, separate gearbox, high speed shaft with spring applied, hydraulic pressure release disc brake.
Tower	Welded tubular Steel
Nominal hub height	55m

General Design Operation

Cut-in wind speed	v_{in}	3 m/s (nominal)
Rated wind speed	v_r	16 m/s
Cut-out wind speed	v_{out}	25 m/s
Design wind class		IEC Class II
Design life		20 years

Blades

Blade length	23.5 m
Material	Glass fiber-polyester/wood-epoxy
Type of rotor brake	Pivotal blade tip
Twist	18.66^{o}
Tip angle	-3.5^{o}
Largest cord	2.25 m
Tip length	3.5 m
Blade area (projected)	38.6 m^2

Drive Train
Main shaft

Type Description	Forged shaft and flange
Material	34 CrNiMo6V

Main bearing

Type description	Spherical roller bearing
Main bearing housing	Flange bearing

Gearbox

Type description	LS planetary, IMS, and HS parallel shaft
Gearbox housing material	Cast iron
Ratio	1:81.491
Mechanical power	800 kW
Oil filling	100 l

Generator

Type description	2 speed generator, water cooled	
Rated power	750 kW	200 kW
Apparent power	825 kVA	238 kVA
Synchronous rotation speed	1800 rpm	1200 rpm
Rotation speed at rated power	1809 rpm	1208 rpm
Slip at rated power	0.5 %	0.67 %
Voltage	3x600 V	
Frequency	60 Hz	

Drivetrain Description

The GRC test turbine has a modular configuration. In this configuration, all individual components of the drivetrain are mounted onto the bed plate or main frame. These components include the main bearing, main shaft, gearbox, brake, high speed shaft, and generator. This configuration is very common within the industry because it allows the outsourcing of independent drivetrain components. The figure below shows the GRC drivetrain configuration [9].

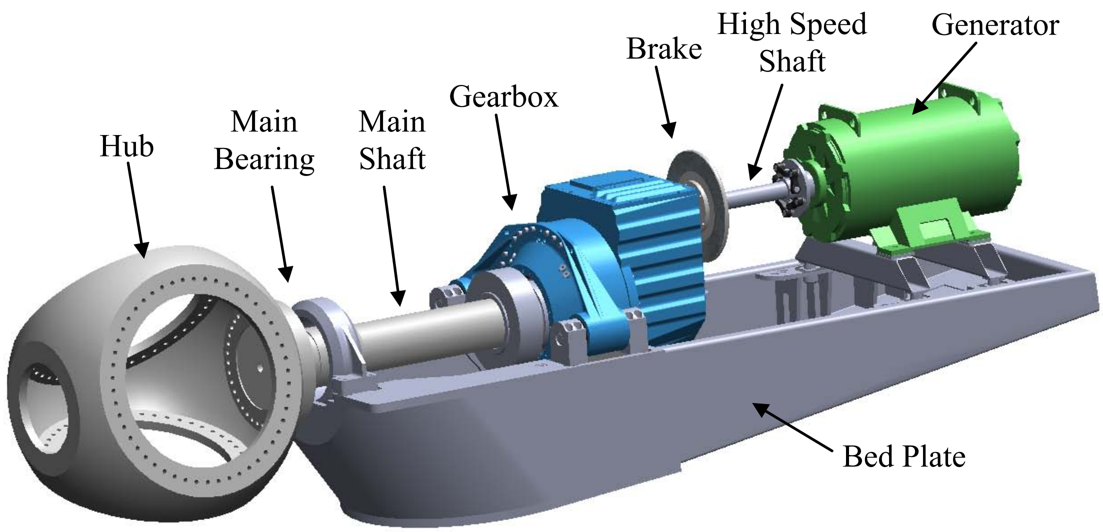

Figure 1: GRC drivetrain configuration.

Detailed Gearbox Description

External Configuration

The configuration of the GRC gearbox is typical of the MW class turbines used today. The gearbox is mounted in a three-point configuration, which transfers loads to the main frame through the main bearing and two torque arms. The torque arms contain two rubber mounts that help to reduce noise. The figure below depicts a front view of the gearbox showing the torque arm configuration and a side view of the rubber mount in the torque arm of the gearbox.

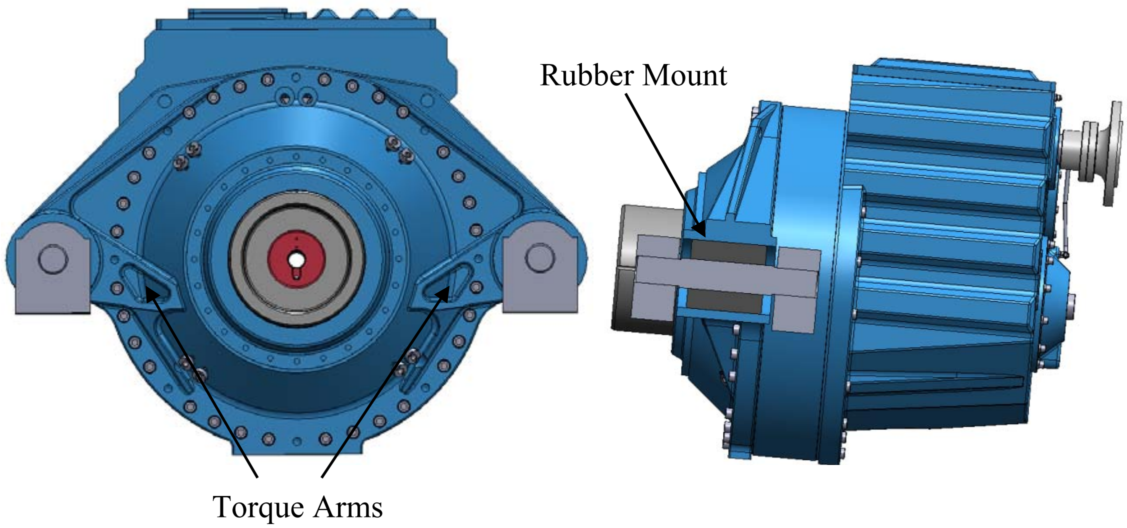

Figure 2: Torque arms and rubber mounts detail

Internal Configuration

The gearbox has an overall ratio of 1:81.491. It is composed of one low speed (LS) planetary stage and two parallel shaft stages. The LS planetary stage accommodates three planet gears, an annulus gear, and a sun gear. As depicted in Figure 4, the annulus gear of this stage is part of the gearbox housing. The sun gear is set in a floating configuration to better equalize the load distribution among the planets. To accommodate the floating sun arrangement, the low speed shaft is hollow and has an internal spline that transfers the torsional loads to the parallel shaft stages. The LS planetary gears have a helix angle of approximately 7.5 degrees, and the IMS and HS gear sets have a helix angle of 14 degrees. The figures below show the internal components as well as the nomenclature used to describe them. Additional gearing information can be found in Appendix A-1.

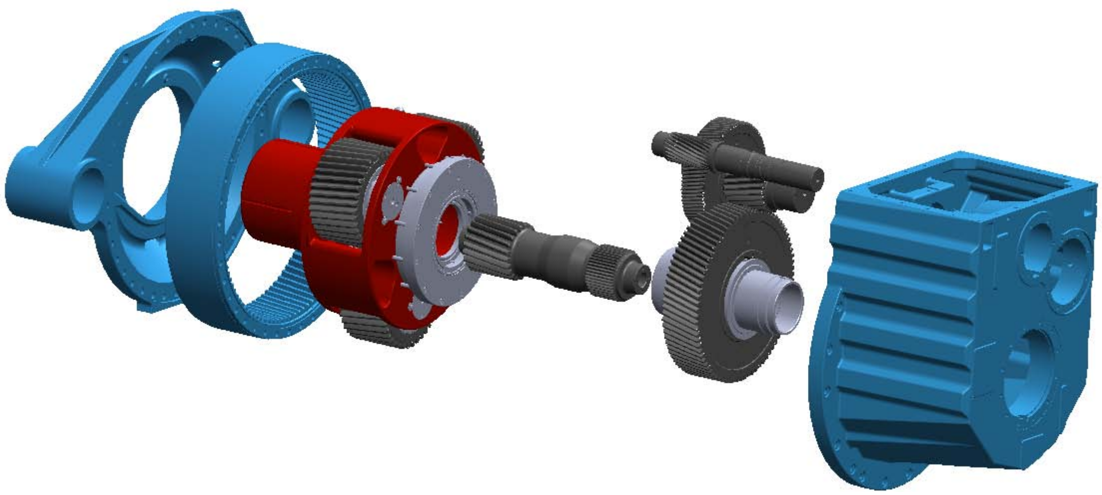

Figure 3: GRC gearbox internal components view

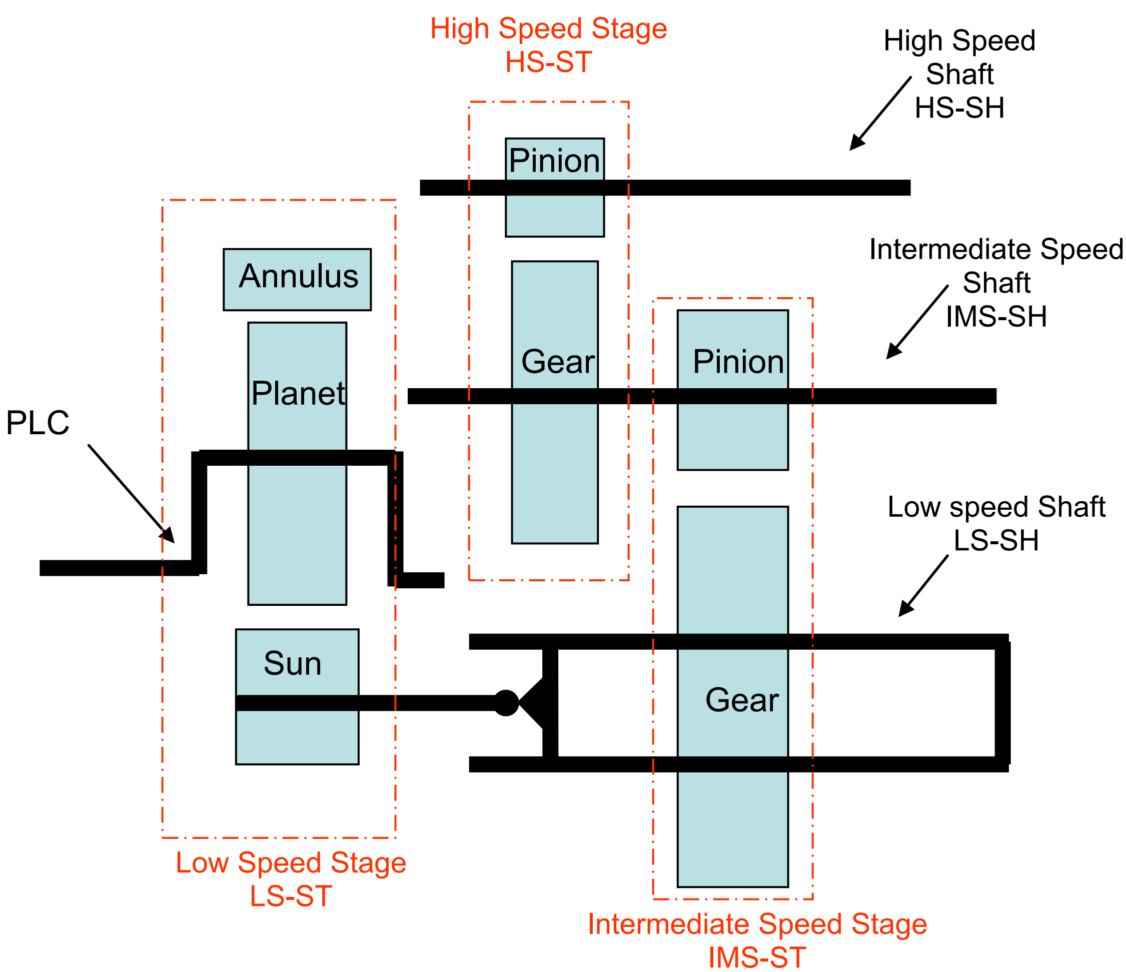

Figure 4: GRC gearbox internal nomenclature and abbreviations

Bearing Configuration

Several roller bearing types are employed in the gearbox according to the loading conditions and gearbox life requirements. The planet carrier is supported by two full-complement cylindrical roller bearings (fcCRB); each planet gear assembly is supported by two identical cylindrical roller bearings (CRB). Each parallel shaft stage in the gearbox is supported by a CRB on the upwind side of the assembly, and by two back-to-back mounted, duplex tapered roller bearings on the downwind side. Table 1 lists the location and bearing number of all bearings in the gearbox. The letter following the abbreviation indicates the position of the bearing according to the component from upwind (A) to downwind (B or C).

Table 1: Bearing number and location

Location	Type	Number	Provider
INP-A	SRB	24076 CC W33	SKF/INA
PLC-A	fcCRB	NCF 1892 V	SKF
PLC-B	fcCRB	SL 18 1880 E	FAG
PL-A	CRB	NJ2232E.M1.C3	FAG
PL-B	CRB	NJ2232E.M1.C3	FAG
LS-SH-A	fcCRB	SL181856E	FAG
LS-SH-B	TRB	32948	SKF
LS-SH-C	TRB	32948	SKF
IMS-SH-A	CRB	NU 2220 ECM	SKF
IMS-SH-B	TRB	32032 X/DF	SKF
IMS-SH-C	TRB	32032 X/DF	SKF
HS-SH-A	CRB	NU 2220 ECM	SKF
HS-SH-B	TRB	32222 A	FAG
HS-SH-C	TRB	32222 A	FAG
CONDUIT	DGBB	6016 Z	SKF

The figure below shows the nomenclature used to describe the locations of the bearings

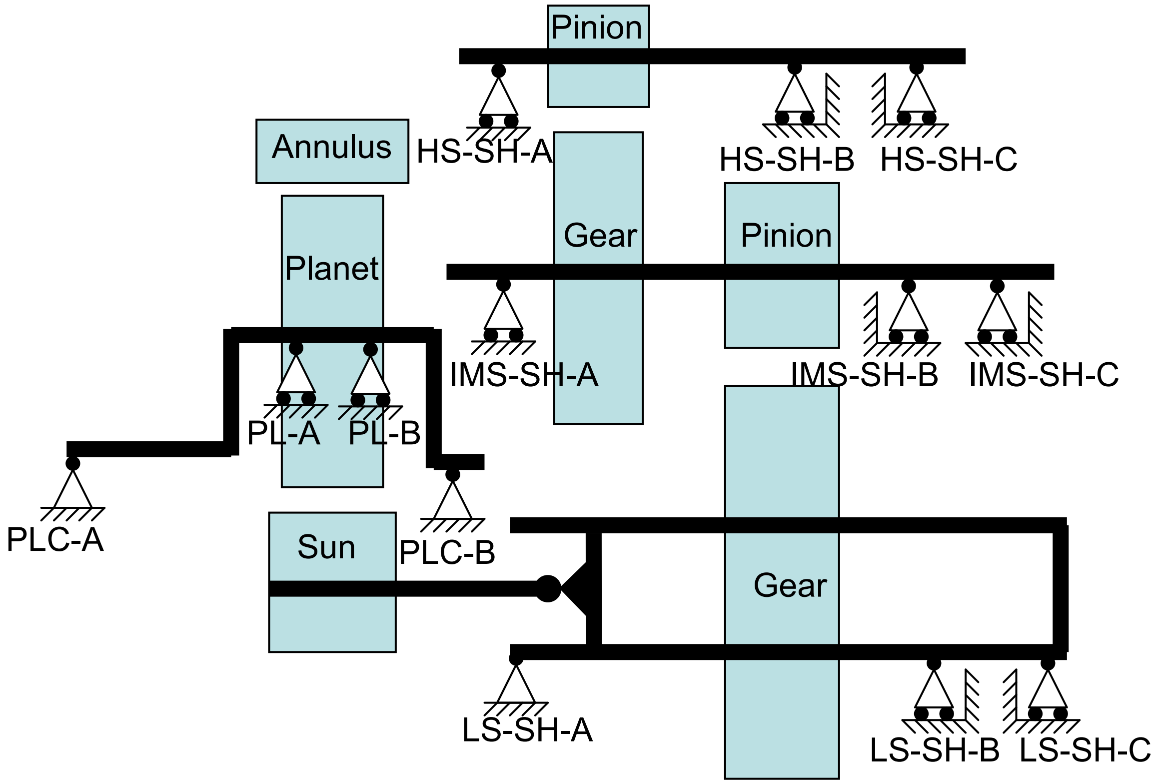

Figure 5: Bearing nomenclature and location

GRC Analysis Round Robin

The GRC Analysis Round Robin seeks to evaluate the different analytical tools and approaches utilized in the development and design of horizontal axis wind turbine drivetrains. The round robin utilizes the GRC drivetrain to provide its participants with a comprehensive characterization of the gearbox and other components. From there, the participants can develop models with different levels of complexity and fidelity.

A series of loading conditions, such as the calibration load case (CLC), are specific to this effort, though they are not a guideline according to the IEC standard. As the round robin progresses, the loading conditions will increase in complexity ranging from fully static to dynamic and transient events. This progressive approach assures that the discrepancies in the analysis results are due to the different tools employed and not the result of an analyst's assumptions.

Load Generation and Load Cases

The loads presented in this document can be classified into calibration load cases (CLC) and design load cases (DLC). The calibration load cases are simplified load cases; some of them are static. These load cases are intended for the initial phase of the code-to-code comparison as described above. The design load cases follow the guidance of the IEC 61400-1 ed.3 standard. These loading conditions reflect the loads experienced by turbines under normal as well as extreme wind conditions.

The intent of these load cases is to provide a global understanding of the loads generated by the turbine under most operational conditions. The load cases can be translated into drivetrain loading conditions, which are implemented in the design process. Table 2 shows a summary of all the simulated load cases.

Table 2: Load spectrum

Design Situation	Load Case	Wind Model	Wind Speed Range	Decryption
Static	**CLC 1.1**	N/A	N/A	25% rated power
	CLC 1.2	N/A	N/A	100% rated power
Dynamic	**CLC 2.1**	N/A	N/A	25% rated power
	CLC 2.2	N/A	N/A	39.5% rated torque
	CLC 2.3	N/A	N/A	100% rated power
Power Production	**DLC 1.1**	NTM	$V_{in} < V_{hub} < V_{out}$	N/A
	DLC 1.2	NTM	$V_{in} < V_{hub} < V_{out}$	N/A
	DLC 1.3	ETM	$V_{in} < V_{hub} < V_{out}$	N/A
	DLC 1.4	ECD	$V_{hub} = V_r$-2m/s, V_r, V_r+2m/s	N/A
	DLC 1.5	EWS	$V_{in} < V_{hub} < V_{out}$	N/A
Emergency shut down	**DLC 5.1**	NTM	$V_{hub} = V_r$-2m/s,V_{out}, V_r+2m/s	N/A
Parked (Idling)	**DLC 6.1a**	Turbulent EWM	$V_{hub} = 0.95*V_{ref}$	N/A
	DLC 6.3a	Turbulent EWM	$V_{hub} = 0.95*V_1$	N/A
	DLC 6.4	NTM	$V_{hub} < 0.7*V_{ref}$	N/A
Parked (Idling) and Fault	**DLC 7.1a**	Turbulent EWM	$V_{hub} = 0.95*V_1$	N/A

Simulated Load Cases

FAST Model Input Parameter and Validation

Simulated load cases are generated with FAST (Fatigue, Aerodynamic Structures and Turbulence) and AeroDyn, which is a medium complexity code for aerodynamic analysis of horizontal axis turbines. FAST allows the simulation of turbines with two or three blades, as well as those with a teetering or rigid rotor [1]. FAST models a wind turbine by combining rigid and flexible bodies. The flexible bodies include the blade tower and drivetrain shaft. The code uses Kane's method to solve the equations of motion that describe the behaviour of all independent components. The model employs generalized coordinates that result in the elimination of constraint equations, thus reducing the computational time [2]. The analysis allows for 14 degrees of freedom including multiple tower bending modes. [1]

The aero-elastic model uses parameters specific to the GRC turbine. The parameters that were not available were taken from similar turbines and tuned with experimental data. The parameters that integrate the model can be classified into the following subdivisions: tower, blades, drivetrain and nacelle.

Tower

Stiffness and mass distribution were calculated from the geometrical characteristics of the tower. These parameters were used to calculate the modal behaviour of the structure. To assure the correlation between the calculated mode shapes and the physical structure, frequencies were experimentally collected and the modal characteristics were then tuned [7].

Blades

Geometrical characteristics such as chord and twist were measured from an existing blade. Parameters such as mass and stiffness distribution were obtained by means of modifying the parameters from similar blades and adjusting them to match the overall mass and center of mass of the GRC blade. The modal behaviour was adjusted to match natural frequencies experimentally collected. Airfoil characteristics were obtained by modifying standard airfoils and matching the power curve and Cp curve of the turbine [7].

Drivetrain

The bulk stiffness characteristics of the drivetrain were calculated from natural frequencies recorded in the field. The damping characteristics were obtained from the torque characteristics exhibited in several braking events.

Generator

The generator is normally considered part of the drivetrain; however, it is a separate item in the FAST simulation. The generator is a dual speed induction generator that changes speed by changing the number of poles in operation. The FAST model included a linear model of the induction generator following the characteristics provided by the generator manufacturer.

Table 3: GRC generator characteristics

GRC 60 Hz Generator				
Rated power	750	**kW**	200	**kW**
Apparent power	825.00	**kVA**	238	**kVA**
Rated current	820.00	**A**	230	**A**
Max power at class F	825.00	**kW**	220	**kW**
Max current at class F	902.00	**A**	253	**A**
No load current	230.00	**A**	71	**A**
Reactive power consumption at rated power (acc. To IEC 60034-1)	405.00	**kvar**	130	**kvar**
Reactive power consumption at no load (acc. To IEC 60034-1)	240.00	**kvar**	74	**kvar**
number of poles	4	**-**	6	**-**
synchronous rotation speed	1800.00	**RPM**	1200	**RPM**
Rotation speed at rated power	1809.00	**RPM**	1208	**RPM**
voltage	0.50	**%**	0.67	**%**
Frequency	6X600	**V**	6X600	**V**
Coupling	60.00	**-**	60	**-**
Enclosure	IP54	**-**	IP54	**-**
Insulation class	F/B	**-**	F/B	**-**

Nacelle

The most relevant parameters for the nacelle, from a modeling standpoint, are mass and inertia. The inertial characteristics of the nacelle were estimated by correlating the overall manufacturer published weight of the nacelle and estimated bulk geometry.

Dynamometer Load Cases

In addition to the simulated load cases presented in this document, a series of dynamometer load cases have been applied to the test subject at the National Wind Technology Center dynamometer facility. The facility is capable of producing up to 2.5 megawatts of power, with a velocity range of 0-146 rpm [3]. This allows for flexibility in the load cases that can be generated. The empirical loading conditions will be correlated to the simulated loading conditions, as well as the field test loading conditions, thus tying the loads together in a global load matrix to better understand their effects. The GRC dynamometer loading conditions, as well as information regarding the channels characteristics, can be found in the GRC test plan [8].

Field Load Cases

The field load cases have been generated with a nearly identical test subject in the dynamometer. The only difference between the model and the test subject is that a small number of channels have been eliminated due to size constraints that exist in the field. A series of transient events and regular operations have been recorded in the field. These events occur in operational conditions that may not be created in the dynamometer [8].

Load Spectrum

The fatigue and ultimate strength load spectrum was generated from the simulated load results. The simulations followed the guidelines provided by the IEC 61400-1 Ed 3 standard for fatigue and ultimate strength. The load spectrum follows the characteristics for a class II turbine specification. Table 3 shows the characteristics for class II turbines.

Table 4: Turbine class II characteristics

GRC Turbine Characteristics	
Wind Turbine Class	II
V_{ref} (m/s)	42.5
V_{ave} (m/s)	8.5
Turbulence Class	B
Turbulence intensity @15m/s	0.14

Fatigue Load Spectrum

The design load cases specified by the IEC 61400-1 Ed.3 standard as fatigue load cases were used to generate the torque at level load spectrum. Because control algorithms are unknown for the GRC turbine, the load cases that depend on the control system are excluded from the load spectrum. These cases include DLC 2.4, 3.1 and 4.1. Therefore, the effects of the load cases 3.1 and 4.1 in the load spectrum are used throughout the experimental data. The table below shows the fatigue load cases as specified by the IEC standard.

Table 5: Fatigue load cases

Design Situation	Load Case	Wind Model	Wind Speed Range	# Wind Speeds
Power Production	**DLC 1.2**	NTM	$V_{in} < V_{hub} < V_{out}$	23
Power Production plus occurrence of fault	**DLC 2.4**	NTM	$V_{in} < V_{hub} < V_{out}$	23
Start up	**DLC 3.1**	NTM	$V_{in} < V_{hub} < V_{out}$	23
Normal shut down	**DLC 4.1**	NWP	$V_{in} < V_{hub} < V_{out}$	23
Parked (Idling)	**DLC 6.4**	NTM	$V_{hub} < 0.7*V_{ref}$	1

The load spectrum was generated using the previously described FAST model. Each individual simulation's duration was 10 minutes, 30 seconds. The first 30 seconds of generated data were truncated to eliminate the influence of the initial conditions. The wind files stipulated by the IEC standard were generated using 25 random numbers. This resulted in 25 simulations for each individual wind speed. In addition to the FAST model characteristics previously mentioned, rotor imbalance was introduced to the model. This was achieved by making one blade 0.5% heavier, another blade 0.5% lighter, and leaving one as reference [6].

Probability density functions were generated from the obtained files and then scaled to a Rayleigh distribution as specified by the standard. The figure below shows the scaled probability function of each wind speed.

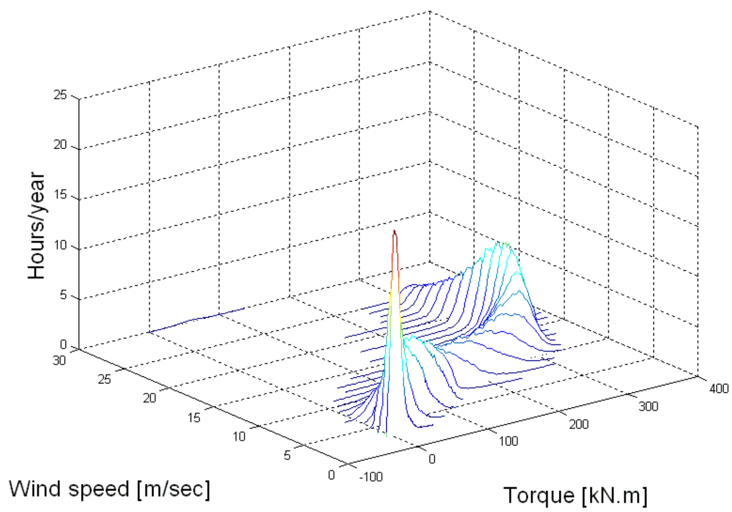

Figure 6: Torque distribution per wind speed

The scaled probability functions were added to obtain the torque at level curve. This was done by subdividing the torque values into 100 bins and linearly interpolating the time that each wind speed would be at that torque level. Finally, the interpolated values were added to obtain the cumulative torque at level. The figure below shows the torque at level for one year of operation.

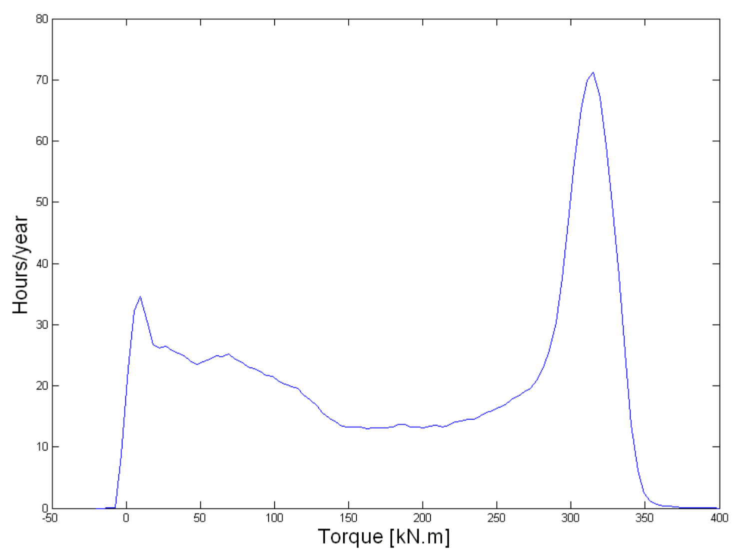

Figure 7: Torque at level hours/year

For gear and bearing calculations it is also relevant to evaluate the number of cycles at which the drivetrain operates. Figure 8 shows the number of cycles for each generator, which can be correlated to the operational speed of the drivetrain. The aggregate or total number of cycles can also be seen in the figure.

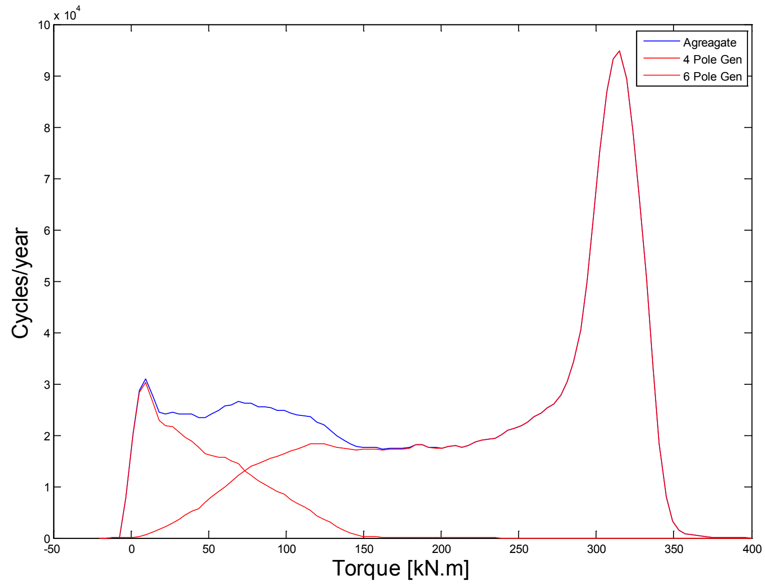

Figure 8: Torque at level cycles/year

Ultimate Strength Load Spectrum

The ultimate strength load spectrum follows the load cases specified by the IEC standard. As mentioned in the fatigue load spectrum, the lack of knowledge of the control algorithm prevented the simulation of load cases that are highly dependent on the control system. The design load cases considered for the ultimate strength events are presented in the table below.

Table 6: Accounted ultimate stregth load cases

Design Situation	Load Case	Wind Model	Wind Speed Range
Power Production	**DLC 1.1**	NTM	$V_{in} < V_{hub} < V_{out}$
	DLC 1.3	ETM	$V_{in} < V_{hub} < V_{out}$
	DLC 1.4	ECD	$V_{hub} = V_r$-2m/s, V_r, V_r+2m/s
	DLC 1.5	EWS	$V_{in} < V_{hub} < V_{out}$
Parked (Idling)	**DLC 6.1a**	Turbulent EWM	$V_{hub} = 0.95*V_{ref}$
	DLC 6.3a	Turbulent EWM	$V_{hub} = 0.95*V_1$
Parked (Idling) and Fault	**DLC '7.1a**	Turbulent EWM	$V_{hub} = 0.95*V_1$

The loading conditions are described in the FAST coordinate system [3]. Parameters such as torque and thrust follow the FAST sign convention and are aligned with the main shaft axis. Parameters such as shear are described at the location of the main bearing. The bending moments are calculated at the center of the hub, 1.293 m upwind from the main bearing. The table below shows the values for the maximum loading condition as well as the file and the design load case associated with the load value. The extreme event for each individual design load case can be found in Appendix A-2.

Table 7: Extreme events table

DLC	File Name	Load	Units	
RotThrust				
DLC6.1	DLC6.1a_0044_40.4V0_000ny_S15.out	2.57E+02	kN	Max
DLC1.3	DLC1.3_0011_03.0V0_S11.out	-2.16E+01	kN	Min
LSShftTq				
DLC1.3	DLC1.3_0327_20.0V0_S02.out	4.01E+02	kN·m	Max
DLC1.3	DLC1.3_0025_07.0V0_S25.out	-1.92E+01	kN·m	Min
LSSGagFzs				
DLC1.3	DLC1.3_0172_13.0V0_S22.out	-1.15E+02	kN	Max
DLC1.3	DLC1.3_0160_13.0V0_S10.out	-1.42E+02	kN	Min
LSSGagFys				
DLC1.3	DLC1.3_0376_22.0V0_S01.out	1.08E+01	kN	Max
DLC1.3	DLC1.3_0328_20.0V0_S03.out	-1.26E+01	kN	Min
LSSTipMys				
DLC6.1	DLC6.1a_0009_40.4V0_008ny_S03.out	467.5	kN·m	Max
DLC1.3	DLC1.3_0172_13.0V0_S22.out	-399.8	kN·m	Min
LSSTipMzs				
DLC1.3	DLC1.3_0189_14.0V0_S14.out	397.7	kN·m	Max
DLC1.3	DLC1.3_0106_11.0V0_S06.out	-443	kN·m	Min

Final Remarks

This document describes the GRC drivetrain in a general manner by providing an overview of the drivetrain configuration, gearbox configuration, as well as fatigue and ultimate strength load spectrum. This information provides the necessary information to assist universities and other interested parties in the development of basic initial drivetrain models. The GRC drivetrain has been heavily studied and there is a large amount of information that was not included in this document. At this point, further information is available only to the participants of the gearbox reliability collaborative. Additional information will be publically released later. This includes drivetrain solid models, material properties, bearing and gear micro geometry, experimental datasets for model validation, time series from the simulated load spectrum, and manufacturing drawings. To gain access to this information, the GRC requires partnership through a substantial contribution.

References

[1] J.F. Manwell J., G. Mc Gowan, A.L. Rogers. *Wind Energy Explained: Theory, Design and Application*.

[2] Jonkman, Jason. *NWTC Design Codes Fast.* http://wind.nrel.gov/designcodes/simulators/fast/

[3] Jonkman, Jason. *NWTC Design Codes Fast Users Guide.* http://wind.nrel.gov/designcodes/simulators/fast/FAST.pdf

[4] http://www.nrel.gov/wind/facilities_dynamometer.html

[5] *International Electrotechnical Commission* Wind Turbines Part 1: Design requirements IEC 61400-1 Ed. 3, 3 December 2003

[6] Jonkman, Jason.. *Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine.* http://www.nrel.gov/docs/fy08osti/41958.pdf NREL/TP-500-41958 November 2007

[7] G.S. Bir, F. Oyague, *Estimation of Blade and Tower Properties for the Gearbox Reliability Collaborative Wind Turbine* http://www.nrel.gov/docs/fy08osti/42250.pdf NREL/TP-500-42250, November 2007

[8] McNiff B., Van Dam J, Gorman D. *Gearbox Reliability Collaborative Phase 1 Test Plan* , NREL/TP-500-47842, National Renewable Energy Laboratory, Golden, Colorado (Forthcoming).

[9] F. Oyague, *Gearbox Modeling and Load Simulation of a Baseline 750-kW Wind Turbine Using State-of-the-Art Simulation Codes*, NREL/TP-500-41160 February 2009

Appendix A-1: Basic Gear Tables

Table 8: Planetary gear data

Parameter	Annulus Gear	Planet Gear	Sun Gear
Drawing Number	251240	251242	251246
Number of Teeth	99	39	21
Normal Module (nm)	10.00	10.00	10.00
Normal Pressure Angle (deg)	20.00	20.00	20.00

Table 9: IMS helical gear data

Parameter	IMS-ST Gear	IMS-ST Pinion
Drawing Number	251341	251243
Number of Teeth	82	23
Normal Module (nm)	8.25	8.25
Normal Pressure Angle (deg)	20.00	20.00

Table 10: HSS helical gear data

Parameter	HS-ST Gear	HS-ST Pinion
Drawing Number	251241	251244
Number of Teeth	88	22
Normal Module (nm)	5.00	5.00
Normal Pressure Angle (deg)	20.00	20.00

Appendix A-2: Extreme Events Tables

Table 11: Extreme events table for DLC 1.2

DLC	File Name	Load	Units	
DLC1.2	**RotThrust**			
	DLC1.1_0451_25.0V0_S01.out	1.30E+02	kN	Max
	DLC1.1_0024_03.0V0_S24.out	-8.44E+00	kN	Min
	LSShftTq			
	DLC1.1_0355_21.0V0_S05.out	4.00E+02	kN·m	Max
	DLC1.1_0006_07.0V0_S06.out	-1.57E+01	kN·m	Min
	LSSGagFzs			
	DLC1.1_0194_14.0V0_S19.out	-1.16E+02	kN	Max
	DLC1.1_0204_15.0V0_S04.out	-1.40E+02	kN	Min
	LSSGagFys			
	DLC1.1_0376_22.0V0_S01.out	9.30E+00	kN	Max
	DLC1.1_0390_22.0V0_S15.out	-9.91E+00	kN	Min
	LSSTipMys			
	DLC1.1_0294_18.0V0_S19.out	3.90E+02	kN·m	Max
	DLC1.1_0272_17.0V0_S22.out	-3.70E+02	kN·m	Min
	LSSTipMzs			
	DLC1.1_0209_15.0V0_S09.out	3.52E+02	kN·m	Max
	DLC1.1_0294_18.0V0_S19.out	-4.28E+02	kN·m	Min

Table 12: Extreme events table for DLC 1.3

DLC	File Name	Load	Units	
DLC1.3	**RotThrust**			
	DLC1.3_0451_25.0V0_S01.out	1.43E+02	kN	Max
	DLC1.3_0011_03.0V0_S11.out	-2.16E+01	kN	Min
	LSShftTq			
	DLC1.3_0327_20.0V0_S02.out	4.01E+02	kN·m	Max
	DLC1.3_0025_07.0V0_S25.out	-1.92E+01	kN·m	Min
	LSSGagFzs			
	DLC1.3_0172_13.0V0_S22.out	-1.15E+02	kN	Max
	DLC1.3_0160_13.0V0_S10.out	-1.42E+02	kN	Min
	LSSGagFys			
	DLC1.3_0376_22.0V0_S01.out	1.08E+01	kN	Max
	DLC1.3_0328_20.0V0_S03.out	-1.26E+01	kN	Min
	LSSTipMys			
	DLC1.3_0195_14.0V0_S20.out	459.6	kN	Max
	DLC1.3_0172_13.0V0_S22.out	-399.8	kN	Min
	LSSTipMzs			
	DLC1.3_0189_14.0V0_S14.out	397.7	kN	Max
	DLC1.3_0106_11.0V0_S06.out	-443	kN	Min

Table 13: Extreme events table for DLC 1.4

DLC	File Name	Load	Units	
DLC1.4	**RotThrust**			
	DLC1.4_0001_ECD+R-20.out	63.56	kN	Max
	DLC1.4_0001_ECD+R-20.out	23.31	kN	Min
	LSShftTq			
	DLC1.4_0003_ECD+R+20.out	346.3	kN·m	Max
	DLC1.4_0002_ECD+R.out	132.9	kN·m	Min
	LSSGagFzs			
	DLC1.4_0002_ECD+R.out	-121.3	kN	Max
	DLC1.4_0002_ECD+R.out	-134.3	kN	Min
	LSSGagFys			
	DLC1.4_0002_ECD+R.out	3.342	kN	Max
	DLC1.4_0002_ECD+R.out	-4.295	kN	Min
	LSSTipMys			
	DLC1.4_0002_ECD+R.out	234.6	kN	Max
	DLC1.4_0002_ECD+R.out	-240.4	kN	Min
	LSSTipMzs			
	DLC1.4_0002_ECD+R.out	195.3	kN	Max
	DLC1.4_0002_ECD+R.out	-276	kN	Min

Table 14: Extreme events table for DLC 1.5

DLC	File Name	Load	Units	
DLC1.5	**RotThrust**			
	DLC1.5_0074_EWSH-25.0.out	7.84E+01	kN	Max
	DLC1.5_0001_EWSH+03.0.out	-3.18E-01	kN	Min
	LSShftTq			
	DLC1.5_0042_EWSH-17.0.out	3.48E+02	kN·m	Max
	DLC1.5_0002_EWSH-03.0.out	1.29E+00	kN·m	Min
	LSSGagFzs			
	DLC1.5_0034_EWSH-15.0.out	-1.21E+02	kN	Max
	DLC1.5_0034_EWSH-15.0.out	-1.35E+02	kN	Min
	LSSGagFys			
	DLC1.5_0038_EWSH-16.0.out	3.34E+00	kN	Max
	DLC1.5_0038_EWSH-16.0.out	-4.30E+00	kN	Min
	LSSTipMys			
	DLC1.5_0038_EWSH-16.0.out	234.6	kN	Max
	DLC1.5_0033_EWSH+15.0.out	-244.2	kN	Min
	LSSTipMzs			
	DLC1.5_0033_EWSH+15.0.out	205.2	kN	Max
	DLC1.5_0033_EWSH+15.0.out	-288.1	kN	Min

Table 15: Extreme events table for DLC 6.1

DLC	File Name	Load	Units	
DLC6.1	**RotThrust**			
	DLC6.1a_0044_40.4V0_000ny_S15.out	2.57E+02	kN	Max
	DLC6.1a_0001_40.4V0_352ny_S01.out	3.85E+01	kN	Min
	LSShftTq			
	DLC6.1a_0007_40.4V0_352ny_S03.out	2.70E+02	kN·m	Max
	DLC6.1a_0025_40.4V0_352ny_S09.out	-2.70E+00	kN·m	Min
	LSSGagFzs			
	DLC6.1a_0030_40.4V0_008ny_S10.out	-1.23E+02	kN	Max
	DLC6.1a_0001_40.4V0_352ny_S01.out	-1.37E+02	kN	Min
	LSSGagFys			
	DLC6.1a_0055_40.4V0_352ny_S19.out	6.82E+00	kN	Max
	DLC6.1a_0051_40.4V0_008ny_S17.out	-8.41E+00	kN	Min
	LSSTipMys			
	DLC6.1a_0009_40.4V0_008ny_S03.out	467.5	kN	Max
	DLC6.1a_0007_40.4V0_352ny_S03.out	-291.9	kN	Min
	LSSTipMzs			
	DLC6.1a_0017_40.4V0_000ny_S06.out	382.9	kN	Max
	DLC6.1a_0053_40.4V0_000ny_S18.out	-378.3	kN	Min

Table 16: Extreme events table for DLC 6.3

DLC	File Name	Load	Units	
DLC6.3	**RotThrust**			
	DLC6.3a_0044_32.3V0_000ny_S15.out	1.57E+02	kN	Max
	DLC6.3a_0003_32.3V0_020ny_S01.out	2.09E+01	kN	Min
	LSShftTq			
	DLC6.3a_0009_32.3V0_020ny_S03.out	2.05E+02	kN·m	Max
	DLC6.3a_0051_32.3V0_020ny_S17.out	4.28E+00	kN·m	Min
	LSSGagFzs			
	DLC6.3a_0030_32.3V0_020ny_S10.out	-1.25E+02	kN	Max
	DLC6.3a_0037_32.3V0_340ny_S13.out	-1.34E+02	kN	Min
	LSSGagFys			
	DLC6.3a_0019_32.3V0_340ny_S07.out	4.64E+00	kN	Max
	DLC6.3a_0051_32.3V0_020ny_S17.out	-7.73E+00	kN	Min
	LSSTipMys			
	DLC6.3a_0011_32.3V0_000ny_S04.out	287.2	kN	Max
	DLC6.3a_0041_32.3V0_000ny_S14.out	-197.1	kN	Min
	LSSTipMzs			
	DLC6.3a_0017_32.3V0_000ny_S06.out	229.9	kN	Max
	DLC6.3a_0053_32.3V0_000ny_S18.out	-244	kN	Min

Table 17: Extreme events table for DLC 7.1

DLC	File Name	Load	Units	
DLC7.1	**RotThrust**			
	DLC7.1a_0044_32.3V0_000ny_S15.out	1.56E+02	kN	Max
	DLC7.1a_0001_32.3V0_352ny_S01.out	2.28E+01	kN	Min
	LSShftTq			
	DLC7.1a_0007_32.3V0_352ny_S03.out	2.20E+02	kN·m	Max
	DLC7.1a_0025_32.3V0_352ny_S09.out	5.06E+00	kN·m	Min
	LSSGagFzs			
	DLC7.1a_0030_32.3V0_008ny_S10.out	-1.26E+02	kN	Max
	DLC7.1a_0001_32.3V0_352ny_S01.out	-1.34E+02	kN	Min
	LSSGagFys			
	DLC7.1a_0019_32.3V0_352ny_S07.out	3.22E+00	kN	Max
	DLC7.1a_0051_32.3V0_008ny_S17.out	-7.84E+00	kN	Min
	LSSTipMys			
	DLC7.1a_0012_32.3V0_008ny_S04.out	290	kN	Max
	DLC7.1a_0042_32.3V0_008ny_S14.out	-206.2	kN	Min
	LSSTipMzs			
	DLC7.1a_0017_32.3V0_000ny_S06.out	230.2	kN	Max
	DLC7.1a_0053_32.3V0_000ny_S18.out	-244.6	kN	Min