Novel Method of Strain Gauging Wind Turbine Blades

Peter Greaves
Offshore Renewable Energy Catapult

CATAPULT Offshore Renewable Energy

Abstract

A new method of interpreting strain data in full scale static and fatigue tests has been implemented as part of the Offshore Renewable Energy Catapult's ongoing development of bi-axial fatigue testing of wind turbine blades [1]. During bi-axial fatigue tests, it is necessary to be able to distinguish strains arising from the flapwise motion of the blade from strains arising from the edgewise motion. The method exploits the beam-like structure of blades and is derived using the equations of beam theory. It offers two major advantages over the current state of the art method of calibrating strain gauges - it allows the angle of the calibration winch cables to be accounted for, and also allows readings from more than 4 strain gauges around any given blade section to be incorporated into results.

The method has made it possible to process strain gauge data from bi-axial fatigue testing which also allows validation of simulation models of blade testing. The simulation model agrees well with the physical test.

Objectives

In service, wind turbine blades are fatigued in the flapwise direction by variations in aerodynamic loading and in the edgewise direction by gravity. These sources of loading occur simultaneously, so when fatigue tests are performed on the blade it is more realistic to perform the flapwise and edgewise tests at the same time.

Strain gauges are used to monitor loading during the test, and it must be possible to determine which strains arise from flapwise loading and which arise from edgewise loading. The objective of this work was to use Euler-Bernoulli beam theory to derive a transfer function that maps strain gauge readings to bending moments acting on blade cross sections.

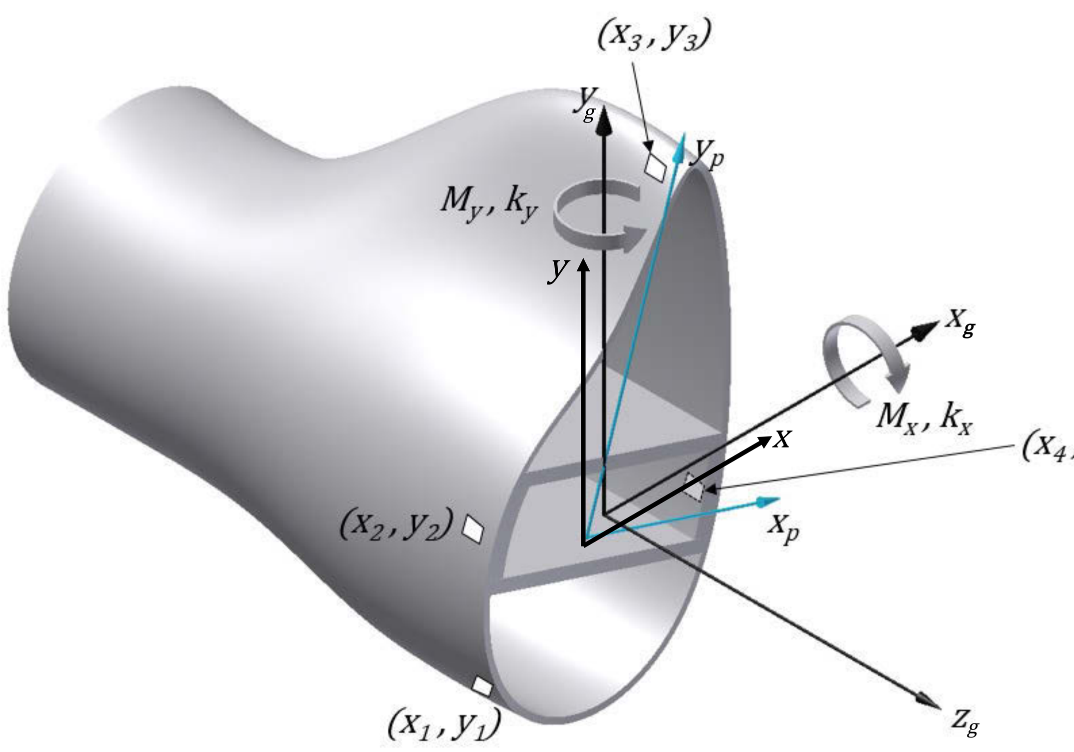
Methods

During wind turbine blade fatigue tests, strain gauges are placed on the blade at intervals along the blade length to monitor the applied loads. Typically, four strain gauges will be placed around each blade section, forming two strain gauge bridges. One of these bridges will respond predominantly to flapwise loads (bridge between the pressure and suction side) and the other will respond mainly to edgewise loads (bridge between the leading and trailing edge).

The current state of the art as described in [2] is to use a calibration matrix which characterizes the strain response to two calibration pulls, one applying a flapwise load and one applying an edgewise load. During test, moments can be calculated from the inverse of this calibration matrix:

$$\begin{Bmatrix} s_f^c \\ s_e^c \end{Bmatrix} = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \begin{Bmatrix} M_f^c \\ M_e^c \end{Bmatrix}$$

This does not allow the angle of winch cables to be accounted for and restricts the number of strain gauge readings which can be used to four. The present work uses Euler-Bernoulli beam theory to derive blade curvature from strain gauge readings. The coordinate system used is parallel to the blade root axes but has its origin at the elastic centre of the blade.



The axial strain at a given point on the blade can then be calculated from the standard equation for asymmetric bending of a beam:

$$\varepsilon_{zz} = -\frac{(M_y EI_{xx} - M_x EI_{xy})}{EI_{xx}EI_{yy} - EI_{xy}^2}x + \frac{(M_x EI_{yy} + M_y EI_{xy})}{EI_{xx}EI_{yy} - EI_{xy}^2} = -\kappa_y x + \kappa_x y = [y \quad -x] \begin{Bmatrix} \kappa_x \\ \kappa_y \end{Bmatrix}$$

Or, in matrix form for n gauges:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{Bmatrix} = \begin{bmatrix} y_1 & -x_1 \\ y_2 & -x_2 \\ \vdots & \vdots \\ y_n & -x_n \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \kappa_y \end{Bmatrix}$$

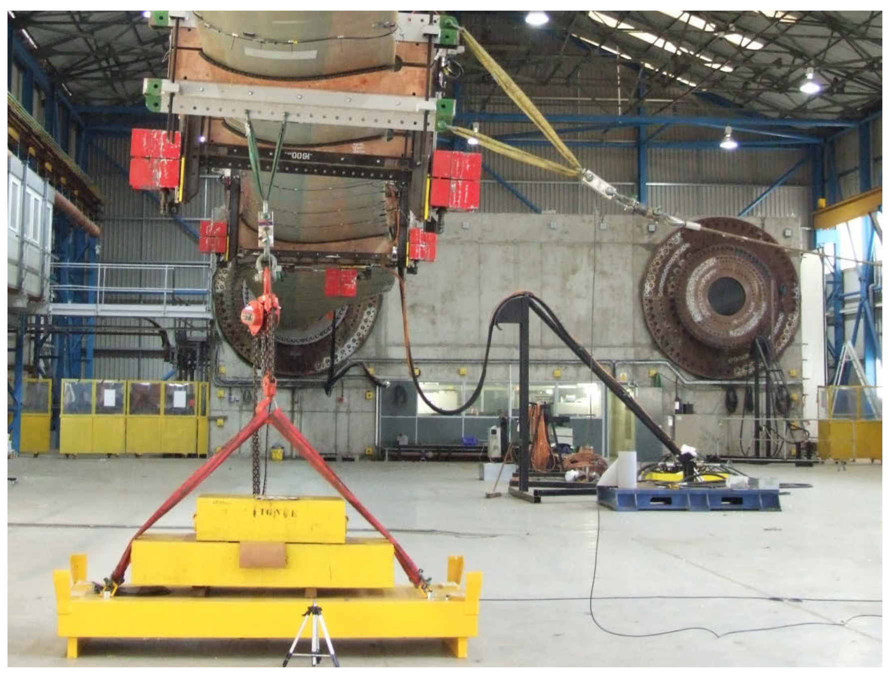
The curvature can then be calculated from strain readings by taking the pseudo inverse of this equation. The curvature for m calibration pulls can be calculated and assembled in matrix form as shown below. This equation can then be solved for the matrix B which relates curvature to applied moments. Note that arbitrary combinations of moments can be applied.

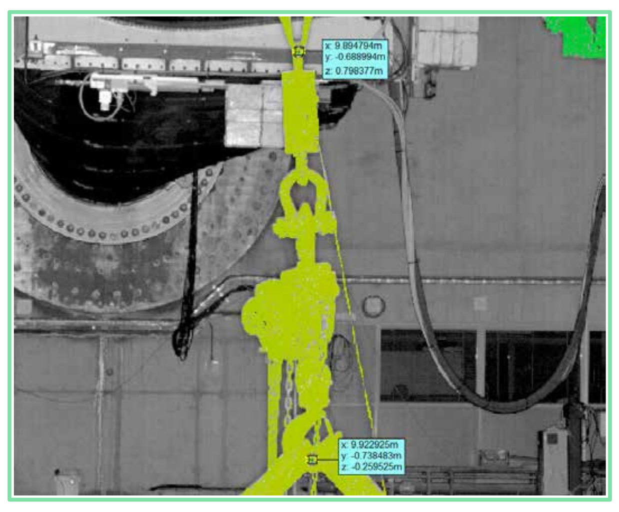
$$\begin{bmatrix} M_{x1} & \dots & M_{xm} \\ M_{y1} & \dots & M_{ym} \end{bmatrix} = \boldsymbol{B} \begin{bmatrix} \kappa_{x1} & \dots & \kappa_{xm} \\ \kappa_{y1} & \dots & \kappa_{ym} \end{bmatrix}$$

During test, the applied moments can be derived from strain readings as below, where the + notation refers to the generalized inverse.

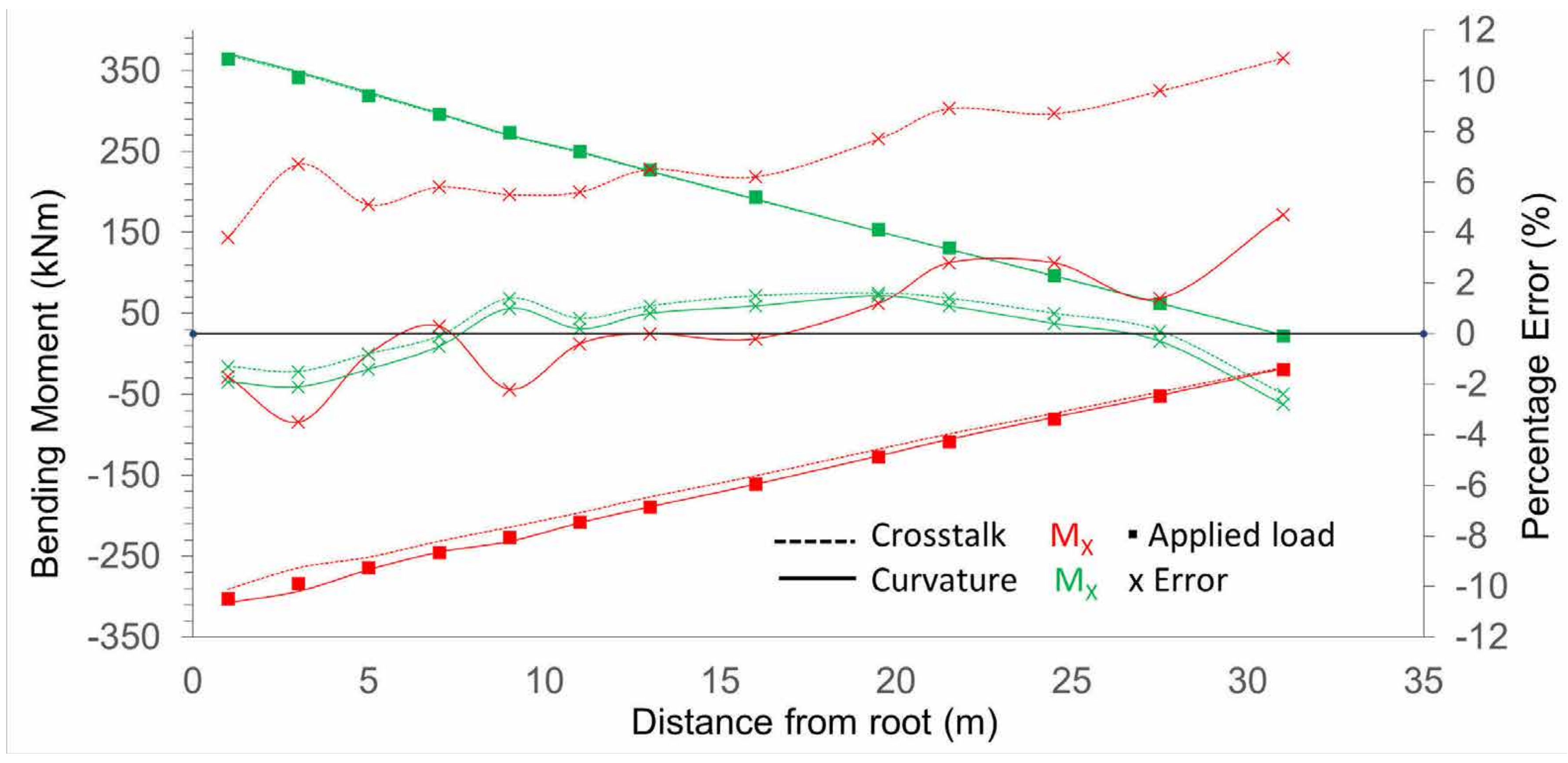
$$\begin{Bmatrix} M_x \\ M_y \end{Bmatrix} = \boldsymbol{B} \begin{bmatrix} y_1 & -x_1 \\ y_2 & -x_2 \\ \vdots & \vdots \\ y_n & -x_n \end{bmatrix}^+ \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{Bmatrix}$$

The x and y components of the applied force during calibration pulls can be accurately determined with laser measurement, as shown in the below figure.





Results and Conclusions



The method has been validated by applying a combined load at approximately 48° from the horizontal. The results demonstrate that the error is much lower with the novel method of strain gauge calibration described here than with the so-called crosstalk method, particularly for M_x loads. This is attributable to the fact that edgewise calibration pull had a significant flapwise component which is accounted for with the curvature method. Further work will focus on investigating if the use of more than four strain gauges improves results.

References

1. P. GREAVES et al, Bi-Axial Fatigue Testing of Wind Turbine Blades, *EWEA 2015. 2015: Paris, France.*
2. IEC *Wind Turbine Generator Systems - Part 13: Measurement of Mechanical Loads*