Damage Detection in Wind Turbine Towers using a Finite Element Model and Discrete Wavelet Transform of Strain Signals

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Abstract. Wind turbine support towers at heights in excess of 90m are nowadays being formed in steel, concrete and hybrid concrete and steel structures. As is the case for all towers of this height, the towers will be assembled using a number of segments, which will be connected in some way. These local connections are to be viewed as areas of potential local weakness in the overall tower assembly and require care in terms of design and construction. This work concentrates on identifying local damage which can occur at an interface connection by either material or bolt/tendon failure. Spatial strain patterns will be used to try to identify local damage areas around a 3-dimensional tower shell. A Finite Element (FE) model will be assembled which will describe a hybrid tower as a continuum of four-noded, two-dimensional Reisser-Mindlin shell elements. In order to simulate local damage, an element around the circumference of the tower interface will be subjected to a reduced stiffness. Strain patterns will be observed both in the undamaged and damaged states and these signals will be processed using a Discrete Wavelet Transform (DWT) algorithm to investigate if the damaged element can be identified.

1. Modelling of the Wind Turbine Tower

A well-established means of generating the elemental stiffness of finite elements in engineering is to follow a variational functional approach commonly used in structural mechanics based on the potential energy functional [1]. What results is an integral expression which implicitly contains the differential equations and is known as the weak form of the problem statement. This method was employed by Kenna and Basu [2] to generate local stiffness matrices for shell elements with in-plane and out-of plane degrees of freedom which were then assembled into a three-dimensional wind turbine FE model. Each model elemental stiffness matrix, [k] is expressed as

\[ k = \int \left( B^T \right) \left( C \right) \left( B \right) dV \] (1)

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The term \([C]\) here is the material constitutive description. The element form used in defining the tower continuum in this paper is an isoparametric bilinear quadrilateral, with membrane and plate bending properties to give the element shell capabilities. The membrane stiffness matrix is to be mapped to local co-ordinates and integrated numerically.

\[
k_m = t \iint (B_m)^T [C_m] B_m \det[J] d\varepsilon d\eta
\]  
(2)

The term \(t\) is the thickness of the shell element. The subscript ‘\(m\)’ here denotes the application to the membrane degrees of freedom of the element. The term \([J]\) denotes the Jacobian matrix, used to transform derivatives of displacements with respect to \(x\) and \(y\) to those with respect of \(\varepsilon\) and \(\eta\). For the out-of-plane bending and transverse displacement degrees of freedom, a separate portion of the element stiffness matrix must be set up as outlined in a text by Zienkiewicz [3]. The Mindlin plate stiffness matrix is defined as follows

\[
k_p = \iint [B_b]^T [C_b] B_b \det[J] d\varepsilon d\eta + \iint [B_j]^T [C_j] B_j \det[J] d\varepsilon d\eta
\]  
(3)

where the subscripts ‘\(b\)’ and ‘\(s\)’ relate to the bending and shear strain-displacement respectively. Once the membrane and plate co-efficients are in place for each element, they are then combined to form the shell element elastic stiffness matrix as follows.

\[
k_{\text{elastic}} = \begin{bmatrix} k_m & 0_{8 \times 12} \\ 0_{12 \times 8} & k_p \end{bmatrix}
\]  
(4)

Note that there are no coupling terms between the membrane and bending co-efficients in this matrix. The material elasticity matrices used in defining the membrane and plate co-efficients are as follows

\[
C_m = \frac{E_c}{(1 - \nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & 1 - \nu \end{bmatrix}, \quad C_b = \frac{E_c t^3}{12(1 - \nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & 1 - \nu \end{bmatrix}, \quad C_s = \frac{E_c t^5}{2(1 + \nu)} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]  
(5)

\(E_c\) is the modulus of concrete and \(\nu\) denotes the poisson’s ratio. It is noted that the same matrix assemblies are used in the case of steel elements, where an appropriate modulus and poisson’s ratio for steel are used. The above local element quantities are defined for each element in the tower model before being transformed to the global structural co-ordinate system and finally assembled to a global stiffness matrix. The global matrix \([K]\) is simply the summation of all individual element matrices which have been transformed as above.

\[
[K] = \sum_{i=1}^{\text{numelement}} [K_i]
\]  
(6)
2. Load Application
The load to be applied to the tower will be a lateral tower top load which will simulate the loading applied by the rotor. The Blade Element Momentum (BEM) method is used to determine a suitable load for this thrust, whereby the aerodynamic properties of an airfoil (rotor blade) are utilised in tandem with the prevailing wind speeds and blade rotational speed to generate nodal drag and lift loadings acting on elements of the blades. Hansen [4] describes this method in detail in his text on the subject. The NREL 5mw baseline wind turbine [5] was used in developing the BEM loading information in terms of the airfoil aerodynamic properties and blade geometry and material properties. The speed of rotation was held to a constant 12.1rpm/0.201Hz, which is the normal operating rotation speed for this rotor. The algorithm was run a number of times to assess the variation of load at different normal operating wind speeds. The results are provided in Table 1.

| Wind Speed (mps) | Thrust (kN) |
|------------------|-------------|
| 7.000            | 370.927     |
| 8.000            | 450.605     |
| 9.000            | 534.139     |
| 10.000           | 617.821     |
| 11.000           | 699.506     |
| 12.000           | 771.966     |
| 13.000           | 833.871     |

3. Damage Detection using Wavelet Transformation
Wavelet transformation can be seen as being an extension of the Fourier transform, being a modern means of decomposing a temporal or spatial signal. Chang and Chen [6] presented a paper proposing the use of a spatial based wavelet approach in order to detect the location of a crack in a rotating blade. They found that the distributions of wavelet coefficients can identify the crack location by showing a peak at the position of the cracking. Liew and Wang [7] presented an earlier work whereby they showed that wavelets can be used to identify a crack location in an Euler-Bernoulli beam element. Law et al [8] studied the use of wavelets from the point of view of assessing the sensitivity of the wavelet coefficient from structural responses with respect to system parameters. Their work concluded that the wavelet co-efficients are more sensitive than the structural responses to local structural changes.

A continuous wavelet transform of a function $f(x)$ is defined as

$$W_f(a, b) = \frac{1}{\sqrt{|a|}} \int f(x) \psi^*(\frac{x-b}{a}) dx$$

(7)

Where $b$ is a translation parameter, $a$ is a scale parameter, $f(x)$ is the input signal expressed spatially and which is to be transformed, $\psi^*(\cdot)$ is the complex conjugate of the basis wavelet function $\psi(\cdot)$. Finally, $W_f$ is the wavelet transform which is to be found. A discrete version of this
transformation is to be employed in this paper given the discretised finite element results and thus signal. The scale and translation parameters are therefore discretized in a binary format as

\[ a = 2^j \quad b = 2^j k \quad j, k \in \mathbb{Z} \]  

(8)

In the above, \( \mathbb{Z} \) is a defined set of positive integers. The signal can now be decomposed into a series as below

\[ d_{j,k} = \int f(x) \psi_{j,k}(x) dx \]  

(9)

Where \( d_{j,k} \) is the wavelet co-efficient. In this paper, the Daubechies wavelet of order 10 and Level 1 is used to decompose the strain signal.

A wind turbine tower is subjected here to a lateral load of 500kN as noted above. The geometry of this tower is approximately based upon a conceptual hybrid tower put forward by the Concrete Centre [9] for a 100m hub height. The said tower has a base and top diameter of 12m and 3m respectively. The concrete-steel interface height is taken as 70m above ground level. The shell thickness taken for the lower concrete segment is 350mm and 24mm for the upper steel shell. The concrete compressive strength is given as 50MPa. Although not provided in the literature, a density of 2450 kg/m\(^3\) and a poisson’s ratio of 0.15 is assumed for the concrete. A density of 7850 kg/m\(^3\) and a poisson’s ratio of 0.30 is assumed for the steel segment. After having applied the lateral load of 500kN, a series of loads increasing from 370kN to 833kN (representing prevalent wind speeds of 7mps to 13mps) were applied to the tower top. This was carried out to investigate any change in the strain pattern as a result of the increase in load for the undamaged tower. It was found that after normalising the strain at each load level that there was no change in pattern and so this pattern is independent of the load intensity.

Figure 1 shows the deflected shape of the overall tower after having imposed the tower top lateral load. Damaged circumferential locations were next simulated by reducing a given finite shell elements’ planar stiffness. This was carried out at three locations. On each occasion, the strain signal was extracted from the interface circumference and this was processed with a discrete wavelet transformation as discussed above.

Figure 2 (a, b and c) shows the strain signals of the undamaged circumference overlaid with the damaged circumference appropriate for each damaging event. It can be seen that the change in strain profile is marginal but nonetheless is present in the region around the damaged finite element. Figure 3 presents a close-up view of the strain signals around the damaged element whose overall strain is shown in Figure 2b.

It was found that after transforming the strain signal of the damaged towers that this lead to a visible change in the pattern of the detail component of the wavelet transform. In order to better show where a change in the peaks has occurred, the component quantities for the damaged and undamaged states were combined. The results are presented in Figure 4 (a, b and c). Here the damaged locations are clearly evident by the new peaks which represent the arithmetic difference between the damaged and undamaged coefficients.

Finally, the tower model which depicted damage at the \( \frac{1}{2} \) circumference length position was taken and strain quantities were extracted for all shell elements in a vertical line from the tower base to the tower top. A DWT was carried out on these spatial signals in the same way as the circumferential signal to observe if the damaged location could be identified. It was found that even though a sudden change in strain profile exists given the change in material at this location, this does not prohibit the ability of the DWT to locate damage in this immediate area. In this case a stiffness reduction from the original 100% to a damaged stiffness of 50% was imposed.
4. Conclusions

It was proposed to use a spatial strain signal extracted from the interface circumference as a means of identifying damage at this location. A first step was to assess if this method would be independent of the size of loading imposed at the tower top due to rotor thrust. After applying a number of loads and normalising the strains, it was found that the strain pattern was not affected by loading intensity. As such, this means damage could be detected at any level of tower response.

After having extracted the normalised strain signal for the undamaged tower, a number of signals for various damaged towers were found. These spatial signals were all transformed using the DWT technique and co-efficients were found for low and high frequency components. The high frequency components of these signals identified the change in slope from one finite element to the next. By combining the coefficients for this high frequency component in terms of taking the undamaged and relevant damaged co-efficients, it can be seen that the region of damage can be clearly identified. Although absolute changes in the strain signal were shown to be minute and possibly undetectable without some form of signal processing, the DWT carried out was well suited to detecting the changes. This method of using Spatial DWT of the strain signal could be a powerful means of locating damage at wind turbine tower interface connections. Strain profiles were taken circumferentially in the majority of cases in this work, with an advantage of this approach being that the strain pattern is independent of the load level.

![Figure a - Tower Mesh, Before and After Loading](image-url)
Figure 2 (a, b and c) - Damaged vs Undamaged Strain Signals
Figure 3 – View of Local Strain Profile in Damaged Region at 1/2 circumference length
Figure 4 (a, b and c) - Wavelet Decomposition, Detail Component Differences

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