(1)



**Selection Criteria**

| | |
|---|---|
| SetID | = "HSE01" |
| Site ID | = "4316742" |
| Site Name | |
| Category | |
| Specialty Type | |
| Service Type | |
| Start Date | |
| Notes | Yes |
| *Include Cases and SOs for the following:* | |
| Provider Group | |
| Staff Name | |
| Rating | Yes |
| Issues | Yes |

Version 3.2.0

**4316742**

**Company** 4316741 Gaia- Wind Ltd
**Site** 4316742 HQ/ Scotland/Gaia Wind Ltd

**Outstanding Invoices** No

**Site Address** Gaia Winds
100 High Craighall Road
GLASGOW
G4 9UD

**Role**
**Type** Fixed

**SIC** 43999 - SPECIALISED CONST NOT SCA

**Directorate** FOD

**Site Group** FOD Central Ops 4 Group 14

**Enclave Group 1**
**Enclave Group 2**

**Employees** Not Known

**National Lead Inspector**

**Telephone**
**Fax**
**Date Created** 21/02/2013
**Date Closed**

**IP Prepared** No
**EA Stakeholder**

**Local Authority** Glasgow UA

**Duty Type**

**V & A Marker** No

**Site Restrictions**

| | | |
|---|---|---|
| **COMAH Emergency Plans** | **Internal** | **External** |
| | **EP Prepared** | **EP Prepared** |
| | **Start Date** | **Start Date** |
| | **Last Test Date** | **Last Test Date** |

**Licences & Approvals** None

**Site Hazard Details**

**Site Hazards**

**Hazardous Substances Notified**

**Hazardous Processes**

Rating Details for Site 4316742

| Rating Type | Rating | Date |
|---|---|---|
| No Ratings for this site | | |

**Site Notes**

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**COMPANY DETAILS**

| | | | |
|---|---|---|---|
| **Company** | 4316741 Gaia- Wind Ltd | **Type** | Private Company |
| **Company Address** | Gaia Winds<br>100 High Craighall Road<br>GLASGOW<br>G4 9UD | **Group Code** | CENTOP4GRP14 |
| | | **Employees** | Not Known |
| | | **IP Prepared** | No |
| **Telephone** | | **Date Created** | 21/02/2013 |
| **Fax** | | **Date Closed** | |

**Company Notes**

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STANDALONE SERVICE ORDERS

| | | | | | |
|---|---|---|---|---|---|
| Service Order ID | SVC4260326 | **Date Created** | 21/02/2013 | **Status** | Complete |
| **Service** | Specialist Assistance | | | | |
| **Provider Group** | SG Mechanical - South | **Assigned To** | Grady,Paul | | |

Service Order Notes

**Summary** North Petherwyn
This SVC relates to North Petherwyn

Job 2: Failure of Gaia 11 kW small turbine at North Petherwyn, North Cornwall. Primary issue due to failure of the holding down bolts.

The scope of specialist support is limited to determine why the bolts failed. This will involve:

- Was there a deficiency in the concrete base, expected bolt strength, alignment.
- What mechanisms were in place to prevent the turbine from being able to overspeed
- Review of the Manufacturer's design to determine compliance with relevant Harmonised Standards. HSL support required.

If the design is found in compliance with relevant standard BS EN 61400-2 there may be a wider product-safety followup – to involve working with the Manufacturer (Glasgow) to review refinements in the design of the turbine components (i.e. bigger brake, bearings, blade interface).

HSE Contact – TBC HSE enforced site
Website: http://www.gaia-wind.com

---

**Summary** Specialist Note - Mechanical - D Nash
08/04/13 - made site visit to Gaia-Wind Ltd at their manufacturing premises in Glasgow. Met with Mr Johnnie Andringa, CEO, [redacted] R13

Discussed basic architecture of the Gaia-wind product(GW133- 11kW turbine), including design of base securing arrangement. Also discussed company findings relating to collapse of GW133 @ Winsdon Farm, North Petherwyn.

07/05/2013 site visit to Lindley Hall farm, Otley to inspect hardware following recent turbine collapse event. Met with [redacted] of Gaia-Wind.

Inspected failed flange, foundation rods and base. Discussed comparisons and similarities between other failures including the collapse at Winsdon Farm.

13/08/2013 Issued Specialist Investigation Report to tasking HM Principal Inspector of H&S, Mr Rob Pearce and HM Principal Specialist Inspector of H&S, Mr Paul Grady. Copy of report attached to COIN file and savec in TRIM 7.1.50 - 2013/0301307.

09/09/2013 Attended review of work on investigation into GW collapse incident at Winsdon Farm, north Petherwyn. Agreed minor changes needed to Specialist report and actions for me to follow up with GW.

12/09/2013 Issued final version of report (V2.0). Saved to Trim (2013/0338034). Sent a version of the report
R13 (v2.1) to [redacted] GW UK Plant Manager, with covering letter which details a number of questions that require answering to address the actions placed on me at the meeting on the 9th Sept. The version V2.1 sent to GW is based on V2.0 but with the recommendations in section 6 removed. Copies of V2.0 and the covering letter are attached.

02/10/2013 E-mail response to HSE letter(12-09-13) received, copy attached to notes. Service Order closed as task complete.

**Filename** Specialist_Report_-_Gaia_Wind_(V1.0).doc

**Description**

**Filename** Specialist_Report_-_Gaia_Wind__V2.pdf

**Description**

**Filename** Letter_120913DNL-001.doc

**Description**

**Filename** Gaia_Wind_response_to_your_letter_of_12th_September_2013.htm

**Description**

**Summary** Specialist note - Mechanical PSI
Review of work scope due to additional HSL request for design review in line with Standards. Timescale reviewed accordingly (draft HSL report identified for September 2013) therefore SG work to complete has been adjusted accordingly. P.Grady (PSI)

HSE
Awdurdod Gweithredol Iechyd a Diogelwch
Health and Safety Executive

(2)

Field Operations Directorate

**Darren Nash**
**HM Specialist Inspector (Mechanical)**

Specialist Group
4th floor, the Pithay
All Saints Street
Bristol
BS1 2ND

Tel: 0117 9886000
Fax: 0117 9262998
darren.nash@hse.gov.uk

http://www.hse.gov.uk/

Gaia-Wind Limited
100 High Craighall Road
Port Dundas
Glasgow
SCOTLAND
G4 9UD

Reference: 120913DNL-001

For the attention of [redacted] R13

Date 12th September 2013

Dear Sir

I am writing to inform you that I have now concluded my investigation into the Wind Turbine collapse incident, which occurred in early February 2013, involving a Gaia-Wind GW133 11kW Wind Turbine installed at [redacted] Devon.
redact - out of scope

The details of my investigation and findings are documented in my Investigation Report, a copy of version 2.1 of this report is enclosed for your information. Recommendations have been excluded from this version of my report.

My colleague, Mr Steven Simmons-Jacobs, Specialist Inspector of Health and Safety (Mechanical) is currently engaged in a broader review of Health and Safety in the Wind Turbine Industry. I have passed my report, including its recommendations to him for his consideration. Mr Simmons-Jacobs will issue a report on his findings and wider recommendations in due course. I will ensure that you receive a copy of this report.

During the course of the HSE's internal review of my work, a small number of issues requiring clarification and follow up action arose:

**1.** I understand that Gaia Wind offer the GW133 11 kW product with both an 18m Monopole Tower or Lattice Pylon and also a 27m Monopole Tower.

redact - out of scope

1.1. *Can you confirm that the [redacted] unit, together with the other four reported failures and the remaining sixty-eight Mk1 design Towers are all 18m Monopole types?*

1.2. *Can you confirm that the calculations passed by Gaia-Wind to Mr Chris Rudall of HSL for his review, relate only to assessment of an 18m Monopole Tower?*

1.3. *Can you clarify how Gaia-Wind have adapted their Tower designs and securing arrangements to accommodate the different Tower/Pylon configurations?*

**2.** During the course of my investigation, Gaia-Wind has presented to me the details of their survey programme used to focus remedial action towards Tower installations considered to be at greatest risk. This is understood to be currently targeting ten installations.

2.1. *Could you clarify how Gaia-Wind determined the risk rating of the installations and advise if and how the implications of the environmental effects of location, frequency of access and/or the nature and density of the surrounding population been factored into the assessments?*

The details of the Gaia-Wind Mk1 survey programme suggested that a full picture of the current status of the total Mk1 Tower community, along with proposals for future management, as agreed with the unit owners, should be completed by the end of September 2013.

To provide the HSE with a full understanding of Gaia-Winds management proposals and discuss any related issues, I would like to meet with the company at an appropriate point later this year. I would propose to use this review to also brief the company on the findings and recommendations from Mr Mr Simmons-Jacobs work. If you could notify me when your work is complete, I will follow up with some proposed meeting dates.

May I take this opportunity to express the thanks of my HSE and HSL colleagues and myself in the assistance and co-operation afforded to us by the staff at Gaia-Wind in this matter.

Yours faithfully

**Darren Nash**
**HM Specialist Inspector of Health and Safety (Mechanical)**

(3)

Reg 13

**From:** [redacted]
**Sent:** 02 October 2013 09:49
**To:** Darren Nash
**Subject:** Gaia Wind response to your letter of 12th September 2013

Hello Darren,

I have made the senior management team and the CEO aware of your letter and report. The answers to your questions are as follows:

× Description:
https://mail.gaia-wind.com/owa/attachment.ashx?id=RgAAAACBW0g3MLn3Q5dYmVpr3v4eBwDbQiBSFdRBTKdr1YBMi

Redact-out of scope

*I can confirm that the* [redacted] *installation, the four reported failures and the remaining 68 are all of the 18m monopole type.*

× Description:
https://mail.gaia-wind.com/owa/attachment.ashx?id=RgAAAACBW0g3MLn3Q5dYmVpr3v4eBwDbQiBSFdRBTKdr1YBMii1H

*Gaia Wind provided two documents to Mr Chris Rudall. The first was GWTD0014 – 18m Tube (Monopole) Mk2 Tower Design Assessment and the second GWTD0020 – The Design Loads for the Gaia Wind 133 11kW Turbine.*

× Description:
https://mail.gaia-wind.com/owa/attachment.ashx?id=RgAAAACBW0g3MLn3Q5dYmVpr3v4eBwDbQiBSFdRBTKdr1YBMii1H

*Gaia wind towers are designed in accordance with the simplified loading requirements of IEC 61400-2 and the structural requirements of Eurocode 3.*

× Description:
https://mail.gaia-wind.com/owa/attachment.ashx?id=RgAAAACBW0g3MLn3Q5dYmVpr3v4eBwDbQiBSFdRBTKdr1YBM

Redact-out of scope

*Gaia Wind's immediate response to the situation at* [redacted] *the four reported failings and the other sixty eight installations was to advise Myriad and the individual customer's concerned that all customer's with a Mk1 tube tower installation should be advised to put their machine on the brake until further investigations were carried out.*
*Our intention was to immediately reduce the risk of a failure until the investigations were carried out and completed thus reducing the risk of injury or damage to livestock or property.*
*After the investigations of each installation were completed Myriad and individual customers were advised that if any installation was found with a defective rod then they should put the machine on the brake until a solution was found. Machines found with a broken rod/s have had a Mk2 foundation and a bottom tower section upgraded to the Mk2 standard installed. Machines found with no defective rods are back in operation and have a regular inspection program of the foundation bolts.*

All of the sites that incurred failures have had the foundations and bottom tower sections supplied and installed with the exception of the last which had the materials delivered in the last two weeks and awaits the installer completing the installation work.

We are currently working on a ultrasonic testing procedure to test the foundation bolts on the 68 remaining Mk1 tube tower installations and when this has been completed we will contact you to arrange your visit to Gaia Wind in Glasgow.

I hope the answers we have provided to the questions are correct and if we have misunderstood the questions then please let me know.

Best Regards

[redacted] R13

Gaia-Wind
GENERATING BETTER VALUE

The Gaia-Wind 133 Turbine Now Available in Single Phase

Gaia-Wind Ltd, 100 High Craighall Road, Port Dundas, Glasgow, Scotland, UK, G4 9UD
Tel: +44 (0) 845 871 4242
Fax: +44 (0) 141 354 1001
www.gaia-wind.com

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5

sthomas3 | **Cases Report** | Date: 22/04/2016 Version 2.0.0

**Report Parameters:**

| | | | |
|---|---|---|---|
| Case ID | = "4317961" | | |
| Include Related Cases | = "Y" | Include Investigation Tracking | = "Y" |

**Master Case 4317961**

| | | | |
|---|---|---|---|
| **Company ID** | 4178193 | **Company Name** | Cornwall Council |
| **Site ID** | 4178194 | **Site Name** | HQ/Cornwall Council |
| **Date Created** | 07/03/2013 | **Status** | Closed-InvestComp |
| **Category** | Non-RIDDOR | **Assigned To** | Jones,Simon |
| **Type** | Related Inv | **Provider Group** | FOD Central Ops 4 Group 14 |
| **Detail** | N/A | | |
| **Problem Summary** | Bangor Wind Turbine | | |
| **Problem Description** | Bangor Wind Turbine<br>related to SVC 4260325 regarding specialist assistance. | | |

**Master Case Detail**

Incident Details

| | |
|---|---|
| **CC ID No.** | **Date Received/Reported** |
| **Notifier Name** | **Date of Incident** |
| **First Name** | **Time of Incident** |
| **Last Name** | **Reportable?** |
| **Sex** | **Mandatory Investigation** |
| **Age** | **Formal Enquiry** |
| **IP Status** | **Coroner's Verdict** |
| **Occupation** | |

Master Case Notes

| | | | |
|---|---|---|---|
| **Note Summary** | | **Date Note Added** | 13/03/2013 05:11:32 PM |
| Mechanical Engineering SG input | | | |
| **Note Details** | | | **Attachments** |

| | |
|---|---|
| W/E 10/3/13 Various discussions with Paul Grady and [redacted] about a couple of incidents where complete turbines have fallen over [redacted] and one for Gaia. Darren is going to investigate the two incidents and I am going to carry out a wider ranging investigation into the whole manufacturing system and the fitness for purpose of the BS EN 61400 suite of standards. | 4317961_SG_Mech_Gaia_Wind_Turbine_Bangors_Farm.pdf<br>4317961_SG_Mech_Gaia_report_conclusion.pdf |
| [redacted] | not relevant |

W/E 31/3/13 Darren has arranged for a Meeting with Gaia on Monday 8th April in Glasgow to be attended by Chris Ruddle, D and me.

Issues to be raised would be the narrow band of acceptable wind speed for turbine to work.

W/E 14/4/13 Darren Nash, Chris Rudall and I attended Gaia Wind's HQ on 8th April [redacted] R13

Looked over site after a sales pitch.

R13
[redacted] had purchased company from Danish owners. The original design met Danish certification body requirements but not MCS. In order to do so, the tower was redesigned to improve the base foundation. Approx 80 Gaia machines are in existence with Mark one tower. All current machines are going out with mark two tower.

Machines are quite efficient using single piece double blade with teetering mechanism. Blades are downwind of generator. Plant and QA is well controlled.

There have been four failures so far all with mark one towers and we were informed that there had been a new failure of the mark one tower in Otley, Yorkshire.

We met [redacted] who is charged with remedial work and were shown drawings of a new
R13

section of tower which would fit the middle section of the mark one tower and have a Mark two flange face for the base. This forms their proposal to repair all eighty towers over a period of time. Ther are ten which have been inspected and found to have more than three broken studs. These are down for urgent remedial work.

Ther are three which have not been inspected yet and we will be given info on their whereabouts to see if we can assist.

Some of the failures are down to an installation problem where in polyurethane foam has been used internally under the flange face of the tower before some grouting has been used around the outside. This could warrant some attention from ourselves. I have spoken to Paul about possible actions over these issues.

Darren and I may go to the Otley site to inspect the failed machine.

W/E 21/4/13 I have tried to contact [redacted] R13 to keep him informed of what D & I are doing. We are confirmed as visiting the Otley site on 7th May [redacted] not relevant

[redacted] not relevant

[redacted] not relevant

W/E 12/5/13 Tuesday 7th May, visited Lindley Hall Farm to look at the toppled Gaia wind turbine. Met [redacted] R13 of Gaia. All studs broken at the underneath nut, some showing signs of beaching, which is indicative of fatigue stress failure. Grout was not structural type and in areas the installer had used a PU foam. Cracking was observed at points where foam was at its largest.

[redacted]

R13 not relevant

[redacted] not relevant

I was made aware by Gaia of a failure with a C&F turbine in Aberdeen [redacted] not relevant

[redacted]

R12(5)(b)

R12(5)(b)

W/E 22/9/13 Visited the Bangor's Farm installation. Confirmed the pylon is the mark 2 version.
I also confirmed that the pylon flange is resting on a complete set of nuts positioned on each stud and that the nuts above the flange have been tightened to the specified torque.
The grouting has been poured to a larger diameter than the pylon flange and this has been moulded around the flange diameter to lay flush with the top of the flange. As a consequence it was not possible to see the interface between flange and grout so I could not determine if a gap was growing.
As far as I could see on the day, the installation was perfectly fine.

[redacted] not relevant

R12(5)(b)

W/E 27/1/14 Visited Gaia-Wind Power with Peter Dodd. We met [redacted] R13 I passed over my conclusions and recommendations following my investigation of the Bangors Farm installation.

We discussed the need for Gaia to have some system for becoming aware of any planning restriction or other problem specific to a site which might impact on the working of the turbine and require increased inspection or maintanence. It was felt this could best be done through the handbook.

I stressed that we were not convinced that Gaia had done enough work to prove that the mark 2 monopole pylon flange foundation was capable of withstanding the various fatigue stresses that were present in their machine.

I discussed the need to comply with the SMSR 2008 regs and the need for a technical file that showed all the potential risks had been considered and dealt with and that all the ESHR's had been met. I explained that the main one most people fail to meet properly is the requirement for full instructions. This would be a good place for the installers to be made aware that they need to inform Gaia of any site issues.

We discussed the need for the grout to be (a) structural (b) larger diameter than the pylon flange and (c) level with the top of the pylon flange.

Gaia admitted there were still eight mark one pylons in existence in the UK.

[redacted] not relevant

Finally I explained that my full report would be available by FOI after the Cornwall Office close the case.

Gaia asked if they could see Darren Nash's report into the failer at Lindley Hall Farm, Otley and Chris Ruddall's report as well.

Service Orders Related to Master Case 4317961

| | | | |
|---|---|---|---|
| **SO ID** | SVC4260325 | **Provider Group** | SG Mechanical - South |
| **Date Created** | 21/02/2013 | **Assigned To** | Grady,Paul |
| **Start Date** | 21/02/2013 | **Service Type** | Assessment |
| **Status** | Complete | **Service** | Specialist Assistance |

**Note Summary** | **Date Note Added** 21/02/2013 10:02:41

Bangor turbine

**Note Description** | **Attachments**

This SVC related to bangor turbine.

Job 3: Response to public concerns over the general safety of Gaia 11 kW small turbine at Bangors Farm, Poundstock, Nr Bude Cornwall.

The scope of specialist support is limited to
- Does the Gaia turbine meet the criteria of Hamonised Standard BS EN 61400-2 (established upon completion of Job 2)
- Are there engineering refinements to improve the mechanical integrity of the components forming the turbines
- Are there wider recommendations to minimise overspeed of the turbines (by automating the monitoring and shutdown process – see PAG report 2407)

HSE must clarify that its remit does not include response to anecdotal references to problems with other wind turbines. Where there are recommendations for technological improvements beyond compliance with the harmonised standard, these are advisory. Separate work is being undertaken by HSE as part of a wider review of standards for small wind turbines.

HSE Contact – TBC
LA contact: [redacted] Complaint by public to LA R13
Website: www.gaia-wind.com

---

**Note Summary** | **Date Note Added** 16/08/2013 16:51:40

Specialist note - Mechanical PSI

**Note Description** | **Attachments**

Review of work scope due to additional HSL requests for design review of various turbines in line with Standards. Timescale reviewed accordingly (draft HSL report identified for September 2013) therefore SG work to complete has been adjusted accordingly. P.Grady (PSI)

(6)

**RESTRICTED**

**INCIDENT REPORT NUMBER: ES/13/54**

Harpur Hill, Buxton
Derbyshire, SK17 9JN
T: +44 (0)1298 218000
F: +44 (0)1298 218590
W: www.hsl.gov.uk

HEALTH & SAFETY LABORATORY

# Design Assessment for the Gaia-Wind 11kW Wind Turbine

**ES/13/54**

Author: **C J Rudall BSc(Hons) CEng MIMechE**
Science Unit: **Engineering and Personal Safety Unit**

# DISTRIBUTION

| | |
|---|---|
| Mr P Grady | HSE Principal Specialist Inspector (Mechanical Engineering) |
| Mr D Nash | HSE Specialist Inspector (Mechanical Engineering) |
| Mr C Simmons-Jacobs | HSE Specialist Inspector (Mechanical Engineering) |
| Dr W Arnold | HSE Principle Specialist Inspector (Mechanical Enginering) |
| Mr P Dodd | HSE Specialist Inspector (Mechanical Engineering) |
| Dr A Curran | HSL Director of Science and Resources |
| Dr P Bridges | HSL Head of Operations |
| Dr N Corlett | Acting Head, Engineering and Personal Safety Unit |
| Mr R Isherwood | HSL Engineering Technical Lead |

HSL Registry File
HSL LIS

## INCIDENT REPORT

### PRIVACY MARKING:

Not to be communicated outside HSE without the approval of the Authorising Officer
**Mr P Grady**



| | |
|---|---|
| HSL report approval: | **Dr N Corlett** |
| Date of issue: | **6 September 2013** |
| Job number: | **PH04834** |
| Registry file: | **032654** |
| Electronic file name: | **K:\mecheng\WORK\HSE\Reactive\Incidents\Inc2013\PH04834 Gaia 11 kW Wind Turbine Failure\Report\Gaia Final Report 6Sept13.pdf** |

# CONTENTS

# EXECUTIVE SUMMARY

## Objectives

Between Dec 2011 and April 2013 five Gaia-Wind 11kW wind turbines have collapsed in the UK. Each of the failed turbines had what is identified as a 1st generation tubular tower and they all failed at the threaded rods to which the base flange was attached. Following the fourth collapse (at North Petherwyn, Cornwall in Jan 2013) I was requested by Mr Paul Grady (HM Principal Specialist Inspector (Mechanical Engineering)) to provide technical support in investigating the Gaia failures as follows:

1. Inspect and analyse the current Gaia small turbine design, in order to highlight limitations of the constructed assembly.
2. Provide scientific support to identify deficiency in the concrete base, expected bolt strength, alignment.
3. Identify what mechanisms were in place to prevent the turbine from being able to overspeed
4. Review the manufacturer's design to determine compliance with relevant Harmonised Standards
5. Provide support to the HSE Specialist in assessing if proposals for remedy by the Company are targeted
6. To feed back recommendations from this case to improving standards for future small wind turbines.

## Main Findings

In my opinion the primary cause of failure was uncontrolled fatigue loading acting on the threaded foundation rods.

The provision for braking and overspeed detection and control is adequate and conforms to the requirements of BS EN 61400-2:2006.

The design load calculations are generally in line with the BS EN 61400-2:2006 Simplified Load Model and Gaia, in my opinion, have given a reasonable justification for deviations from the model requirements.

The overall conclusion from the metallurgical reports (carried out for Gaia by [redacted] R12(5)(e) on three sets of failed foundation rods was that failure was due to fatigue. A visual inspection on site at the most recent failure (Lindley Hall Farm, Otley) indicated that these rods failed at the same location beneath the adjusting nuts.

Whilst the 2nd generation tower design is substantially stronger at the base, the foundation rods remain, in my opinion, susceptible to fatigue.

A check on the natural frequencies of the 1st and 2nd generation tower designs indicated that both are within the required frequency range as defined by Gaia.

## Recommendations

1) That Gaia should be encouraged to improve the fatigue design of the tower bottom connection, for example by preloading the threaded foundation rods as described in their report [redacted] R12(5)(e)

2) That the quality and consistency of the heat treatment and galvanising of the threaded rods should be carefully monitored.

**INCIDENT REPORT NUMBER: ES/13/54**

# 1 INTRODUCTION

Following the collapse of a Gaia-Wind 11 kW wind turbine at North Petherwyn, Cornwall on 30 January 2013, I was requested by Mr Paul Grady (HM Principal Specialist Inspector (Mechanical Engineering)) to provide the following technical support in investigating the failure:

1) Inspect and analyse the current Gaia small turbine design, in order to highlight limitations of the constructed assembly.
2) Provide scientific support to identify deficiency in the concrete base, expected bolt strength, alignment.
3) Identify what mechanisms were in place to prevent the turbine from being able to overspeed
4) Review the manufacturer's design to determine compliance with relevant Harmonised Standards
5) Provide support to the HSE Specialist in assessing if proposals for remedy by the Company are targeted
6) To feed back recommendations from this case to improving standards for future small wind turbines.

On 8 April 2013, together with Mr Darren Nash and Mr Steve Simmons-Jacobs (both HSE Mechanical Engineering Specialist Inspectors), I attended a meeting at the office of Gaia-Wind Ltd in Glasgow. Representing Gaia were Mr Johnnie Andringa (CEO); [redacted] At the meeting Mr Andringa reported that the Cornwall turbine was the fourth to collapse since December 2011, and that a fifth turbine had collapsed in West Yorkshire on 5 April 2013. Each of the failed turbines had what is identified as a $1^{st}$ generation tubular tower and they all failed at the threaded rods to which the base flange is attached. R13

On 7 May 2013 Mr Nash, Mr Simmons-Jacobs and I visited the most recent failure site at Lindley Hall Farm near Otley, West Yorkshire. The site appeared to be largely undisturbed and provided a useful insight into the tower base configuration and the mode of failure. We were accompanied on that occasion by [redacted] Gaia-Wind). R13

I have since reviewed documentation supplied by Gaia-Wind covering the Tower Design[1] and Design Loads for the 11 kW turbine[2]. Gaia-Wind have also provided metallurgical investigation reports on three sets of failed rods, which they commissioned from [redacted][4][5]. R12(5)(e)

This report gives some background history of the company, as described at the meeting on 8 April 2013, and a brief description of the turbine. The design loads acting on the turbine are then considered in relation to the relevant standard, BS EN 61400-2:2006 [6] and the effect of the loads on the threaded rods supporting the tower is assessed. The mode of failure of the threaded rods, and possible underlying causes are then discussed. Appendix A is a check on the design loads calculated by Gaia according to BS EN 61400-2:2006. Appendix B gives calculations for the loads acting on the threaded rods. In Appendix C (and paragraph 3.6) the natural frequencies of the turbine structure are considered with reference to the rotor and blade-pass forcing frequencies.

During the visit to the Lindley Hall Farm turbine, I removed two samples of grout from the tower foundation. I placed these in separate evidence bags and on returning to the Health and Safety Laboratory (HSL) I assigned unique numbers (10612 and 10613) on HSL's Sample Management Database.

The photograph of the Gaia-Wind 11kW turbine (Figure 1) is reproduced from Gaia-Wind's website.

The photographs of the Lindley Hall Farm Turbine failure (Figures 3, 4 and 5) were taken by the author.

The calculations (Appendices A, B and C) have been reviewed by Mr R Isherwood (HSL Engineering Technical Lead).

## 1.1 COMPANY HISTORY

The following information was provided by Gaia at the meeting at their office on 8 April 2013.

The company was originally Danish (established in 1993) and built around 100 units. In 2000 a Conservative government took over in Denmark. It was unfavourable towards wind energy and the market shrank as a result. Mr Andringa took over the company in 2006, and realising there was a favourable market in UK, he moved the office and manufacturing facility to Glasgow in 2011. 122 turbines were built in 2010 and 280 in 2012. [redacted] 80% of sales are in the UK, the rest being mainly in the US, Italy and Denmark. There is also interest in island communities such as Tonga. As the Feed-in Tariff (FIT) for wind reduces, Gaia plan to improve efficiency and reduce costs. They are also hoping to enter growing markets such as Brazil and the Philippines. The 133-11kW turbine is Gaia's only model. They now have approx. 800 turbines installed and operating.

R13
R12(5)(e)

## 1.2 BRIEF DESCRIPTION OF THE TURBINE DESIGN

The Gaia-Wind 133-11kW turbine is a 2-bladed, downwind machine with passive yaw (Figure 1). The design has a teetering hub (derived from "teeter-totter", a US term for a seesaw, i.e. a rigid beam that can tilt on a fulcrum at its centre). Hence the two blades are a single (glass-fibre) item, hinged at the hub to allow tilting away from the vertical plane. This reduces differential wind loads caused by the blades passing behind the tower, and boundary layer wind shear. The teetering is controlled by two pairs of springs and rubber buffers if the teetering angle becomes too great. Compared with its competitors of similar power rating, the Gaia unit has a large diameter (13 m with a swept area of 133 m$^2$). This is claimed to make it more efficient at lower wind speeds. The nominal rotation speed is 56 rpm. The design is optimised for a moderate wind regime, equating to BS EN 61400-2 Class III ($V_{ref}$=37.5 m/s; $V_{ave}$=7.5 m/s).

The rotor shaft is supported at the rotor end by a self-aligning bearing, which also accommodates axial thrust. The rotor shaft is inserted into the keyed hollow input shaft of the 2-stage gearbox. The gearbox has an 18:1 ratio and steps-up the speed to a nominal 1000 rpm. A vehicle-type disc brake is on the gearbox output shaft which is then coupled to an asynchronous induction generator.

Gaia supply lattice or tubular towers according to customer preference. In both cases the foundation is a 5 m x 5 m x 0.5 m concrete slab. A steel reinforcing framework for the foundation is supplied as a kit. Grade 8.8 galvanised threaded steel rods emerge from the concrete and these are bolted to a flange at the tower base (Figure 2). The tower is levelled by adjusting a nut beneath the flange on each of the threaded rods. As a result of this installation method the threaded rods are not preloaded beneath the levelling nuts. Grout is applied between the flange and the foundation.

[redacted] All R12(5)(e) components come together at Glasgow, with the exception of the tower, which will usually go straight to site. Manufacturing at the Glasgow facility is then limited to nacelle assembly and testing. Final assembly is on site.

There are 3 levels of system protection. The base level is passive blade stall which limits power output. The second level is the fail-safe electro-mechanical disc brake which is activated by the control system. There are trips for wind in excess of 25 m/s (anemometer), abnormal vibration, disconnected grid, overheating generator or twisted cable in tower. The third level is the centrifugally (i.e. speed) activated aerodynamic brakes built into the rotor tips. If either tip brake is activated it will slow down the turbine. Because activation of a tip brake implies a failure elsewhere (e.g. a broken anemometer or worn brake pads), it must be reset manually. A proximity sensor allows the blades to be parked horizontally using the disc brake. Some operational data is stored on site via the control system, and Gaia are in the process of introducing on-line monitoring, including error messages.

Gaia use web data to determine wind speed at each new site location, together with their own data drawn from experience with their existing turbines. They also visit the location to check its suitability, taking into account ground slope, proximity of trees and buildings. They may also carry out anemometer tests at a site. Occasionally, if they feel a location is unsuitable, they will refuse to supply a turbine. Customers are typically farmers, country homes and rural businesses.

In Scotland Gaia have usually sold directly to a re-seller who would be responsible for erection and commissioning, but in England until 2012 they used a distributor who would supply the re-seller. Their main distributor was Myriad, but that relationship has come to an end. Gaia are now selling directly to re-sellers in both Scotland and England. Gaia insist that all installers attend a (free) course run be one of their experienced technicians.

Gaia inspect all new turbines 3 months after commissioning. Thereafter an annual inspection by the installer is required to keep the 5 year warranty valid.

# 2 DESIGN TO BS EN 61400-2

## 2.1 THE SIMPLIFIED LOAD MODEL

The design standard for small wind turbines, BS EN 61400-2:2006[6], is currently under review. According to TUV NEL Ltd[7], Edition 3 of EN 61400-2 is due for release in 2013. As of 18 July 2013, according to the British Standards Online website, BS EN 61400-2:2006 remained the current edition.

The Simplified Load Model (SLM) was first introduced into IEC 1400-2:1996[8] and has evolved since then as part of BS EN 61400-2. Alongside aeroelastic modelling and physical testing, it represents an important method of assessing the design adequacy of small wind turbines. Field testing on several turbine designs has been carried out to verify the SLM loads, and various recommendations have been introduced to improve its reliability as a design tool[7]. There remain, however, concerns within the industry about aspects of the Simplified Load Model, in particular with reference to fatigue. Unfortunately, although these concerns are being addressed within the industry, any outcome will be too late to be included in Edition 3 of BS EN 61400-2. From Section 5.2 of the TUV NEL report: "*It is expected that the third edition will be published in 2013 with several significant amendments, however, the simplified load model remains unchanged.*" [7]

## 2.2 REVIEW OF THE GAIA SLM CALCULATIONS

The Gaia design has Danish type certification and also Microgeneration Certification Scheme (MCS) certification. The MCS design certification was carried out by TUV NEL using the SLM. I have checked Gaia's own design load calculations[2] also using the SLM (Appendix A) and apart from the following exceptions, found them to be in accordance with the standard.

### 2.2.1 Teetering hub

Gaia acknowledge that use of the SLM is incorrect according to BS EN 61400-2:2006 due to the teetering hub design. Quoting Clause 7.4.1 of the standard:

"*For certain turbine configurations, the loads can be derived using simple, conservative equations for a limited set of load cases... If the turbine configuration does not meet these configuration requirements, the simple equations cannot be used, instead the alternative aeroelastic modelling or load measurements shall be used.*

*The turbine configurations that are able to use the simple equations shall meet all of the following requirements:*

- *Horizontal axis;*
- *2 or more bladed propeller-type rotor;*
- *Cantilever blades; and*
- *Rigid hub (not teetering or hinged hub).*"

This was discussed at the meeting in Glasgow on 8 April 2013. Gaia's defence is that the teetering hub will reduce the bending moments acting on the rotor shaft, which I believe to be true. They also have their operational experience and, more recently, an aerodynamic analysis (via links with Glasgow University). In addition they now have an aerodynamicist in-house. Overall they are confident with their design, and have had no major problems with the hub and nacelle machinery.

### 2.2.2 Yawing rate

Gaia have reduced the yawing rate based on field measurements . This is described in Chapter 6 of their Design Load Report,[2]. In Clause 4.3 of the report they comment:

*"The yaw rate according to IEC* (i.e. BS EN 61400-2) *is ...over a factor of 4 above the yaw rate that has been previously used and has been confirm*ed *by measurements.*

*For these design loads a value of twice the measured yaw rate (or roughly half the IEC yaw rate) will be used."*

In view of the fact that Gaia report no problems other than with the threaded foundation rods, this pragmatic approach is, in my opinion, acceptable.

# 3 TOWER DESIGN

## 3.1 TOWER DESIGN BACKGROUND

Each of the failed turbines had what is identified as a 1$^{st}$ generation tubular tower. These towers are to a 2006 Danish design and about 80 were built. When the MCS scheme was introduced in 2010 Gaia realised higher load and safety factors would be required for the towers and that a redesign would be necessary. To meet these requirements the 2$^{nd}$ generation tower design was commenced in 2010 and entered production at the start of 2011. Quoting from the [redacted] R.2(5)(e)

*"It is noted the redesign was not started based on concerns about structural integrity of* (the) *FirstGen Tube tower. Prior to the failure in Dec 2011 (by which time the redesign had already been completed), no structural failures in First Gen tube towers had occurred."*

In late 2010 a new tube design was introduced and MCS certification was granted by TUVNEL in Jan 2011. Gaia began using these second generation towers in Feb/Mar 2011 and have had no problems with them. These towers are more substantially built, particularly at the bottom flange, and have an increased tube diameter at the base. They also use 24 x M30 threaded rods at the base whereas the 1$^{st}$ generation towers used 16 x M27 threaded rods.

## 3.2 TOWER FAILURES

The locations of the five tower failures were:

| | |
|---|---|
| Huddersfield | Dec 2011 |
| Masscliff /Stowmarket | Dec 2012 |
| Peters/Perthshire | Dec 2012 |
| North Petherwyn, Cornwall | Jan 2013 |
| Otley, West Yorkshire | Apr 2013 |

Gaia have identified various faults associated with the failed 1$^{st}$ generation design. All the five towers had failed at the threaded rods. Reports on two of the sets of failed rods examined by [redacted] indicated that the rods had probably not been galvanised correctly, and decarburisation had occurred up to a depth of about 150µm on some of the rolled threads [3],[5]. This was discussed at the meeting on 8 April 2013, in particular whether galvanising of rolled threads was likely to cause decarburisation. I have since raised this briefly with Dr Steve Joel and Dr Liz Geary (both of the Engineering Materials Team, Engineering and Personal Safety Unit, HSL). They have not examined examples of the failed rods, but commented in general terms that decarburisation can occur prior to galvanising, as a result of heat treatment following thread formation. They agreed that decarburising can lower the crack initiation stress for fatigue, but they also pointed out that rolled threads are in surface compression at the root which will improve fatigue resistance.

At least two of the failed towers were found to have been inadequately grouted by the same installer. The installer had injected a foam filler around the inside of the base connections, probably to retain the inner formwork while the grout was setting. However the foam had filled some of the volume that should have contained grout. This would have altered the load distribution around the bottom flange.

On 7 May 2013 I visited the site of the most recent tower failure at Lindley Hall Farm near Otley, West Yorkshire, with Mr Darren Nash and Mr Steve Simmons-Jacobs. The grouting on this turbine was also found to have been partially displaced by foam (Figures 3 and 4). The foam may have been used to help retain the inner grout former, but it had also partially filled the volume beneath the bottom flange that should have contained only grout. All the rods had failed immediately beneath the lower (levelling) nut (i.e. the nut on the underside of the flange). Figure 5 shows a typical failed rod.

Gaia indicated that there were possible siting problems at the failure sites, with nearby trees and steep slopes, causing high turbulence and wind shear. They also pointed out that the 50 year extreme gust on which BS EN 61400-2 is based, was exceeded on two occasions during the winter of 2011/12. In the case of the Otley failure, the turbine had been subject to several weeks of strong northerly wind, and Gaia reported that their records indicated a peak wind speed of 46 m/s at the time of the incident.

All but four of the remaining (approximately) 80 1st generation towers had been inspected at the time of the 8 April 2013 meeting. Ten out of the 80 were found to have one or two broken rods. One of the towers had ten broken rods. The tower that failed in Cornwall was known to have five broken rods before it fell. The turbine that failed on 5th April 2013 was one of the four that had not been inspected. Gaia advised the remaining three customers to put their turbines on brake until the re-seller had inspected them.

Gaia are now in the process of developing an upgrade for the turbines that have the 1st generation tube towers. At the time of our meeting on 8 April 2013, the upgrade was to involve a new tower bottom section, and cutting out and replacing the 16 x M27 threaded rods with 24 x M30 rods. The rods were to be anchored to the foundations by a combination of bolting to an encast plate, and using a specially developed epoxy to fix the lower parts of the rods into holes drilled into the concrete. Gaia's [redacted]xplained the proposal in some detail. However according t[redacted] subsequent trials have indicated that the complexity of the alterations suggests that a completely new foundation may be a better option.

R13

## 3.3 METALLURGICAL REPORTS ON THE FAILED THREADED RODS

At Gaia's request, [redacted] carried out metallurgical assessments on three sets of failed rods(3)(4)(5).

R12(5)(e)

**Report No. F-12-004**

This report considers the failure of nine threaded bars (i.e. rods) and the column/flange weld from the failed tower of a Gaia wind turbine. These components were from one of the first generation towers which used 16 x M27 rods equispaced around the base flange. Quoting from the report summary:

"*...the threaded bars which held the bottom flange of the tower had failed by a fatigue mechanism. The tower itself had ultimately failed through the bottom column at the flange/column weld. Evidence of a fatigue mechanism was again found.*

*Analysis of the relative proportions of slow crack growth and final fracture regions on the fracture surface indicated that the threaded bars had failed under the action of a relatively low*

---

[a] *Comment made at Lindley Hall Farm, 7 May 2012.*

*stress whereas the failure of the column/flange weld had been subject to a relatively large stress.*

*It is thought most likely that initial failure had occurred through the threaded bars. This led to a redistribution of stresses that subsequently produced fatigue and final failure of the column. This sequence of failure is supported by the extreme plastic distortion exhibited by the flange indicating that the flange was free from the retaining effect of the threaded bars prior to final failure."*

The materials were as specified (column: Q235, rods: Grade 8.8) and no microstructural abnormalities were found in the flange.

R.12(5)(e)

[redacted] are non-committal about the effect of incorrect grouting:

*"The Client has reported that there is evidence of the tower not having been correctly grouted into its foundation. Although it is not possible to be certain with regard to any detrimental effect incorrect grouting would have had on the service stresses experienced by the tower, the possibility that incorrect grouting may have led to conditions favourable for fatigue cannot be dismissed. However a further analysis by a specialist, such as a civil or structural engineer, may be required to establish the effect of incorrect grouting."*

Regarding corrosion treatment:

*"The bolts and flange exhibited a dull grey coating which was consistent with them having been supplied in a galvanised condition."*

The fractures are described as follows:

*"The fracture of the column followed a line along the weld toe on the column side of the column/flange weld. At one location the fracture was flat, extending through the entire cross section over a length of approximately 150 mm. Faint beach marks and ratchet marks were apparent on the fracture surface.... giving a clear indication of a fatigue fracture with multiple crack origins. Additionally, the ratchet marks indicated that a fatigue had initiated at the outer circumferential weld toe."*

*"The bars were all noted to have fractured with a flat transverse fracture surface in line with the bottom surface of the securing nuts. The flat fracture covered almost the entire cross section of the bar (approximately 90%) with a shear lip... Oxide was present on the fracture surfaces... However two bolts... did show evidence of beach markings, a clear indication of fatigue fracture...*

*In both cases fracture had initiated at the thread root and had progressed by fatigue across almost the entire cross section before final failure as indicated by the presence of a shear lip."*

**Report No. F-12-009**

This report considers a set of 16 threaded bars from the base of a Gaia wind turbine tower, nine of which had failed by fatigue. In this instance, the tower did not collapse.

The fractures are described as follows: *"The fracture surfaces were mainly flat and perpendicular to the bar* (i.e. threaded rod) *axis... on those bars where detail was apparent there was evidence of beach marks and ratchet marks indicative of a failure by a fatigue mechanism.... ...failure had initiated at the thread root and... there had been multiple initiation sites which later merged into a single crack front as failure progressed."*

Regarding the probable stress levels:

*"The relative proportions of slow crack growth and rapid final fracture surfaces are an indicator of the nominal service stress. In this case the large slow crack growth proportion of the fracture surface implied that a relatively low nominal stress had been experienced."*

Regarding corrosion treatment, the thickness of the decarburisation layer was measured on three bars and found to be greater than the specified maximum of 15 µm. The bars were believed to have been hot dip galvanised. Hardness and chemical composition complied with the specification.

**Report No. F-13-001**
This report considers eight fractured threaded bars which formed part of a set of 16 failed bars from the base of a collapsed Gaia wind turbine tower.

*"Failure had occurred at the same location on each of the failed bars, approximately 145 mm from the end of the bar, at the edge of the nut..."*

*"In this case, the large slow crack growth proportion of the fracture surface implied that a relatively low nominal stress had been experienced."*

As with the rods examined in the other two [redacted] reports, there was evidence of beach marks and ratchet marks indicative of failure by a fatigue mechanism.

Regarding corrosion treatment:

*"The coating exhibited a columnar structure, typical of that produced by a hot dipped galvanising process. The coating is relatively thick and also contains a lot of cracks through the thickness."*

*"The decarburisation layer measured varied from 100-170 µm."*

*"The decarburised layer on the bars examined was greater in depth than that permitted by the specification by up to a factor of 10. The hardness in this layer was approximately 30-40HV below that of the bulk, but was still within the specified range."*

[redacted] conclude:

*"Decarburisation and hot dip galvanising on a threaded bar are quoted as reducing fatigue resistance with a sliding scale of risk. High stress concentration in combination with these two factors has resulted in failure."*

The overall conclusion from the three [redacted] reports is that the rods failed in fatigue.

R12(5)(e)

## 3.4 BOTTOM FLANGE HEIGHT ADJUSTMENT

R13

During the Lindley Hall Farm site visit, Mr [redacted] commented that the turbine is run for 2-3 months before the grout is inserted. This is also stated clearly on page 33 of the Gaia-Wind 18m Tubular Tower Foundation Guide[10]: "*The pouring of grout beneath the bottom flange is carried out at the three month servicing of turbines with a tubular tower only.*" This raised the question of the structural significance of the grout. If the tower is designed to sit on the threaded rods without additional support, the fact that foam was used may not be so relevant.

R12(5)(e)

Gaia have since provided the grout specification: [redacted] which is suitable for anchoring of reinforcing steel bars. The compressive strength is $\geq$45 MPa. In other words they are specifying a structural grout, but the load is transferred mainly through the threaded rods (and entirely for the first three months of operation).

The Foundation Guide[10] is for the assembly of the 18 m version of the second generation tower design, which uses 24 x M30 threaded rods at the tower base. All of the reported failed towers were to the first generation design which has 16 x M27 threaded rods. However whilst changes have been made to the number and size of the threaded rods, and to the size of the bottom flange, the installation method is largely unchanged from the first generation tower.

According to page 26 of the Foundation Guide[10], the M30 threaded rods are set to a height of 160 mm above the chamber ring (i.e. the outer ring of the exposed concrete foundation). The nuts that will eventually support the tower base flange are adjusted to 100 mm below the top of the threaded bar (page 25 of the Foundation Guide). This places the underside of the tower base flange 60 mm above the concrete foundation Referring to BS 3692:2001[11], an M30 nut is 24 mm thick, and the exposed length of thread between the concrete foundation and the underside of the lower nut is then 60 – 24 = 36 mm. This is a nominal figure since some final adjustment of the nuts may be necessary to level the tower flange.

Assuming that the first generation tower design had the same set-up of the tower base flange relative to the chamber ring, the exposed length of M27 threaded bar would then be 60 – 22 = 38 mm. This is consistent with the Gaia tower design assessment [1] which gives the unsupported length range as 35 – 50 mm.

Two grout samples were retrieved from the Lindley Hall Farm site. These have been assigned unique numbers from the HSL Sample Management Database. The approximate vertical thickness of these samples is as follows:

| | |
|---|---|
| HSL Sample No. 10612 | 80 mm |
| HSL Sample No. 10613 | 85 mm |

The length of threaded rod between the foundation and the underside of the levelling nuts is then:

| | |
|---|---|
| HSL Sample No. 10612 | 80 – 22 = 58 mm |
| HSL Sample No. 10613 | 85 – 22 = 63 mm |

Hence the samples from the Lindley Hall Farm turbine indicate a larger gap between the foundation and the levelling nuts than is indicated in the Gaia tower design assessment[1].

## 3.5 LOADS ACTING ON THE THREADED RODS

Gaia's tower calculations[1] consider flange flexing, and fatigue in the threaded rods.

I have applied the loads derived from the BS EN 61400-2:2006[6] Simplified Load Model to the threaded rods (Appendix B). The calculations indicate that the rods on both the 1st and 2nd generation towers are adequate for the maximum load condition (SLM, Load Case D – Maximum thrust).

The 1st generation tower rods are shown to be inadequate for fatigue when assessed using BS EN 1993-1-9:2005[12]. The calculations indicate that the 2nd generation tower rods may also be susceptible to fatigue within the design life of the turbine.

## 3.6 TOWER NATURAL FREQUENCY

It is unclear from the tower design assessment[1] if it takes account of the stiffness of the threaded rods when calculating the tower natural frequency. The frequency calculations on pages 44 and 45 of the assessment appear to treat the towers as built-in at the bottom flange. Since tower resonance could potentially produce high fatigue loads, I decided to check Gaia's frequencies. I used the Ansys finite element software[15] to carry out modal analyses of simplified models of the 1st and 2nd generation tower designs (see Appendix C).

[redacted] Reg 12(5)(e)

The Ansys results are broadly in agreement with the Gaia calculations and indicate that both the 1st and 2nd generation towers remain within the required frequency range.

# 4 ASSESSMENT

The provision for braking and overspeed detection and control is, in my opinion, adequate and conforms to the requirements of BS EN 61400-2:2006.

The design load calculations are generally in line with the BS EN 61400-2:2006 Simplified Load Model. Gaia have, in my opinion, given a reasonable justification for use of the model despite the teetering hub design. They have also justified using reduced yaw loading by quoting field measurements. Use of full scale load measurements is, according to BS EN 61400-2:2006, an alternative acceptable design method. However the standard also states in the context of the maximum yaw rate (Clause 9.2.3): "*Measured values cannot be used in the simple load calculations.*" but does not elaborate on the reason for this stipulation. For design purposes Gaia have used a value of twice their measured yaw rate, or approximately half the value required by the standard. Taking account of the turbine configuration (downwind and with a relatively slow operating speed) and Gaia's experience with this configuration, I am inclined to regard their approach as a reasonable compromise.

The overall conclusion from the metallurgical reports on three sets of failed foundation rods was that failure was due to fatigue. Failure was typically through a horizontal section of the threaded rods immediately beneath the adjusting nuts (Figure 2). A visual inspection on site at the most recent failure (Lindley Hall Farm, Otley) indicated that these rods failed at the same location beneath the adjusting nuts.

Gaia have proposed various reasons why fatigue should have developed in the threaded rods on the 1st generation design:

**Decarburisation of the rod material.** Decarburisation was reported by [redacted] on two sets of failed rods. This can cause a reduction of the crack initiation stress for fatigue.

**Inadequate grouting.** At least two of the first four failed towers were found to have been inadequately grouted by the same installer. The installer had injected a foam filler around the inside of the base connections and this had filled some of the volume that should have contained grout. There was also evidence of the use of foam at the Lindley Hall Farm site. In Gaia's opinion, this would have altered the load distribution around the bottom flange.

**Siting problems.** Although it is Gaia's policy to visit locations prior to installation, they have indicated that nearby trees and steep slopes may have caused high turbulence and wind shear at the failure sites. Severe wind conditions may also have contributed to the failures.

**Limited margin for error in the 1st generation towers.** Quoting from the [redacted] R12(5)(e)
"*The FirstGen tube towers have a lower safety factor than the SecondGen tube towers as currently used. This low safety factor makes it imperative that all further factors impacting structural integrity should be (as close to) perfect. The integrity of the rods might be compromised whenever there is a discrepancy in: material quality, wind speeds and turbulence on a specific site, quality of finishing of rods, foundation and undergrouting quality, torqueing of the nuts, installation quality, service and inspection, etc.*"

Whilst all or some of the above factors may have influenced the failures, in my opinion the main reason for the very poor fatigue performance is the lack of preload in the threaded rods which allowed them to be subjected to cyclic loading. Gaia are aware of this aspect of the design, and comment in their report entitled [redacted] Reg 12(5)(e) "*Putting the turbines back into unrestricted operation is subject to a significant improvement in the structural integrity of the tower/foundation connection.*" A key element of the improvement is given as "*creating pre-stress in the rods and the foundation foot-flange connection by disengaging the levelling nuts (underneath the foot flange) for all (or most) of the rods.*"

The 2nd generation tower design is substantially stronger at the base, due to the increased flange thickness and diameter. The rod diameter and number of rods have also been increased. However according to BS EN 1993-1-9:2005, the rods are still likely to be susceptible to fatigue within the design life of the turbine due to the high stress concentration associated with threaded components (see Appendix B).

The frequency results from the Ansys modal analysis are broadly in agreement with the Gaia calculations and indicate that both the 1st and 2nd generation tower designs are within the required frequency range.

# 5 CONCLUSIONS

1) In my opinion the primary cause of failure of the 1st generation towers was uncontrolled fatigue loading on the threaded foundation rods.

2) Stresses in the threaded rods on the 2nd generation towers are considerably lower than on the 1st generation towers. However according to BS EN 1993-1-9:2005, these rods are still likely to be susceptible to fatigue within the design life of the turbine.

3) Calculations indicate that the fundamental natural frequency of the combined turbine and tower for both 1st and 2nd generation designs are clear of the rotor excitation frequencies and therefore unlikely to cause resonance.

4) The provision for braking and overspeed detection and control is, in my opinion, adequate and conforms to the requirements of BS EN 61400-2:2006.

5) The design load calculations are generally in line with the BS EN 61400-2:2006 Simplified Load Model and Gaia, in my opinion, have given a reasonable justification for deviations from the model requirements.

# 6 RECOMMENDATIONS

a) That Gaia should be encouraged to improve the fatigue design of the tower bottom connection, for example by preloading the threaded foundation rods as described in their report [redacted] R12(5)(e)

b) That the quality and consistency of the heat treatment and galvanising of the threaded rods should be carefully monitored.

# 7 REFERENCES

1) [redacted]

2)

3)

4)

5)

R12(5)(e)

6) BS EN 61400-2:2006 "*Wind turbines – part 2: Design requirements for small wind turbines*". ISBN 0 580 48551 X

7) "*A Feasibility Study of the Scope for Revising the Simplified Load Model in IEC 61400-2:2006 June 2012*". TUV SUD NEL Ltd Report No. 2012/211

8) IEC 1400-2:1996 "*Wind turbine generator systems – Part 2: Safety of small wind turbines*".

9) [redacted]

10)

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11) BS 3692:2001 "*Strength grade designation of steel bolts and screws*". ISBN 0 580 33262 4.

12) BS EN 1993-1-9:2005 "*Eurocode 3: Design of steel structures – Part 1-9: Fatigue*". ISBN 978 0 580 66400 7

13) "*Handbook for the training course on bolting technology and the analysis of bolted joints.*" B Eccles. Bolt Science Ltd.

14) BS EN 1993-1-8:2005 "*Eurocode 3: Design of steel structures – Part 1-8: Design of joints*". ISBN 978 0 580 72497 8

15) Ansys finite element software, version 14.5.

# 8 FIGURES

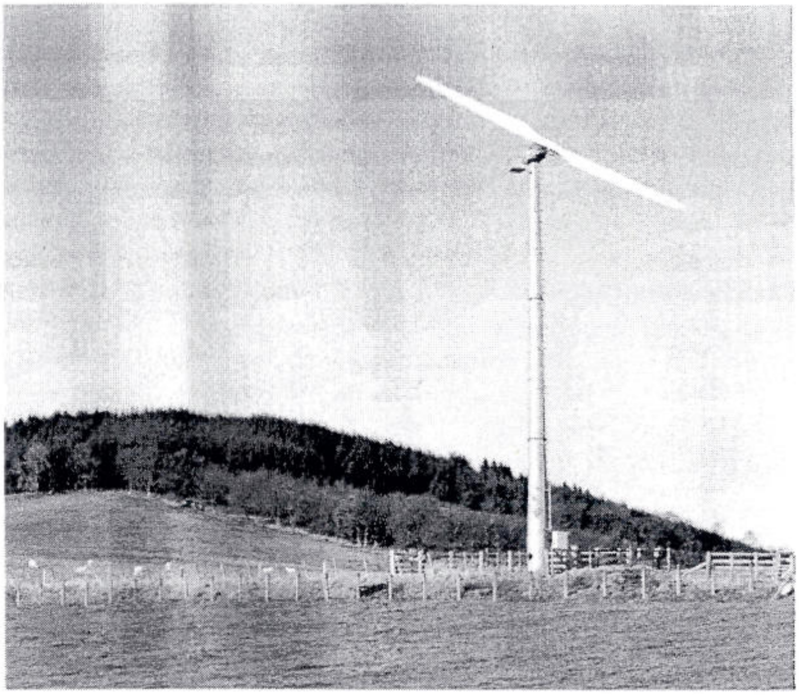


**Figure 1.** General view of the Gaia-Wind 11 kW wind turbine.
(Gaia website)

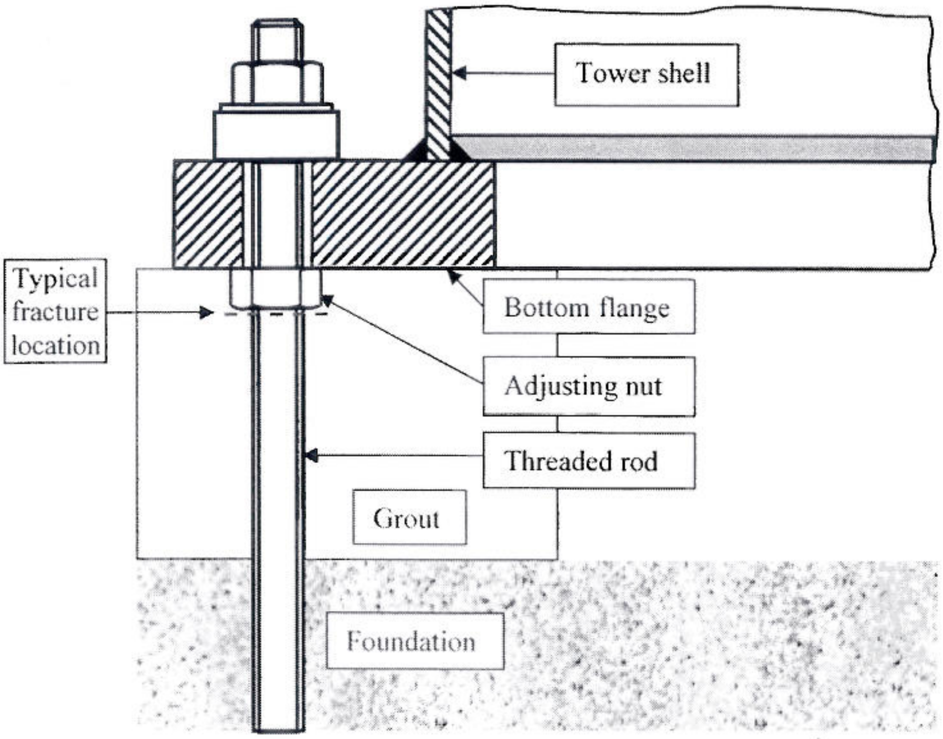



**Figure 2.** Sketch of bottom flange arrangement showing typical fracture location.
C Rudall (Not to scale)

**Figure 3.** Grouting remains (Lindley Hall Farm).
(Photograph 001.jpg, C Rudall)

**Figure 4.** Grouting remains showing foam filler and failed rod ends (Lindley Hall Farm).
(Photograph 003.jpg, C Rudall)

**Figure 5.** Typical rod failure (Lindley Hall Farm).
(Photograph 012.jpg, C Rudall)

# 9 APPENDICES

# APPENDIX A. TURBINE DESIGN LOADS

This appendix uses the Mathcad software application to assess the design loads acting on the Gaia-Wind 11 kW turbine according to the BS EN 61400-2:2006 Simplified Load Model. The results are in close agreement with Gaia's own SLM design load calculations[2].

**BS EN 61400-2 Section 7.4. Simplified Load Model for the Gaia-Wind 11 kW Turbine**
**Input data** (Ref[redacted] R12(5)(e)

| | | |
|---|---|---|
| Rotor radius | $R := 6.5m$ | |
| Wind speed at hub (1 min av) | $V_{design} := 10.5\frac{m}{s}$ | |
| | $rev := 2\pi$ | $rpm := \frac{rev}{min}$ |
| Design rotational speed | $n_{design} := 56rpm$ | |
| Rotational speed | $\omega_n := n_{design}$ | |
| | $\omega_n = 5.864\frac{1}{s}$ | |
| Electrical power | $P := 11kW$ | |
| System efficiency | $\eta := 0.65$ | |
| Blade mass | $m_b := 101kg$ | |
| Rotor mass | $m_r := 250kg$ | |
| Radial distance between CofG of blade and rotor centre | $R_{cog} := 2.62m$ | |
| Number of blades | $B := 2$ | |
| Distance from Cof G of rotor to the rotational axis | $e_r := 0.0325m$ | |
| Distance between rotor centre and first bearing | $L_{rb} := 0.75m$ | |
| Distance between rotor centre and the yaw axis | $L_{rt} := 2.15m$ | |
| Yaw rate | $\omega_{yaw} := 0.7\frac{rad}{s}$ | |
| Mass moment of inertia of the blade about the blade root flap axis | $I_B := 1001kg\cdot m^2$ | |
| Air density | $\rho := 1.225kg\cdot m^{-3}$ | |
| The component area projected onto a plane perpendicular or parallel to the wind direction | $A_{projB} := 2.6m^2$ | |

| | |
|---|---|
| Lift coefficient | $C_{lmax} := 2$ |
| Thrust coefficient | $C_T := 0.5$ |
| Annual average wind speed at hub height | $V_{ave} := 7.5\frac{m}{s}$ |
| Drag coefficient | $C_d := 1.5$ |
| Tip speed ratio (once per 50 year extreme) | $\lambda_{e50} := 1.28$ |
| Wind speed (once per 50 year extreme) | $V_{e50} := 52.5\frac{m}{s}$ |
| Design rotor torque | $Q_{design} := 3023N\cdot m$ (i.e. $Q_{design}=P/\omega_n\eta$ ) |
| Torque on low speed shaft caused by brake | $M_{brake} := 4171N\cdot m$ |
| Acceleration due to gravity | $g = 9807\frac{mm}{s^2}$ |
| Ratio between rated torque and short circuit torque for generator | $G$ 2 |

Then

Tip speed $\quad V_{tip} := \omega_n \cdot R \quad\quad V_{tip} = 38.12\frac{m}{s}$

Design tip speed ratio $\quad \lambda_{design} := \frac{V_{tip}}{V_{design}} \quad\quad \lambda_{design} = 3.63$

**Load case A : Normal operation**

**Blade loads**

The following equations assume constant range fatigue loadings on the blade and shaft.

Centrifugal loading $\quad \Delta F_{zB} := 2m_b \cdot R_{cog} \cdot \omega_n^2 \quad\quad \Delta F_{zB} = 18201N$ [21]

Blade bending moment $\Delta M_{xB} := \left(\frac{Q_{design}}{B}\right) + 2m_b \cdot g \cdot R_{cog} \quad\quad \Delta M_{xB} = 6702 N\cdot m$ [22]

Blade bending moment $\Delta M_{yB} := \left(\frac{\lambda_{design} \cdot Q_{design}}{B}\right) \quad\quad \Delta M_{yB} = 5487 N\cdot m$ [23]

**Shaft loads**

Shaft thrust load $\quad \Delta F_{xshaft} := \left(\frac{3}{2}\right)\cdot\left(\frac{\lambda_{design} \cdot Q_{design}}{R}\right) \quad\quad \Delta F_{xshaft} = 2533N$ [24]

Shaft torsional moment $\Delta M_{xshaft} := Q_{design} + 2\cdot m_r \cdot g \cdot e_r \quad\quad \Delta M_{xshaft} = 3182 N\cdot m$ [25]

Shaft bending moment $\Delta M_{shaft} := 2\cdot m_r \cdot g \cdot L_{rb} + \left(\frac{R}{6}\right)\cdot \Delta F_{xshaft} \quad\quad \Delta M_{shaft} = 6421 N\cdot m$ [26]

**Load case B : Yawing**

The Gaia-Wind 11 kW is a free yawing, downwind turbine.

Yaw rate $\omega_{yawmax} := 3 - 0.01\left(\pi\, R^2 - 2\right)^{\blacksquare}$ [27]

$\omega_{yawmax} := 1.69 \frac{rad}{s}^{\blacksquare}$

Gaia have used a figure of approximately half of this (based on field measurements). (Note that the small black rectangle indicates that an equation is not used in subsequent calculations).

Gaia value: $\omega_{yawmax} := 0.70 \frac{rad}{s}$

and taking $\omega_{yaw} := \omega_{yawmax}$

Blade bending moment $M_{yb} := m_b \cdot \omega_{yaw}^2 L_{rt} \cdot R_{cog} + 2 \cdot \omega_{yaw} \cdot I_B \cdot \omega_n + \left(\frac{R}{9}\right) \cdot \Delta F_{xshaft}$ [28]

$M_{yb} = 10326 N \cdot m$

Shaft bending moment $M_{shaft} := 4 \cdot \omega_{yaw} \cdot \omega_n \cdot I_B + m_r \cdot g \cdot L_{rb} + \left(\frac{R}{6}\right) \Delta F_{xshaft}$ [30]
(for 2-bladed turbine)

$M_{shaft} = 21019 N \cdot m$

**Load case C : Yaw error**

Blade bending moment

$$M_{yB} := \left(\frac{1}{8}\right) \rho \cdot A_{projB} \cdot C_{lmax} \cdot R^3 \omega_n^2 \left[1 + \left(\frac{4}{3 \cdot \lambda_{design}}\right) + \left(\frac{1}{\lambda_{design}}\right)^2\right]$$ [31]

$M_{yB} = 10853 N \cdot m$

**Load case D : Maxumum thrust**

Maximum thrust load $F_{xshaft} := C_T \cdot 3.125 \cdot \rho \cdot V_{ave}^2 \cdot \pi \cdot R^2$ [32]

$F_{xshaft} = 14291 N$

**Load case E : Maximum rotational speed**

Maximum rotational speed taken as $\omega_{nmax} := 1.25 \cdot \omega_n$

Centrifugal load in blade root $F_{zB} := m_b \cdot \omega_{nmax}^2 \cdot R_{cog}$ [33]

$F_{zB} = 14219 N$

Shaft bending moment $M_{shaft} := m_r \cdot g \cdot L_{rb} + m_r \cdot e_r \cdot \omega_{nmax}^2 \cdot L_{rb}$ [34]

$M_{shaft} = 2166 N \cdot m$

**Load case F : Short at load connection**

Generator shaft torque due to short circuit

*In the absence of any values proven to be more accurate, two times the* $Q_{design}$ *is to be taken as the short circuit torque acting on the generator shaft.*

$$M_{xshaft} := G \cdot Q_{design} \qquad [35]$$

$M_{xshaft} = 6046 N \cdot m$

Blade bending moment

$$M_{xB} := \frac{M_{xshaft}}{B} \qquad [36]$$

$M_{xB} = 3023 N \cdot m$

**Load case G : Shutdown (braking)**

Maximum shaft torque under braking $M_{xshaft} := M_{brake} + Q_{design}$ [37]

$M_{xshaft} = 7194 N \cdot m$

Blade load during shutdown $M_{xB} := \left(\frac{M_{xshaft}}{B}\right) + m_b \cdot g \cdot R_{cog}$ [38]

$M_{xB} = 6192 N \cdot m$

**Load case H : Parked wind loading**

Quoting from BS EN 61400-2:2006: "*In this load case, the wind turbine is parked in the normal way. The loads on the exposed parts of the SWT shall be calculated assuming wind speed of* $V_{e50}$."

Quoting from the Gaia Design Loads report: "*The Gaia control system brakes and parks the rotor for wind speeds above 25 m/s. At* $V_{e50} = 52.5$ *m/s the rotor will therefore be parked.*

*The loads for a spinning rotor have been checked but lead to less conservative values and are therefore not used.*"

**For rotor parked at $V_{e50}$:**

Blade root bending moment due to drag: $M_{yB} := C_d \cdot \left(\frac{1}{4}\right) \rho \cdot V_{e50}^2 \cdot A_{projB} \cdot R$ [39]

$M_{yB} = 21398 N \cdot m$

Shaft thrust load: $F_{xshaft} := B \cdot C_d \cdot \left(\frac{1}{2}\right) \rho \cdot V_{e50}^2 \cdot A_{projB}$ [41]

$F_{xshaft} = 13168 N$

**For rotor spinning at $V_{e50}$:**

Blade root bending moment: $M_{yB} := C_{lmax} \cdot \left(\frac{1}{6}\right) \rho \cdot V_{e50}^2 \cdot A_{projB} \cdot R$ [40]

$M_{yB} = 19020 N \cdot m$

Shaft thrust load:

Assuming $n_{max} := 1.25 n_{design} = 70 \frac{rev}{min}$

The tipspeed ratio at $V_{e50}$: $\lambda_{e50} := \frac{n_{max} \cdot R}{V_{e50}}$ $\lambda_{e50} = 0.91$

$$F_{xshaft} := 0.17 B \cdot A_{projB} \cdot \lambda_{e50}^2 \rho \cdot V_{e50}^2 \qquad [42]$$

$F_{xshaft} = 2458N$

The maximum tower bending moment is calculated using Equation (41) or (42) as appropriate. Equation (44) is used to calculate the additional load due to the drag or lift force on the tower or nacelle. For free standing towers (e.g. Gaia-Wind 11 kW) the maximum bending moment occurs at the tower base.

$$F_{xnacelle} := C_f \left(\frac{1}{2}\right) \rho \cdot V_{e50}^2 \cdot A_{proj} \qquad [44]$$

Force coefficients, $C_f$ are from BS EN 61400-2 Table 3.

Values of $A_{proj}$ are the component projected areas (in the most unfavourable position) that are appropriate for the force coefficients.

For the hub: $C_f := 1.1$ $A_{projH} := 0.40 m^2$

Drag force due to turbine hub $F := C_f \left(\frac{1}{2}\right) \rho \cdot V_{e50}^2 \cdot A_{projH} = 743N$

Gaia have calculated the drag force for each of the three tower sections using appropriate wind speeds and projected areas. A force coefficient, $C_f = 0.7$ is used throughout.

Drag forces due to turbine tower:

$F_{xtowertop} := 3511N$ $F_{xtowermid} := 4152N$ $F_{xtowerbot} := 4043N$

**Load case I : Parked wind loading, maximum exposure**

In the case of a failure of the yaw mechanism, the worst case drag on all the components (blades, nacelle, tower) is calculated using equation [45] and a reference wind speed, $V_{ref}$, averaged over 10 min. (Values of $V_{ref}$ are given in BS EN 61400-2:2006 Table 1).

$V_{ref} := 37.5 \frac{m}{s}$ $$F := C_f \left(\frac{1}{2}\right) \rho \cdot V_{ref}^2 \cdot A_{proj} \qquad [45]$$

In this case Gaia argue that wind loading from any direction will produce loads below those based on $V_{e50}$ and already calculated in load case H.

**Load case J : Transportation, Assembly, Maintenance and Repair**

For this load case Gaia have described the assembly procedure and indentified two cases during the lifting operation that are subject to a "*dynamic amplification factor*". The value of this factor is taken as 2. The cases are:

1) Turbine horizontal, lifting just started.

2) Turbine vertical suspended from crane.

Gaia say that "*In the detail design calculations of the components involved (lifting points, machine frame, yaw bearing and tower) these two load cases will be taken into consideration.*"

# APPENDIX B. LOADS ACTING AT THE THREADED RODS

## B.1 TOWER LOADS

This appendix applies loads calculated according to the BS EN 61400-2:2006 Simplified Load Model to the threaded foundation rods. I have considered the threaded rod configurations for both the 1st and 2nd generation towers.

There is no pre-loading on the threaded rods beneath the nuts on the underside of the bottom flange. The rods are therefore exposed to the following loads:

1) Compression due to the self-weight of the wind turbine (static)
2) Compression/tension due to the wind overturning moment (cyclic)
3) Lateral shear due to wind loading (cyclic)
4) Bending due to wind loading (cyclic)

The threaded rods are understood to be made of Grade 8.8 galvanised steel[a]. The minimum tensile strength = 800N/mm$^2$ and the 0.2% proof stress = 640N/mm$^2$ [(11)].

Note that from the 18 m Tubular Tower Foundation Guide[(10)], there is also an option for a 27 m tower (Page 2). This will be subject to increased wind loading and overturning moment.

According to the Gaia's Simplified Load Model calculations[(2)], the moments and loads applied to the tower are as follows:

**Table B1.** SLM tower loads

| Load Case | Shaft bending moment, $M_{shaft}$ (Nm) | Shaft axial load, $F_{x\text{-}shaft}$ (N) |
|---|---|---|
| A – Normal operation (fatigue) | 6399 | 2511 |
| B – Yaw | 20984 | |
| E – Maximum rotational speed | 2167 | |
| D – Maximum thrust | | 14296 |
| H – Parked wind loading | | 13168 |

Note that according to the BS EN 61400-2:2006 Simplified Load Model, the yaw moment is not considered with respect to fatigue, although there is ongoing discussion within the industry as to whether it should be considered.

Gaia have calculated the drag force for each of the three tower sections using the 50 year extreme wind speed, $V_{e50}$ = 52.5 m/s, applied to the projected areas (Table B2). A force coefficient, $C_f$ = 0.7 was used throughout. The moments acting at the base of the tower due to these drag forces are added to the moments due to the SLM tower loads shown in Table B1 for the maximum load condition.

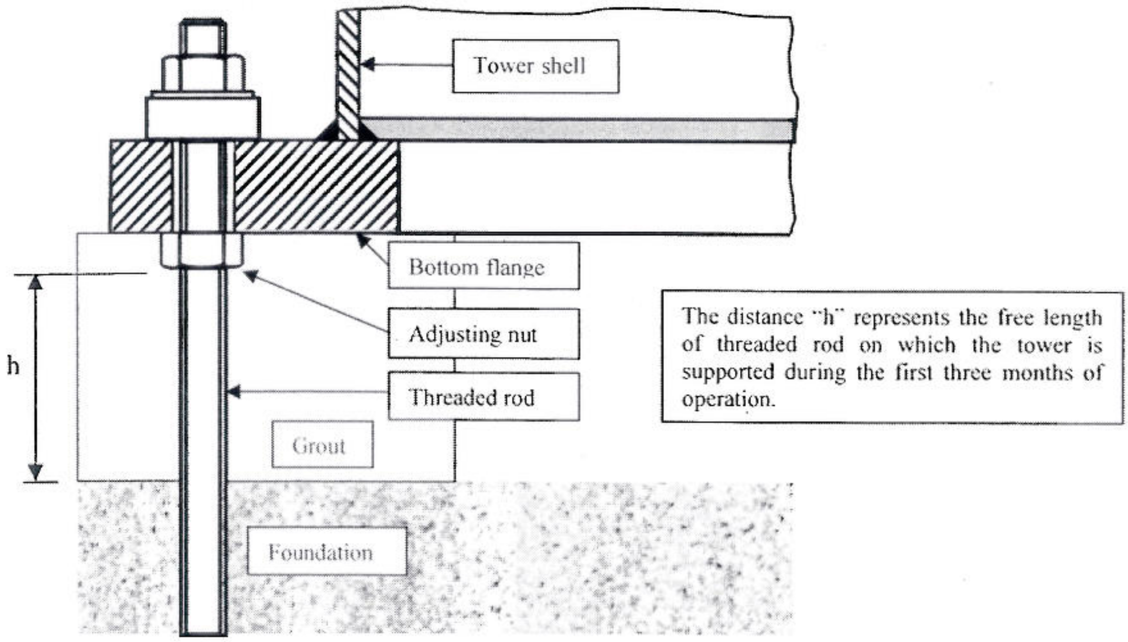
[a] *Meeting at Gaia-Wind's offices, 8 April 2013.*

**Table B2.** Wind drag on tower components

| Component | Wind drag ($V_{e50}$=52.5 m/s) (N) |
|---|---|
| Nacelle (acting at18.4 m) | 743 |
| Tower upper section (acting at 15.3 m) | 3511 |
| Tower mid section (acting at 9.2 m) | 4152* |
| Tower lower section (acting at 3.1 m) | 4043* |

*Note that these values vary slightly from the figures quoted in the Gaia tower design assessment [1].

**Figure B1.** Sketch of bottom flange arrangement.
(Not to scale)



## B.2 TOWER MASSES

The mass of the nacelle (including rotor) = 954 kg[1].

The total turbine mass (including 1st generation tower) = 3144 kg[1].

The total turbine mass (including 2nd generation tower) = 3357 kg[1].

## B.3 ROD COMPRESSION DUE TO THE SELF-WEIGHT OF THE TURBINE (STATIC)

### B.3.1 1st Generation tower

Total mass acting at threaded rods, $m_{tot,1stgen} = 3144kg$

M27 tensile stress area , $As_{M27} = 459mm^2$ [13]

Number of threaded rods , $N_{M27} = 16$

Compressive stress, $\sigma_{ax,1stgen,static} = \dfrac{m_{tot,1stgen} \times g}{As_{M27} \times N_{M27}} = \dfrac{3144 \times 9.81}{459 \times 16} = 4.2N/mm^2$

(Note this assumes equal load sharing between the threaded rods)

### B.3.2 2nd Generation tower

Total mass acting at threaded rods, $m_{tot,2ndgen} = 3357kg$

M30 tensile area , $As_{M30} = 561mm^2$ [13]

Number of threaded rods , $N_{M30} = 24$

Compressive stress, $\sigma_{ax,2ndgen,static} = \dfrac{m_{tot,2ndgen} \times g}{As_{M30} \times N_{M30}} = \dfrac{3357 \times 9.81}{561 \times 24} = 2.4N/mm^2$

(Note this assumes equal load sharing between the threaded rods)

## B.4 ROD COMPRESSION/TENSION DUE TO THE THRUST AND WIND LOADING (CYCLIC)

### B.4.1 1st Generation tower (Maximum load condition)

**Moment due to rotor shaft axial load**

Height to rotor shaft centreline , $h_{rotor} = 18.3m$

Maximum thrust at rotor shaft (load case D), $F_{x-rotor,max} = 14296N$

Moment acting at the tower base,

$M_{rotor,max} = h_{rotor} \times F_{x-rotor,max} = 18.3 \times 14296 = 261.6 \times 10^3 Nm = 261.6 \times 10^6 Nmm$

**Moment due to nacelle wind drag**

Height to nacelle centreline , $h_{nacelle} = 18.4m$

Maximum wind drag, $F_{x-nacelle,max} = 743N$

Moment acting at the tower base,

$M_{nacelle,\max} = h_{nacelle} \times F_{x-nacelle,\max} = 18.4 \times 743 = 13.7 \times 10^3\ Nm = 13.7 \times 10^6\ Nmm$

**Moment due to tower upper section wind drag**

Height to tower upper section, $h_{upper} = 15.3m$

Maximum wind drag, $F_{x-upper,\max} = 3511N$

Moment acting at the tower base,

$M_{upper,\max} = h_{upper} \times F_{x-upper,\max} = 15.3 \times 3511 = 53.7 \times 10^3\ Nm = 53.7 \times 10^6\ Nmm$

**Moment due to tower mid section wind drag**

Height to tower mid section, $h_{mid} = 9.2m$

Maximum wind drag, $F_{x-mid,\max} = 4152N$

Moment acting at the tower base,

$M_{mid,\max} = h_{mid} \times F_{x-mid,\max} = 9.2 \times 4152 = 38.2 \times 10^3\ Nm = 38.2 \times 10^6\ Nmm$

**Moment due to tower lower section wind drag**

Height to tower lower section, $h_{lower} = 3.1m$

Maximum wind drag, $F_{x-lower,\max} = 4043N$

Moment acting at the tower base,

$M_{lower,\max} = h_{lower} \times F_{x-lower,\max} = 3.1 \times 4043 = 12.5 \times 10^3\ Nm = 12.5 \times 10^6\ Nmm$

**Total moment (rotor shaft + wind drag)**

$$M_{tower,\max} = M_{rotor,\max} + M_{nacelle,\max} + M_{upper,\max} + M_{mid,\max} + M_{lower,\max}$$

$$M_{tower,\max} = (261.6 + 13.7 + 53.7 + 38.2 + 12.5) \times 10^6 = 379.7 \times 10^6\ Nmm$$

Rod PCD, $PCD_{1stgen} = 1020mm$

Referring to: "*Handbook for the training course on bolting technology and the analysis of bolted joints.*" B Eccles [13].

Consider the moment acts about centre-line A-A

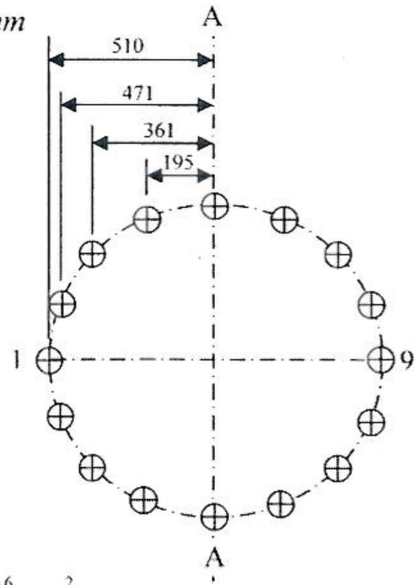



**Figure B2**
1st generation rod layout

Then $F_n = \dfrac{M_{tower,\max} \times z_n}{\sum z_n^2}$

Where $F_n$ = the axial force acting on the rod, $n$

$z_n$ = the distance of the rod from the centroid

$$\sum z_n^2 = (4 \times 195^2) + (4 \times 361^2) + (4 \times 471^2) + (2 \times 510^2) = 2.081 \times 10^6\ mm^2$$

For rods 1 and 9, the axial force is:

$$F_{1,9} = \frac{M_{tower,\max} \times z_{1,9}}{\sum z_n^2} = \frac{379.7 \times 10^6 \times 510}{2.081 \times 10^6} = 93055N$$

and the maximum axial stress (tensile/compressive) stress is:

$$\sigma_{ax,1stgen,max} = \frac{F_{1,9}}{As_{M27}} = \frac{93055}{459} = 202.7 N/mm^2 \qquad \text{(Rigid flange assumed)}$$

### B.4.2 1st Generation tower (Fatigue load condition)

**Moment due to rotor shaft axial load**

Height to rotor shaft centreline, $h_{rotor} = 18.3m$
Axial load at rotor shaft (load case A), $F_{x-rotor,fat} = 2511N$
Moment acting at the tower base,
$M_{rotor,fat} = h_{rotor} \times F_{x-rotor,fat} = 18.3 \times 2511 = 46.0 \times 10^3 Nm = 46.0 \times 10^6 Nmm$

**Moment due to rotor shaft bending**
Bending at rotor shaft (load case A), $M_{shaft,fat} = 6399Nm = 6.4 \times 10^6 Nmm$

**Total moment**
The total fatigue moment at the tower base is then,
$M_{tower,fat} = M_{rotor,fat} + M_{shaft,fat}$ $\qquad M_{tower,fat} = (46.0 + 6.4) \times 10^6 = 52.4 \times 10^6 Nmm$

And the corresponding fatigue range (peak-to-peak Ref BS EN 61400-2:2006 Clause 7.4.2) is

$$\sigma_{ax,1stgen,fat} = \frac{M_{tower,fat}}{M_{tower,max}} \times \sigma_{ax,1stgen,max} = \frac{52.4 \times 10^6}{379.7 \times 10^6} \times 202.7 = 28.0 N/mm^2$$

### B.4.3 2nd Generation tower (Maximum load condition)

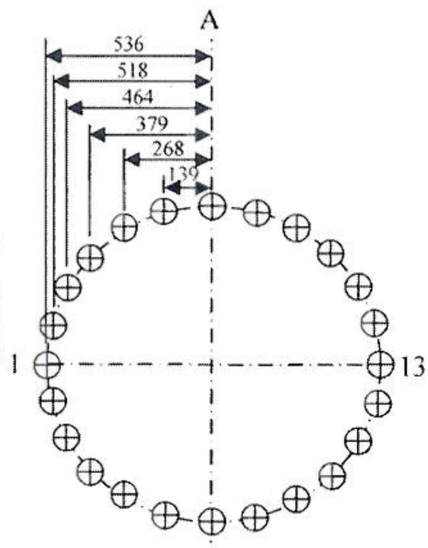
Consider $M_{tower,max}$ acting on the 24 x M30 rods.

Rod PCD, $PCD_{2ndgen} = 1071mm$

Referring to: "*Handbook for the training course on bolting technology and the analysis of bolted joints.*" B Eccles [13].

Consider the moment acts about centre-line A-A

**Figure B3**
2nd generation rod layout




Then $F_n = \frac{M_{tower,max} \times z_n}{\sum z_n^2}$

Where $F_n$ = the axial force acting on the rod, $n$

$z_n$ = the distance of the rod from the centroid

$$\sum z_n^2 = (4 \times 139^2) + (4 \times 268^2) + (4 \times 379^2) + (4 \times 464^2) + (4 \times 518^2) + (2 \times 536^2) \doteq 3.448 \times 10^6 mm^2$$

For rods 1 and 13, the axial force is:

$$F_{1,13} = \frac{M_{tower,\max} \times z_{1,13}}{\sum z_n^2} = \frac{379.7 \times 10^6 \times 536}{3.448 \times 10^6} = 59025N$$

and the axial stress (tensile/compressive) stress is:

$$\sigma_{ax,2ndgen,\max} = \frac{F_{1,13}}{As_{M30}} = \frac{59025}{561} = 105.2N/mm^2 \qquad \text{(Rigid flange assumed)}$$

### B.4.4 2nd Generation tower (Fatigue load condition)

The corresponding fatigue range (peak-to-peak Ref BS EN 61400-2:2006 Clause 7.4.2) is

$$\sigma_{ax,2ndgen,fat} = \frac{M_{tower,fat}}{M_{tower,\max}} \times \sigma_{ax,2ndgen,\max} = \frac{52.4 \times 10^6}{379.7 \times 10^6} \times 105.2 = 14.5N/mm^2$$

## B5 ROD LATERAL SHEAR DUE TO THRUST LOADING + WIND

### B5.1 1st Generation tower (Maximum load condition)

Total lateral shear force at the threaded rods,

$$F_{x,\max} = F_{x-shaft,\max} + F_{x-nacelle,\max} + F_{x-upper,\max} + F_{x-mid,\max} + F_{x-lower,\max}$$
$$F_{x,\max} = 14296 + 743 + 3511 + 4152 + 4043 = 26745N$$

The lateral shear force per rod at the tower base, $F_{shear,1stgen,\max} = \frac{F_{x,\max}}{16} = \frac{26745}{16} = 1672N$

M27 root area, $A_{root,M27} = 427mm^{2\,(13)}$

And the lateral shear stress per rod, $\tau_{1stgen,\max} = \frac{F_{shear,1stgen,\max}}{A_{root,M27}} = \frac{1672}{427} = 3.9N/mm^2$

### B5.2 1st Generation tower (Fatigue load condition)

Shaft axial load, $F_{x-shaft,fat} = 2511N$

$F_{shear,1stgen,fat} = \frac{F_{x-shaft,fat}}{16} = \frac{2511}{16} = 157N$ i.e. lateral shear stress per rod is very small.

### B5.3 2nd Generation tower (Maximum load condition)

The lateral shear force per rod at the tower base, $F_{shear,2ndgen,\max} = \frac{F_{x,\max}}{24} = \frac{26745}{24} = 1114N$

M30 root area, $A_{root,M30} = 519mm^{2\,(13)}$

And the lateral shear stress per rod, $\tau_{2ndgen,\max} = \frac{F_{shear,2ndgen,\max}}{A_{root,M30}} = \frac{1114}{519} = 2.0N/mm^2$

**B5.4 2nd Generation tower (Fatigue load condition)**

Shaft axial load, $F_{x-shaft,fat} = 2511N$

$$F_{shear,2ndgen,fat} = \frac{F_{x-shaft,fat}}{24} = \frac{2511}{24} = 105N$$ i.e. lateral shear stress per rod is very small.

**B6 ROD BENDING DUE TO THRUST LOADING + WIND**

**B6.1 1st Generation tower (Maximum load condition)**

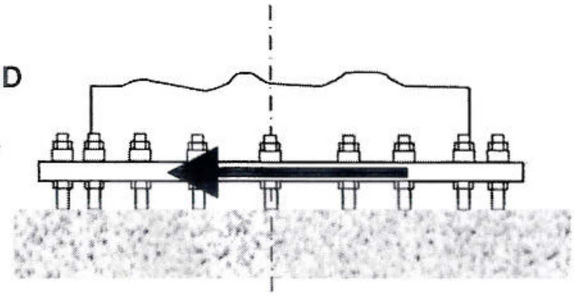


**Figure B4** Thrust load acting at tower base.

The bending moment acting at each threaded rod,

$$M_{M27} = \frac{F_{shear,1stgen,max} \times h}{2}$$

Where $h$ is the unsupported length of rod $= 63mm$ (see Figure B1)
(i.e. based upon a distance of 85 mm beneath the underside of the bottom flange and the top of the foundation, as measured from grout sample 10613 retrieved from the Lindley Hall Farm turbine).

Then $M_{M27} = \frac{1672 \times 63}{2} = 52668Nmm$

Using the section modulus for the rod, based on the M27 minor diameter,

$$S_{M27} = \frac{\pi \times d^3}{32} = \frac{\pi \times 23.3^3}{32} = 1242mm^3$$

The maximum bending stress in each rod is then

$$\sigma_{B,1stgen,max} = \frac{M_{M27}}{S_{M27}} = \frac{52668}{1242} = 42.4N/mm^2$$ (Rigid flange assumed)

**B6.2 1st Generation tower (Fatigue load condition)**

The maximum fatigue stress in each rod is

$$\sigma_{B,1stgen,fat} = \frac{F_{shear,1stgen,fat}}{F_{shear,1stgen,max}} \times \sigma_{B,1stgen,max} = \frac{157}{1672} \times 42.4 = 4.0N/mm^2$$

**B6.3 2nd Generation tower (Maximum load condition)**

$$M_{M30} = \frac{F_{shear,2ndgen,max} \times h}{2}$$

Where $h$ is the unsupported length of rod $= 61mm$ (see Figure B1)

$$M_{M30} = \frac{1114 \times 61}{2} = 33977Nmm$$

(i.e. based upon a distance of 85 mm beneath the underside of the bottom flange and the top of the foundation, as measured from grout sample 10613 retrieved from the Lindley Hall Farm turbine).

Using the section modulus for the rod, based on the M30 minor diameter,

$$S_{M30} = \frac{\pi \times d^3}{32} = \frac{\pi \times 25.7^3}{32} = 1666mm^3$$

The bending stress in each rod is then

$$\sigma_{B.2ndgen,max} = \frac{M_{M30}}{S_{M30}} = \frac{33977}{1666} = 20.4N/mm^2 \text{ (Rigid flange assumed)}$$

### B6.4 2nd Generation tower (Fatigue load condition)

The maximum fatigue stress in each rod is

$$\sigma_{B,2ndgen,fat} = \frac{F_{shear,2ndgen,fat}}{F_{shear,2ndgen,max}} \times \sigma_{B,2ndgen,max} = \frac{105}{1114} \times 20.4 = 1.9N/mm^2$$

## B7 COMBINED ROD STRESS

### B7.1 1st Generation tower (Maximum load condition)

The combined axial maximum stress in the M27 rods is

$$\sigma_{combined,1stgen,max} = \sigma_{ax,1stgen,static} + \sigma_{ax,1stgen,max} + \sigma_{b,1stgen,max}$$

$$\sigma_{combined,1stgen,max} = 4.2 + 202.7 + 42.4 = 249.3N/mm^2$$

According to BS EN 1993-1-8:2005[14], the design tension resistence is:

$$F_{t,Rd} = \frac{k_2 f_{ub} A_s}{\gamma_{M2}}$$

where

factor, $k_2 = 0.9$ (BS EN 1993-1-8:2005 Table 3.4)

bolt tensile strength, $f_{ub} = 800N/mm^2$ (BS EN 1993-1-8:2005 Table 3.1)

tensile stress area, $A_s = 459mm^2$ (Ref. [13])

partial factor, $\gamma_{M2} = 1.25$ (BS EN 1993-1-8:2005 Table 2.1)

then $F_{t,Rd} = \frac{0.9 \times 800 \times 459}{1.25} = 264384N = 264.3kN$

and the corresponding permissible tensile stress, $\sigma_{pt} = \frac{k_2 f_{ub}}{\gamma_{M2}} = \frac{0.9 \times 800}{1.25} = 576N/mm^2$

Hence the combined axial stress is 43% of the permissible tensile stress for the rods and therefore acceptable.

### B7.2 1st Generation tower (Fatigue load condition)

The combined axial fatigue stress in the M27 rods is

$$\sigma_{combined,1stgen,fat} = \sigma_{ax,1stgen,fat} + \sigma_{b,1stgen,fat}$$

$$\sigma_{combined,1stgen,max} = 28.0 + 4.0 = 32.0N/mm^2$$

Referring to BS EN 1993-1-9:2005 Eurocode 3[12], Table 8.1 categorises constructional details with respect to fatigue. "Bolts and rods with rolled or cut threads in tension" are detail category 50 (i.e. the fatigue reference value $\Delta\sigma_C = 50N/mm^2$).

Ref. Clause 7.1 of BS EN 1993-1-9 2005 gives a constant amplitude fatigue limit, $\Delta\sigma_D = 0.737\Delta\sigma_C = 36.9N/mm^2$ corresponding to $2 \times 10^6$ cycles. For the Gaia turbine, this equates to a period of 25 days, assuming a continuous rotor speed of 56 rpm. If blade-pass frequency is considered (i.e. twice per revolution), then $2\times10^6$ cycles equates to about 12.5 days.

Clause 7.1 also gives a fatigue cut-off limit,
$\Delta\sigma_L = 0.549\Delta\sigma_D = 20.2N/mm^2$ corresponding to $1\times10^8$ cycles and above.

With reference to BS EN 61400-2:2006[6], Clause 7.9.2,
*"In case the simplified load model ... is used, the ranges of load case A shall be applied for the number of fatigue cycles given in equation (49).*

$$n = \frac{B\times n_{design}\times T_d}{60}$$

*Where $T_d$ is the design life of the turbine in seconds."*
So for the Gaia turbine, assuming a design life of 20 years,

$$n = \frac{2\times56\times60^2\times24\times365\times20}{60} = 1.2\times10^9\,cycles$$

Hence the nominal tensile fatigue range for the threaded rods is equal to the cut-off limit, $\Delta\sigma_L = 20.2N/mm^2$ corresponding to $1\times10^8$ cycles and above. Gaia have applied a (high consequence) partial factor for fatigue strength, $\gamma_{Mf} = 1.35$, taken from Table 3.1 of BS EN 1993-1-9:2005. The permissible combined axial fatigue stress is then reduced to

$$\frac{\Delta\sigma_L}{\gamma_{Mf}} = \frac{20.2}{1.35} = 15.0N/mm^2$$

This fatigue range is exceeded in the case of the 1st generation tower design. (Note fatigue shear stress is small and is neglected).

### B7.3 2nd Generation tower (Maximum load condition)

The combined axial maximum stress in the M30 rods is

$$\sigma_{combined,2ndgen,max} = \sigma_{ax,2ndgen,static} + \sigma_{ax,2ndgen,max} + \sigma_{b,2ndgen,max}$$

$$\sigma_{combined,1stgen,max} = 2.4 + 105.2 + 20.40 = 128.0N/mm^2$$

According to BS EN 1993-1-8:2005[14], the design tension resistence is:

$$F_{t,Rd} = \frac{k_2 f_{ub} A_s}{\gamma_{M2}}$$

where

| | |
|---|---|
| factor, $k_2 = 0.9$ | (BS EN 1993-1-8:2005 Table 3.4) |
| bolt tensile strength, $f_{ub} = 800N/mm^2$ | (BS EN 1993-1-8:2005 Table 3.1) |
| tensile stress area, $A_s = 561mm^2$ | (Ref. [13]) |
| partial factor, $\gamma_{M2} = 1.25$ | (BS EN 1993-1-8:2005 Table 2.1) |

then $F_{t,Rd} = \frac{0.9 \times 800 \times 561}{1.25} = 323136N = 323.1kN$

and the corresponding permissible tensile stress, $\sigma_{pt} = \frac{k_2 f_{ub}}{\gamma_{M2}} = \frac{0.9 \times 800}{1.25} = 576N/mm^2$

Hence the combined axial stress is 22% of the permissible tensile stress for the rods and therefore acceptable.

### B7.4 2nd Generation tower (Fatigue load condition)

The combined axial fatigue stress in the M30 rods is

$\sigma_{combined,2ndgen,fat} = \sigma_{ax,2ndgen,fat} + \sigma_{b,2ndgen,fat}$

$\sigma_{combined,2ndgen,fat} = 14.5 + 1.9 = 16.4N/mm^2$

This falls just below the BS EN 1993-1-9:2005[12] constant amplitude fatigue cut-off limit $\Delta\sigma_L = 0.549\Delta\sigma_D = 20.2N/mm^2$ corresponding to $1 \times 10^8$ cycles and above. Applying the (high consequence) partial factor for fatigue strength, $\gamma_{Mf} = 1.35$, taken from Table 3.1 of BS EN 1993-1-9:2005, the permissible combined axial fatigue stress is then reduced to $\frac{\Delta\sigma_L}{\gamma_{Mf}} = \frac{20.2}{1.35} = 15.0N/mm^2$

On this basis the 2nd Generation design exceeds the permissible combined axial fatigue stress.

Comparing with the Gaia calculation[1], they have calculated a value of $14.59N/mm^2$ for the axial fatigue stress, taking it slightly below the permissible value. My value is higher mainly because I have included rod bending in the fatigue calculation. Rod bending will occur during the first three months of operation, but should be eliminated after the grout has been added. (Note that any deviation from the calculated figures, for example due to unequal load-sharing among the rods, could be expected to increase the fatigue stress).

**Table B3.** Summary of rod stresses

| | 1st generation threaded rods (M27) | | 2nd generation threaded rods (M30) | |
|---|---|---|---|---|
| | Maximum stress (N/mm²) | Fatigue stress (N/mm²) | Maximum stress (N/mm²) | Fatigue stress (N/mm²) |
| Axial self-weight stress (static) | 4.2 | - | 2.4 | - |
| Axial stress due to thrust and wind loading (cyclic) | 202.7 | 28.0 | 105.2 | 14.5 |
| shear stress due to thrust and wind loading (cyclic) | 3.6 | - | 2.0 | - |
| Bending due to thrust and wind loading (cyclic) | 42.4 | 4.0 | 20.4 | 1.9 |
| Combined stress (excluding shear) | 249.3 | 32.0 | 128.0 | 16.4 |
| Permissible stress<br>BS EN 1993-1-8:2005 (strength)<br>BS EN 1993-1-9:2005 (fatigue) | 576.0 | 15.0 | 576.0 | 15.0 |

# APPENDIX C. FREQUENCY CALCULATIONS

The Gaia design assessment for the 18 m tubular tower[1] includes spreadsheet calculations for the primary natural frequency of the 1st and 2nd generation towers. The calculations appear to assume a rigid connection between the bottom flange and the foundation. In reality the connection has a finite stiffness depending upon the flange and rod materials and geometry which would be expected to reduce the overall tower stiffness and frequency compared with the rigid connection assumption.

According to the Gaia tower design assessment, the turbine's excitation frequencies are 1P = 0.93 Hz (i.e. rotor frequency), and 2P = 1.87 Hz (i.e. blade-pass frequency). For design purposes and to avoid resonance, Gaia require that the fundamental combined turbine and tower frequency falls either within the range1.20 – 1.50 Hz or above 2.5Hz. Note that BS EN 61400-2:2006 does not specify vibration requirements other than to comment in general terms that resonance should be avoided (Clauses 7.3.1 and 11.2).

In order to check Gaia's frequency calculations I have used the Ansys finite element software[15] to perform a modal analysis on simplified models of the 1st and 2nd generation tubular towers. I used dimensions and masses taken from the tubular tower design assessment[1]. The tower mass calculated using Ansys was about 10% less than the masses calculated by Gaia. This may have been due in part to fixtures such as the ladder and nuts and bolts. Weld material will also increase the mass by a small percentage. To compensate for the difference in mass I adjusted the density of the tower tube components in the Ansys models.

Table C1 gives the dimensions used for the Ansys models.

**Table C1** 1st and 2nd generation tower dimensions

| | **1st generation tower** | | **2nd generation tower** | |
|---|---|---|---|---|
| Tower shell thickness | 6 mm | Ref 1 p13 | 6 mm | Ref 1 p13 |
| Shell OD (at base) | 938 mm | Ref 1 p13 | 975 mm | Ref 1 p13 |
| Shell OD (at top) | 410 mm | Ref 1 p13 | 10 mm | Ref 1 p13 |
| Base flange thickness | 25 mm | estimate | 35 mm | Ref 1 p10 |
| Base flange OD | 1070 mm | estimate | 1151mm | Ref 1 p10 |
| Base flange ID | 920 mm | estimate | 951 mm | estimate |
| Base flange width | 75 mm | estimate | 100 mm | estimate |
| No of rods (at base) | 16 x M27 | Site measurement | 24 x M30 | Ref 1 p10 |
| Rod PCD | 1020 mm | Site measurement | 1071 mm | Ref 1 p10 |

The fundamental natural frequencies for the two tower designs were calculated for the different foundation conditions using Ansys as follows:

1. 1st generation tower supported at the lower surface of the bottom flange.

2. 1st generation tower supported on threaded rods and adjusting nuts, with the underside of the bottom flange 85 mm above the foundation (i.e. as for the Lindley Hall Farm Turbine)

3. 2nd generation tower supported at the lower surface of the bottom flange.

4. 2nd generation tower supported on threaded rods and adjusting nuts, with the underside of the bottom flange 85 mm above the foundation (for comparison with the 1st generation design).

The results are shown in Table C2.

**Table C2.** Tower fundamental natural frequencies

| | 1st generation tower Hz | 2nd generation tower Hz |
|---|---|---|
| Gaia calculation [1] | 1.33 | 1.37 |
| Ansys calculation (flange support) | 1.44 | 1.50 |
| Ansys calculation (rod support) | 1.30 | 1.43 |

The Ansys results are broadly in agreement with the Gaia calculations. The results indicate that by including the stiffness of the rods in the model, the 1st generation tower fundamental frequency is lowered by approximately 10%, and the 2nd generation tower fundamental frequency by about 5%. However the Ansys results for both the 1st and 2nd generation towers remain within Gaia's required range.

**Report Parameters:**

Case ID = "4325261"

Include Related Cases = "Y" Include Investigation Tracking = "Y"

**Master Case 4325261**

| | | | |
|---|---|---|---|
| **Company ID** | 4325024 | **Company Name** | David Rider |
| **Site ID** | 4325025 | **Site Name** | Lindley Hall Farm/David Rider |
| **Date Created** | 02/05/2013 | **Status** | Open-New Case |
| **Category** | Inspection | **Assigned To** | Grady,Paul |
| **Type** | Other | **Provider Group** | SG Mechanical - South |
| **Detail** | N/A | | |
| **Problem Summary** | Lindley Hall Farm Gaia Wind Turbine Failure | | |
| **Problem Description** | Lindley Hall Farm Gaia Wind Turbine Failure | | |

**Master Case Detail**

Master Case Notes

**Note Summary** **Date Note Added** 02/05/2013 09:39:34 AM

Lindley Hall Farm Gaia Wind Turbine Failure (Steve's Input)

**Note Details** **Attachments**

Darren and I visited this site with Chris Rudall of HSL to look at a wind turbine that had fallen down. We met [redacted] plant manager for GAIA and [redacted] Operations Director for Gaia. R13 R13

The studs had failed just flush with or very close to the lower surface of the nuts under the flange. The monpole was a Mark one with 16 off M24 studs concreted into the base on a 1 metre PCD. The column flange rested on 16 nuts which ere adjusted to set the column vertical. The flange was then secured to the studs with 16 nuts on the top face with 40mm spacers. The Mark two column is secured with 24 off M30 studs and nuts. After the turbine has been in situ for a period of time, the installers return and grout the gap between turbine flange and concrete.

[redacted]

R12(5)(6)

| | | | |
|---|---|---|---|
| **SO ID** | SVC4265625 | **Provider Group** | SG Mechanical - South |
| **Date Created** | 08/05/2013 | **Assigned To** | Simmons-Jacobs,Steve |
| **Start Date** | 06/05/2013 | **Service Type** | Assessment |
| **Status** | Complete | **Service** | Specialist Assistance |

**Note Summary** — **Date Note Added** 08/05/2013 09:03:13

Specialist support to look at wind turbine failure

**Note Description**

**Attachments**

Provide specialist overview to inspection of failed Gaia small wind turbine at Otley site.

1. Observe findings in relation to wider issues relating to base failures.
2. Advise of any wider issues to be incorporated into investigation of failures
3. Report to Operational PI (H. Whittaker) Leeds in relation to any local or further issues arising from site visit