

may become ill-conditioned and alternate methods to estimate damage parameters must be sought. In an effort to overcome this difficulty, an algorithm was formulated using a frequency-change ratio and a sensitivity ratio that are based on earlier works presented by Cawley (1979), Stubbs (1991)

Consider a structural system with NE elements ($j = 1, 2, \dots, q, \dots, NE$) and a measured set of NM vibration modes ($i = 1, \dots, m, n, \dots, NM$). Eq. (1) is rewritten for any two modes m and n ($m \neq n$), respectively. Dividing Eq. (1) for mode m by the Eq. (1) for mode n , gives:

$$\frac{Z_m}{Z_n} = \frac{\sum_{j=1}^{NE} F_{mj} \alpha_j}{\sum_{j=1}^{NE} F_{nj} \alpha_j} = \frac{F_{m1} \alpha_1 + F_{m2} \alpha_2 + \dots + F_{mq} \alpha_q + \dots + F_{mNE} \alpha_{NE}}{F_{n1} \alpha_1 + F_{n2} \alpha_2 + \dots + F_{nq} \alpha_q + \dots + F_{nNE} \alpha_{NE}} \quad (4)$$

Assuming that the structure is damaged at a single location q , such that $\alpha_j \neq 0$ when $j = q$ but $\alpha_j = 0$ when $j \neq q$, Eq. (4) is rewritten by:

$$Z_m / Z_n = F_{mq} / F_{nq} \quad (5)$$

in which Z_m/Z_n is the ratio of the fractional change in m^{th} eigenvalue to the fractional change in n^{th} eigenvalue. Note also that F_{mq}/F_{nq} is the ratio of the sensitivity for m^{th} mode and q^{th} element to the sensitivity of n^{th} mode and q^{th} element. Thus, the damage inflicted at that location is defined by Eq. (5) equaling the L.H.S to the R.H.S.

For all measured NM modes, Eq. (5) can be extended into:

$$Z_m / \sum_{k=1}^{NM} Z_k = F_{mq} / \sum_{k=1}^{NM} F_{kq} \quad (6)$$

Note that Eq. (6) is true only if element q is damaged. An error index is introduced in Eq. (6) as follows:

$$e_{ij} = Z_m / \sum_{k=1}^{NM} Z_k - F_{mq} / \sum_{k=1}^{NM} F_{kq} \quad (7)$$

where e_{ij} represents localization error for the i^{th} mode and the j^{th} location, and $e_{ij} = 0$ indicates that the damage is located at the j^{th} location using the i^{th} modal information. A single damage indicator (DI) for the j^{th} member as:

$$DI_j = \left[\sum_{i=1}^{NM} e_{ij}^2 \right]^{-1/2} \quad (8)$$

where $0 \leq DI_j < \infty$ and the damage is located at element j^{th} if DI_j approaches the local maximum point.

3. NUMERICAL EXPERIMENT

3.1 Description of Test Structure

In this study, a numerical modeling of wind turbine tower (WTT) was performed to evaluate the FBDD method. The target structure was 3 MW onshore WTT located at

Woljeong-ri, Jeju Island, Korea shown in Fig. 1. In order to obtain dynamic properties, the mass of the rotor blades, the rotor and the nacelle were considered as concentrated mass. Thus, it was assigned to a rigid node at the nacelle's level. The modal responses of the structure were generated using finite element (FE) models before and after damaged states.



Fig. 1 A target onshore WTT

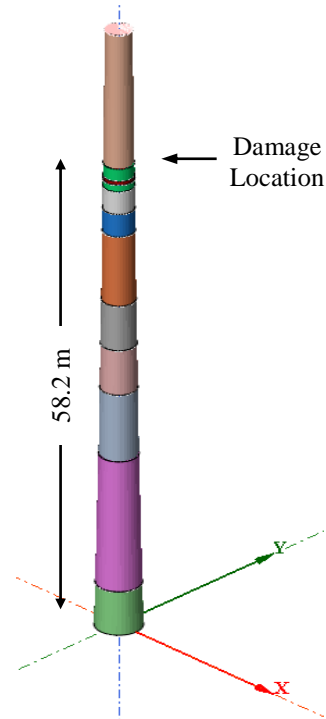


Fig. 2 FE model of the WTT

The real WTT structure consists of 27 segments with different cross-sections. In the FE model, the tower was simulated by shell elements with 10 segments corresponding to the changes in the thickness as shown in Fig. 2. The flanges were also combined to the nearest segments as an integral ones.

In the present study, the element size in vertical direction was chosen in such a way that almost square grid occurs. The same discretization with 36 quadrilateral elements in the circumferential direction was applied throughout the tower to ensure the mesh consistency. As shown in Fig. 1, the WTT was model with the height $H = 77.3$ m. The diameter D at the bottom and the top levels were 4.15 m and 2.3 m, respectively. For modal analysis purposes, the FE model was divided into 773 block elements along to symmetric axis of the tower with 0.1 m intervals in height. A mass node was established in the center of the top circle. It was connected with 36 nodes at the top level by rigid link. Then, a total mass (107.8 tons) represented for the mass of rotor and nacelle was

assigned to mass node (Fig. 3). The connection between tower bottom and the base of tower was assumed as rigid. In other words, the tower was considered to be fixed at the bottom level (Fig. 4). The vibrations of the rotor blades were neglected. Material properties of FE model were defined for steel elements as the elastic modulus $E = 210 \text{ GPa}$, Poisson's ratio $\nu = 0.3$ and the linear mass density $\rho = 7850 \text{ kg/m}^3$.

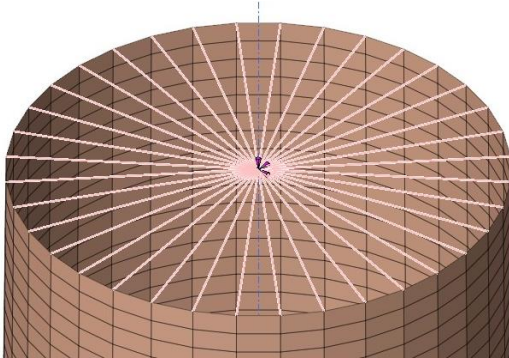


Fig. 3 Modeling of concentrated mass

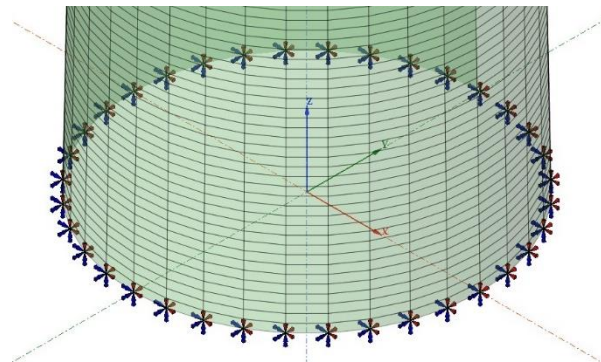


Fig. 4 Modeling of bottom's constraints

The pre-damage and post-damage modal parameters of the FE model were generated numerically using commercial software midas FEA. Here, three single damage cases were investigated corresponding to stiffness reduction ($\alpha = -0.1, \alpha = -0.2, \alpha = -0.3$). The damage region was located from 58m to 58.4m in height (Fig. 2). The damage was simulated by reducing elastic modulus E to change the flexural rigidity EI because of assuming no change in structural mass.

The extracted modal parameters of the test structure included the pre-damage and post-damage frequencies and mode shapes of the first three bending modes. The natural frequencies for the undamaged state and the three damage cases are listed in Table 1. The mode shape vectors were read at 12 locations outside surface that are equally spaced along the tower's longitudinal axis (e.g., 7m between two adjacent locations). The undamaged mode shapes of the test structure are shown in Fig. 5

Table 1. Damage cases and natural frequencies of the WTT FE model

Damage Case	Inflicted Damage		Natural Frequency (Hz)		
	Location (m)	Severity ($\Delta EI/EI$)	Mode 1	Mode 2	Mode 3
Reference	-	-	0.330101	2.71884	7.74009
Case 1	58.2	-0.1	0.330054	2.71754	7.73674
Case 2	58.2	-0.2	0.329995	2.71592	7.73257
Case 3	58.2	-0.3	0.329919	2.71385	7.72725

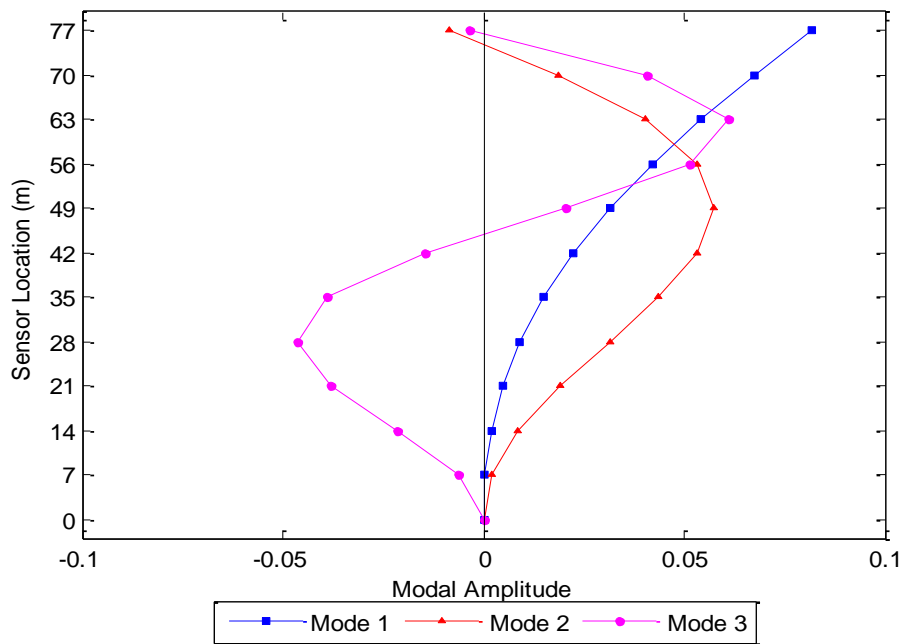


Fig. 5 Mode shapes of the WTT

3.2 Damage Detection by FBDD Method

The Euler–Bernoulli beam model was selected as the damage detection model (DDM). Modal parameters needed for the FBDD process are pre-damage and post-damage natural frequencies and pre-damage mode shapes. The DDM of the structure consists of a total of 770 beam elements with different size (the 0.3m-height section at the top is neglected). We justify the use of a 0.1m wide element by interpolating measured modal vectors at the 771 nodal points of the damage detection model obtained by the use of spline functions and the element modal amplitude values from the mode shapes of the FE model. Using the interpolated modal coordinates for the beam, we generated functions $\phi(z)$, where z is the coordinate along the symmetric axis of the tower.

The modal sensitivity of mode i^{th} and element j^{th} between two locations (z_j, z_{j+1}) was computed by Kim (1995), Kim (2003):

$$F_{ij} = \int_{z_j}^{z_{j+1}} EI \{\phi_i''(z)\}^2 dz / K_i ; K_i = \int_0^l EI \{\phi_i''(z)\}^2 dz \quad (9)$$

The curvatures of the mode shapes were generated at the 771 nodes of the damage detection model. Since two natural frequencies are available, the sensitivities are defined for 2 modes and 770 DDM elements.

The fractional changes in frequencies (i.e., Eq. (2)) were computed by using the frequency results listed in Table 1. Because the j^{th} and $(j+1)^{th}$ are different in cross section, the inertial moment I is also not consistent. Therefore, the sensitivity ratio (i.e., the right-hand side of Eq. (6)) for an element q and for any two modes m and n can be rewritten by:

$$\frac{F_{mq}}{F_{nq}} = \frac{\int_q I_q \{\phi_m''\}^2 dz}{\int_q I_q \{\phi_n''\}^2 dz} \cdot \frac{\int_0^l I \{\phi_n''(z)\}^2 dz}{\int_0^l I \{\phi_m''(z)\}^2 dz} \quad (10)$$

Next, localization errors were computed using Eq. (7) for 3 modes and 770 locations (i.e., e_{1j} and e_{2j} , $j=1 \div 770$) by implementing the sensitivity ratios and the fractional changes in frequencies. Finally, we computed the single damage index given by Eq. (8) to decide potential crack locations. As the mention above, damage indices of two single damage cases are plotted in Fig. 6. Note that the prediction was made by indicating DDM elements. In Fig. 6(a), the crack was simulated at the 58~58.4m and it is identical to the DDM element 582 corresponding to $\alpha = -0.1, \alpha = -0.2$, respectively. The predicted peak was exact to point out the simulated location (i.e. DDM element 580~584). Also, the similar result is performed in Fig. 6(b) in which the predicted peak was DDM element 583.

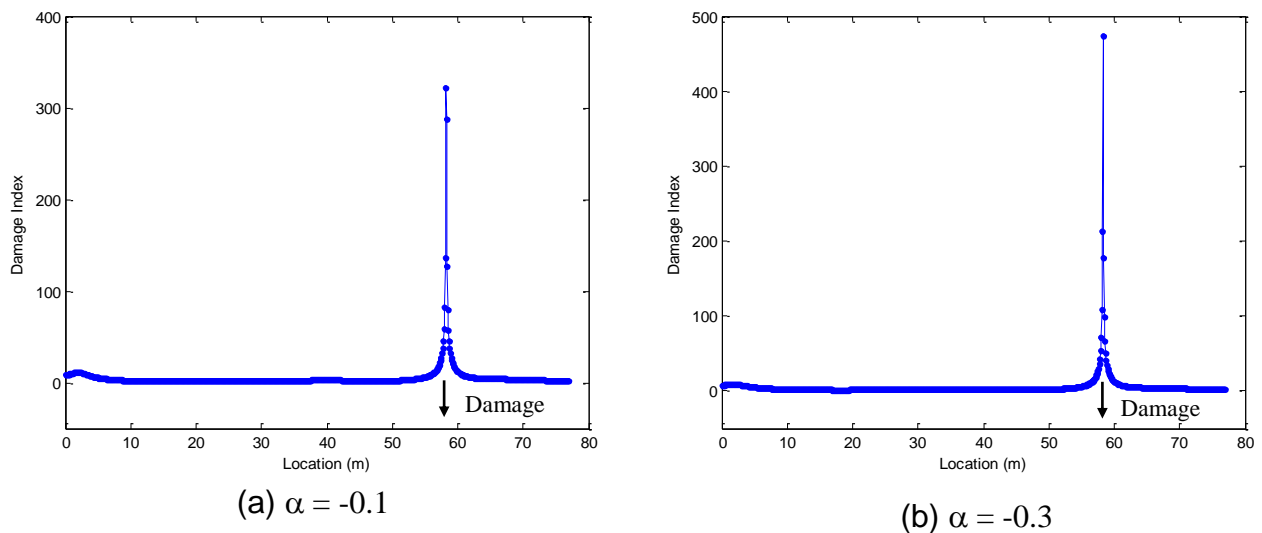


Fig. 6 Damage localization results of the FBDD method

4. CONCLUSIONS

A methodology to nondestructively locate damage in wind turbine tower (WTT) structures for which a few frequencies and mode shapes are available was presented. A frequency-based damage detection (FBDD) method was selected. A damage-localization algorithm that locates damage from changes in natural frequencies were formulated. From the numerical studies, the FBDD method performed well with several damage scenarios by locating in numerically simulated WTT structure for which only three sets of modal parameters were available. For the verification test, natural frequencies and mode shapes of the first three bending modes were generated from finite element models.

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