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A novel method of strain - bending moment calibration for blade testing

P Greaves^{1,5}, R Prieto¹, J Gaffing¹, C van Beveren², R Dominy³, G Ingram⁴

¹ ORE Catapult, Offshore House, Albert St, Blyth, Northumberland, NE24 1LZ, UK

² LM Wind Power, J. Duikerweg 15A, 1703 DH, Heerhugowaard, The Netherlands

³ Northumbria University, Newcastle upon Tyne, NE1 8ST, UK

⁴ Durham University, South Road, Durham, DH1 3LE, UK

⁵ Corresponding author - peter.greaves@ore.catapult.org.uk

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. 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 several advantages over the current state of the art method of calibrating strain gauges.

1. Introduction

The rotor blades are some of the most critical components of a wind turbine. Structural failure of a blade can cause widespread damage to the turbine and its surroundings, so certifying bodies require full scale testing of new designs of blades to ensure that they can withstand the loads which are predicted in service.

These tests are typically performed by cantilevering the blade from a static hub and applying loads to it. During the process of testing a full size wind turbine blade both static and fatigue tests will be performed.

Static tests involve using winches to load the blade at several points along its length, and are designed to demonstrate that the blade can survive the extreme loads which are expected in service. The loads are introduced using saddles, which closely conform to the surface profile of the blade at the location at which they are mounted.

Fatigue tests can be performed using several methods, but the overall goal is always to demonstrate that the blade can survive its fatigue life. This is done by calculating loads that would cause an equivalent amount of damage to the service life after a given number of test cycles at multiple points along the blade length, with the number of cycles chosen so that the duration of the test is acceptable without increasing the loads so much that unrealistic failure modes occur.

During their service life, blades are loaded predominantly by aerodynamic forces in the flapwise (out of the rotor plane) direction and predominantly by gravitational forces in the edgewise (in the rotor plane) direction. These loads occur simultaneously and they interact, so it is desirable to perform a fatigue test in which the flapwise and edgewise loads are applied together. A literature review discussing different approaches to this problem is performed in [1].



The work presented here was performed by the Offshore Renewable Energy (ORE) Catapult to enable test loads to be monitored during bi-axial resonant testing, in which the first flapwise and edgewise modes of the system (the blade with test equipment mounted on it) are excited simultaneously. The methods used to optimize the test configuration are described elsewhere [2]. However, the strain gauging method presented is equally applicable to other methods of fatigue testing and static testing, as well as load monitoring in service.

Clearly, it is essential during both static and fatigue tests that the applied loads along the blade length can be monitored, and this is usually done using strain gauges. There will usually be 4 strain gauges mounted around each cross section of the blade (bridges between the pressure/ suction side and leading/ trailing edge can be achieved by analog means or by post processing data), with cross sections every few meters along the blade length. On a 70m blade we might therefore expect to see around 100 strain gauges being used to monitor the test loads.

These strain gauges must be calibrated several times during a test campaign with a known load, which allows the applied load to be inferred from strain readings during the test. Several calibration methods are available, with the so called ‘crosstalk matrix’ method described in [3] being the current state of the art. This method involves using a flapwise strain gauge bridge to measure the flapwise bending moment and an edgewise strain gauge bridge to measure the edgewise bending moment. The possible crosstalk effect of the flapwise bending moment on the edgewise signal and vice versa is determined by calibration and corrected during load measurements.

The calibration is performed by applying ascending known bending moments in the flapwise direction only, followed by applying known bending moments in the edgewise direction only. At the same time, both bridge signals are measured. The dependencies of the signals on the bending moments are determined by linear regression of the signals and moments (with the resulting offset values ignored). The values for the slopes form the calibration matrix as shown in equation (1).

$$\begin{Bmatrix} s_f^c \\ s_e^c \end{Bmatrix} = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \begin{Bmatrix} M_f^c \\ M_e^c \end{Bmatrix} \quad (1)$$

In equation (1), s^c is the strain gauge bridge signal, M^c is the applied calibration bending moment and A_i are the calibration coefficients. The subscripts f and e refer to the flapwise and edgewise directions respectively, and if A_2 and A_3 are non-zero then crosstalk is present. The method is substantially better than ignoring crosstalk, but it has several disadvantages. The main issue with this method is that it cannot account for uncertainties arising from the angle of the winch cables (other than by reducing the moment to account for the cosine of the load angle error – the method does not account for an unwanted flapwise component arising during an edgewise calibration pull or vice-versa), and it is restricted to signals from 4 strain gauges.

The method presented here exploits the fact that wind turbine blades are beam-like structures, and uses beam theory to derive applied loads from strains measured on the blade surface.

2. Method

During tests, wind turbine blades will have multiple strain gauges around each cross section being monitored (typically 4, with gauges placed at the leading and trailing edge of the blade, and on the pressure and suction side spar caps). Multiple cross sections along the blade length will be monitored.

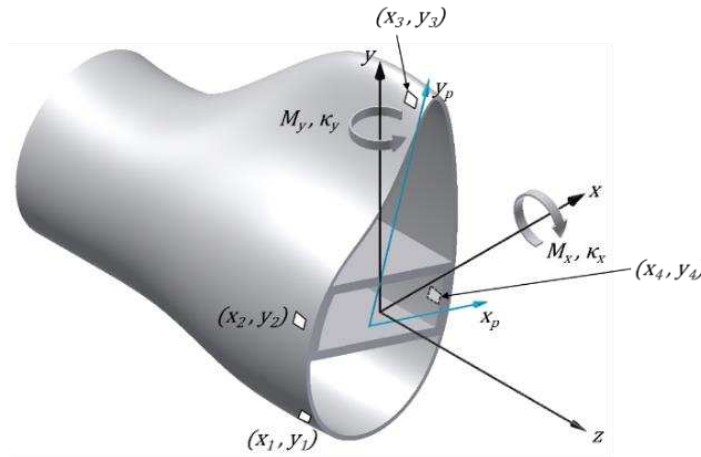


Figure 1. Cross section of a typical wind turbine blade.

Figure 1 shows a cross section through a typical wind turbine blade, along with several strain gauges defined by their location relative to the blade reference axis (marked by x_i, y_i) and the sign convention adopted for bending moments and curvatures (M and κ). The blue axes are the principal axes of the blade, with their origin at the elastic centre. There exists a matrix relating the applied forces and moments on a beam cross section and the resulting strains and curvatures as shown in equation (2). During a blade test, we are interested in monitoring the applied bending moments - M_x and M_y .

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} \gamma_x \\ \gamma_y \\ \epsilon_z \\ \kappa_x \\ \kappa_y \\ \kappa_z \end{Bmatrix} \quad (2)$$

Assuming that only bending moments and axial force contribute to strains in the axial direction and that axial forces can be neglected during blade testing (necessary assumptions which capture the most important effects during a blade test) we can reduce equation (2) to the form shown in equation (3).

$$\begin{Bmatrix} M_x \\ M_y \end{Bmatrix} = \begin{bmatrix} C_{44} & C_{45} \\ C_{54} & C_{55} \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \kappa_y \end{Bmatrix} \quad (3)$$

If the beam elastic centre (or as it is sometimes called, the neutral axis) is chosen as the reference point then equation (3) takes the form shown in (4) [4].

$$\begin{Bmatrix} M_x \\ M_y \end{Bmatrix} = \begin{bmatrix} EI_{xx} & EI_{xy} \\ EI_{xy} & EI_{yy} \end{bmatrix} \begin{Bmatrix} \kappa_x \\ \kappa_y \end{Bmatrix} \quad (4)$$

Taking the inverse of equation (4) and expanding it we can arrive at the well-known equation (5) for strain caused by asymmetric bending [4].

$$\epsilon_{zz} = -\frac{(M_y EI_{xx} - M_x EI_{xy})}{EI_{xx} EI_{yy} - EI_{xy}^2} x + \frac{(M_x EI_{yy} + M_y EI_{xy})}{EI_{xx} EI_{yy} - EI_{xy}^2} y = -\kappa_y x + \kappa_x y = [y \quad -x] \begin{Bmatrix} \kappa_x \\ \kappa_y \end{Bmatrix} \quad (5)$$

Using beam theory, the axial strain at n strain gauges located on a given cross section can be represented using equation (6). This matrix takes a block diagonal form which allows the curvature for $i = 1:m$ calibration pulls to be calculated at the same time.

$$\begin{aligned} \begin{Bmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_m \end{Bmatrix} &= \begin{bmatrix} \mathbf{X} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{X} \end{bmatrix} \begin{Bmatrix} \kappa_1 \\ \vdots \\ \kappa_m \end{Bmatrix} = [\mathbf{P}]\{\kappa\} \\ \mathbf{X} &= \begin{bmatrix} y_1 & -x_1 \\ y_2 & -x_2 \\ \vdots & \vdots \\ y_n & -x_n \end{bmatrix}, \quad \varepsilon_i = \begin{Bmatrix} \varepsilon_{1i} \\ \varepsilon_{2i} \\ \vdots \\ \varepsilon_{ni} \end{Bmatrix}, \quad \kappa_i = \begin{Bmatrix} \kappa_{xi} \\ \kappa_{yi} \end{Bmatrix} \end{aligned} \quad (6)$$

Taking the pseudo-inverse of equation (6) as shown in equation (7), we can arrive at an expression for the bending curvature from the strains.

$$\begin{Bmatrix} \kappa_1 \\ \vdots \\ \kappa_m \end{Bmatrix} = (\mathbf{P}^T \mathbf{P})^{-1} \mathbf{P}^T \begin{Bmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_m \end{Bmatrix} = \mathbf{Q} \varepsilon \quad (7)$$

Using calibration pulls, which need not be performed in line with the x and y axes as they are with the crosstalk matrix method, a matrix \mathbf{B} which relates the applied moment to the curvature can be obtained, as shown in equations (8) and (9). Whilst these calibration pulls do not need to be performed at right angles to one another or at different load levels, better results will be obtained if graduated load levels are applied in two mutually perpendicular directions.

$$\begin{bmatrix} M_{x1} & M_{x2} & \dots & M_{xm} \\ M_{y1} & M_{y2} & \dots & M_{ym} \end{bmatrix} = \mathbf{M} = \mathbf{B} \begin{bmatrix} \kappa_{x1} & \kappa_{x2} & \dots & \kappa_{xm} \\ \kappa_{y1} & \kappa_{y2} & \dots & \kappa_{ym} \end{bmatrix} = \mathbf{B} \mathbf{K} \quad (8)$$

$$\mathbf{B} = (\mathbf{K}^T (\mathbf{K} \mathbf{K}^T)^{-1} \mathbf{M}^T)^T \quad (9)$$

Finally, during test the strain gauge data from n strain gauges at each section can be processed to obtain the bending moments using equation (10).

$$\begin{Bmatrix} M_x \\ M_y \end{Bmatrix} = \mathbf{B} (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{Bmatrix} \quad (10)$$

The mean bending moment due to the blade self-weight and test equipment must also be accounted for. This is calculated from the blade mass distribution and the mass and location of the test equipment.

3. Experimental Configuration

The proposed method of calibrating strain gauges has been applied to a full scale blade in the ORE Catapult 50m Blade Test Facility (BTF 1). Some key features of the facility are shown in Table 1.

Table 1. ORE Catapult BTF 1 Capabilities

Facility Capability	Facility 1
Maximum blade length	50m
Number of static winches	7
Hub height	4.2m
Hub inclination angle	1° on both hubs
Winch Height	3.9m (Adjustable)
Maximum lift	30t
Dynamic testing	Hydraulic resonant mass
Maximum hub moment	50MNm
Maximum static tip deflection	13m
Dynamic tip-to-tip deflection	10m (vertical), 8m (horizontal)
DAQ (strain gauge channels)	128
Slew drive capability	Rotate blade on test hub

An LM 40.3 P2 blade has been used for this exercise, and some key features of the blade are shown in Table 2. The blade has been instrumented with 64 strain gauges, plus two strain gauges for control of dynamic testing. The strain gauges are mounted at 16 sections, with 4 uniaxial strain gauges at each section. The strain gauges were calibrated using winches attached to a saddle mounted 33m from the root, which was the furthest position for which a wooden profile to clamp the saddle to the blade was available. This means that the 12 strain gauges at the 3 stations beyond this point could not be calibrated, so they are not included in this analysis.

The pressure and suction side strain gauges are mounted centrally on the spar cap, whilst the leading and trailing edge gauges are mounted on the suction side 50mm from the leading or trailing edge. Their coordinates relative to the blade reference axis (which are required for the method described here to be applied) were found from a surface model of the blade provided by LM Wind Power.

Table 2. LM 40.3 P2 Blade Data

Blade Type	LM 40.3 P2
Turbine Rated Power	1.5MW
Blade Length	40m
Bolt circle diameter	1.8m
Max Chord	3.25m
Pre-bend	2m
Blade mass	6270kg

For the purposes of this experiment, the blade was mounted on the hub with the 0° marker plate as close to the horizontal as was possible, given the restrictions caused by the number and position of the blade mounting bolts. This results in the blade being slightly pitched on the test stand, with the pressure side facing up and the trailing edge raised by 0.4°.

Calibration pulls were performed at 5 load levels for both the flapwise and edgewise directions. For the flapwise direction the forces were evenly spaced between 10kN and 20kN, and for the edgewise direction the forces were evenly spaced between 10kN and 24kN. These forces do not correspond to either the static or dynamic fatigue loads – they are appropriate because of the sensitivity of the test equipment.

For the flapwise calibration, the blade was pulled down against a 6.75t reaction block using a chain block with a load cell mounted in the load path as shown in Figure 2. The reaction block was placed so

that the force was applied vertically down from the shear centre of the blade at the saddle location to minimise the induced torsional moment.

For the edgewise calibration, the blade was pulled using a static test winch mounted 31.95m from the blade root on the winch wall, which is 14.75m from the hub centreline and 3.9m from the floor. The winch cable can be seen in Figure 2. The chain block used for the flapwise calibration was completely disconnected for the edgewise calibration.



Figure 2. Flapwise calibration pull configuration also showing edge winch cable

During both calibration pulls, the test configuration was scanned at each hold point using a FARO Focus 3D scanner [5]. This device uses a laser to measure the distance to objects whilst simultaneously recording the angle of the scanning head in the vertical and horizontal plane, allowing it to record a point cloud with images superimposed on top. The coordinates of a point in 3D space relative to the scan head can then be read off in the post processing software (FARO Scene LT). For this exercise, the test hall was scanned only in the direction of the blade and 7.3 million points were recorded over a 45° horizontal angle and a 50° vertical viewing angle. The accuracy of the measurement is $\pm 2\text{mm}$, so by choosing points which are sufficiently far apart on the load introduction cables it is possible to obtain highly accurate load vectors, as shown in Figure 3 and Table 3. The load vector was calculated multiple times from the same image using different points on the winch cables to ensure that the results were repeatable.

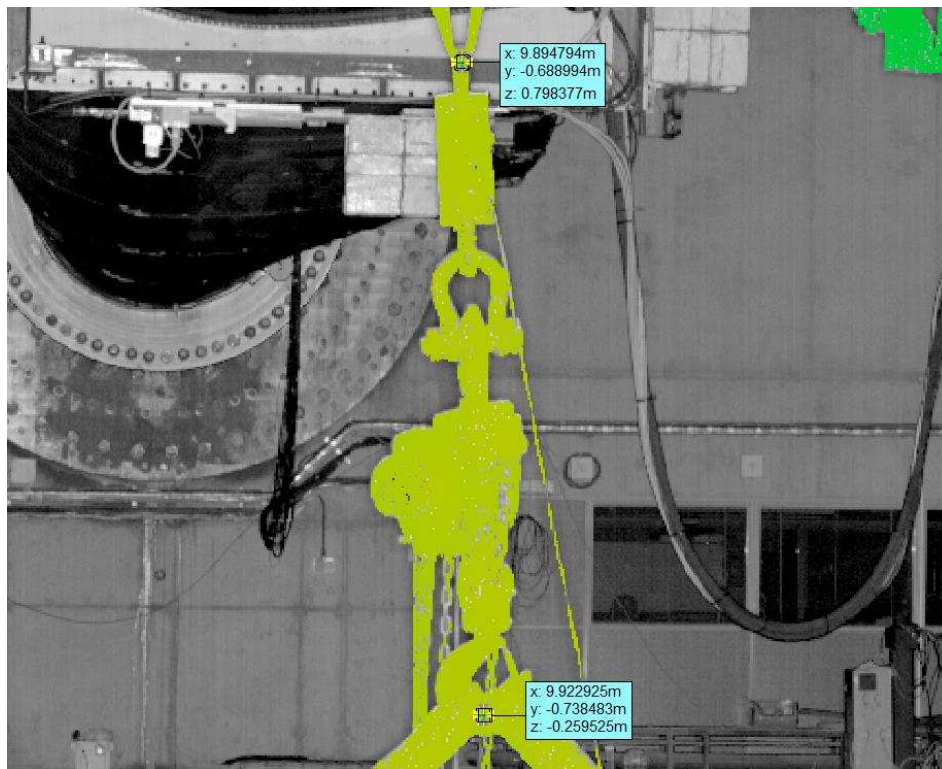


Figure 3. Load vector calculation using FARO Focus 3D Scanner

Table 3. Calibration pull forces and load vectors (in DNV-GL coordinate system [6])

Hold Point	Winch Force (kN)	u	v	w	F _x (kN)	F _y (kN)
Flap 1	10.22	1.00	0.03	0.01	10.22	0.25
Flap 2	12.64	1.00	0.03	0.00	12.63	0.38
Flap 3	15.00	1.00	0.04	-0.01	14.98	0.54
Flap 4	17.51	1.00	0.04	-0.02	17.49	0.72
Flap 5	20.09	1.00	0.05	-0.03	20.06	0.94
Edge 1	10.14	0.02	1.00	-0.05	0.17	10.13
Edge 2	15.05	0.02	1.00	-0.04	0.27	15.03
Edge 3	17.72	0.02	1.00	-0.03	0.33	17.70
Edge 4	20.07	0.02	1.00	-0.02	0.39	20.05
Edge 5	24.71	0.02	1.00	-0.01	0.50	24.70

In order to validate the proposed strain gauging method, a combined flapwise and edgewise pull has been applied using the test configuration shown in Figure 4.



Figure 4. Combined load test configuration

As the loading was being applied by hand using the chain block, the coefficient of friction of the steel masses on the concrete floor had safety implications. For this reason, it was checked prior to loads being applied by pulling a 2000kg steel block using the winch. The winch cable made an angle of 19.95° from horizontal, and the block slid when the cable tension was 7kN. This corresponded to a friction coefficient of 0.38. Using the 5000kg blocks, it was therefore safe to apply a load of 15kN at an initial angle of approximately 54° from the horizontal.

The FARO Focus 3D system was used in the same way as it was used for the calibration pulls to determine the load vector when the full load was applied.

4. Results

The curvature based method of strain gauging has been assessed by comparing the bending moments derived from the crosstalk method described in [3], the curvature method described in the present work and the applied bending moments. The applied bending moments were calculated from the axial distance of each section from the calibration saddle, the applied load as measured by the load cell and the load vector as measured by the FARO Focus 3D scanner. The applied loads vector at a load of 14.79kN was: $x = 0.769$, $y = 0.638$, $z = -0.035$. At the saddle the change in height from the root was less than 0.3m (a result of the blade pre-bend and the test stand inclination angle) so the z component of the force could be neglected. At most, this would introduce an error of less than 0.05%.

A sensitivity analysis to the strain gauge coordinates showed that the method is very insensitive to these values. This is because the \mathbf{B} matrix found in equations (8) and (9) will just change to accommodate inaccuracies in strain gauge coordinates as part of the ‘least squares’ fitting process.

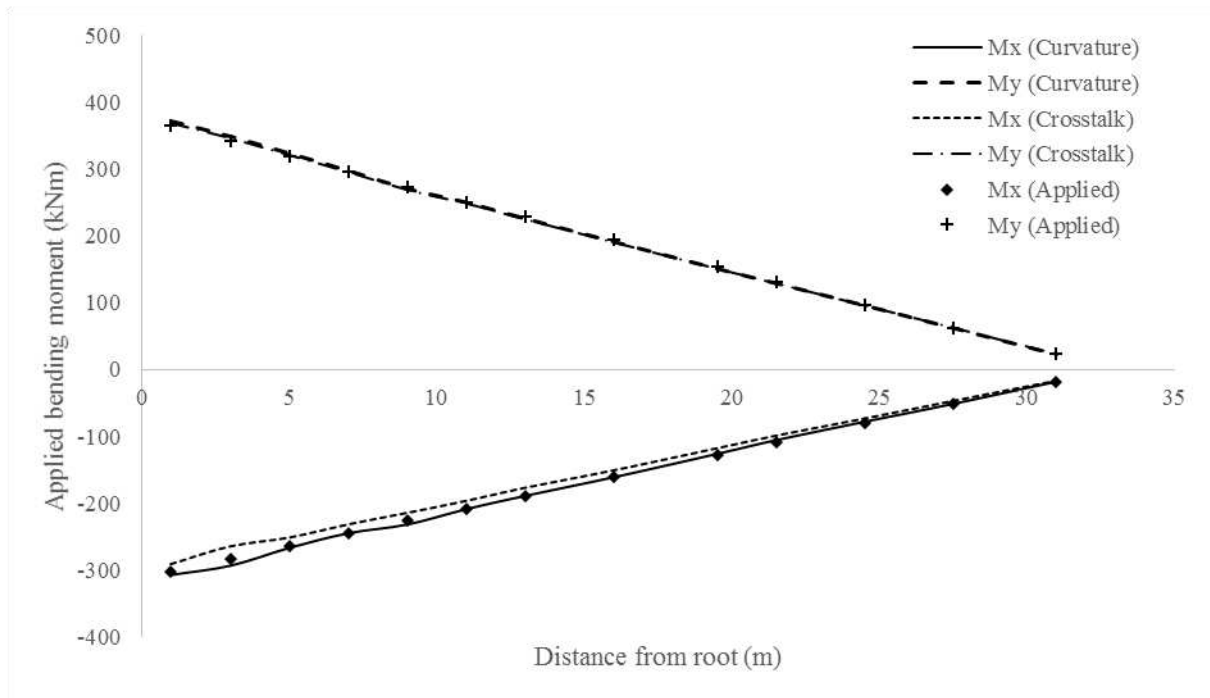


Figure 5. Comparison of applied versus derived bending moments for crosstalk and curvature methods

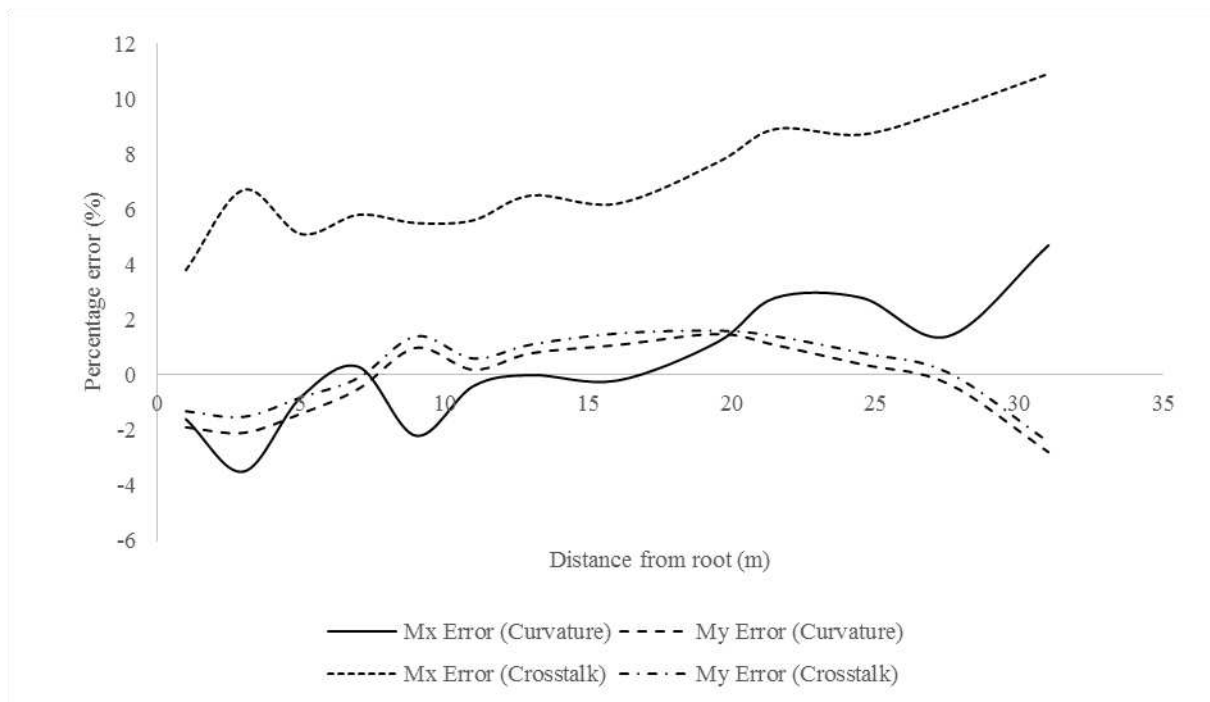


Figure 6. Comparison of percentage error for different calculation methods

The curvature method clearly results in reduced error overall, in particular for the edgewise (M_x) moments. This is a result of the fact that it is possible to account for the angle of the winch cables during the calibration pulls – In Table 3 it can be seen that almost 5% of the flapwise calibration force acts in the edgewise direction.

It would be possible to improve the crosstalk matrix method by calculating the \mathbf{A} matrix using a different method that accounts for the angle of the winch cables during calibration. Replacing the curvatures in equations (8) and (9) with strain bridge values we can solve for \mathbf{A} in a different way to that described in [3] as shown in equations (11) and (12). The strain bridge sensitive to M_x loads ε_x is the difference between the leading and trailing edge gauge values, whilst the strain bridge sensitive to M_y loads ε_y is the difference between the pressure and suction side gauge values. This eliminates the need to know the strain gauge coordinates, but means that only four strain gauges per cross section can be used.

$$\begin{bmatrix} M_{x1} & M_{x2} & \dots & M_{xm} \\ M_{y1} & M_{y2} & \dots & M_{ym} \end{bmatrix} = \mathbf{M} = \mathbf{A} \begin{bmatrix} \varepsilon_{x1} & \varepsilon_{x2} & \dots & \varepsilon_{xm} \\ \varepsilon_{y1} & \varepsilon_{y2} & \dots & \varepsilon_{ym} \end{bmatrix} = \mathbf{AE} \quad (11)$$

$$\mathbf{A} = (\mathbf{E}^T (\mathbf{E}\mathbf{E}^T)^{-1} \mathbf{M}\mathbf{E}^T)^T \quad (12)$$

This may be a useful intermediate step using the same number of strain gauges that are typically placed on a blade.

5. Conclusions

A novel method for calibrating strain gauges has been developed. It properly accounts for the misalignment of the applied loads by including the effects of winch cable angle during calibration pulls which are only partially accounted for with the crosstalk method. This has been shown to be a significant cause of errors with the current best practice technique proposed in the standards. The method also has the advantage that it allows strain readings from an arbitrary number of gauges to be included for any given blade section, which would reduce errors arising due to noise. Future work will focus on validating the use of the technique with more than 4 strain gauges.

6. Acknowledgements

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