Guided wave based wire breakage detection of multi-wire cables

Junwei Chen, Yuanfeng Duan, Chungbang Yun

College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China;
ceyfduan@zju.edu.cn

Xiaodong Sui

College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China;
Department of Civil Engineering, Hangzhou City University, China;

ABSTRACT

Health monitoring of cables in civil engineering structures is a big challenge. A damage localization and severity assessment method is proposed using the guided wave. The wave energy transmission coefficient at the damage location is used as a measure of the damage severity. The semi-analytical finite element method is used to analyze the wave dispersion characteristics of an example cable with 37 parallel wires, from which the excitation frequency is selected and the corresponding wave group velocity is determined. A numerical study is carried out for the wire breakage detection by a pitch-catch method. The time-of-flight information of the wave packet reflected from the damage is used for the damage localization, and the wavelet coefficients are used to analyze the wave energy transmission and reflection. It has been found that the proposed method can accurately determine the wire breakage location and severity.

KEYWORDS: guided wave; SAFE analysis; cable with multiple wires; wavelet coefficients; wire breakage

1. INTRODUCTION

Multi-wire cables are commonly used as load-carrying members such as prestressed tendons, hangers, stay-cables in various civil engineering structures. Some local damage such as wire breakage and corrosion may occur on the cables during the long-term service period in extreme environments under the influence of environmental factors and fatigue loads, which may seriously affect the remaining service lives of the structures. In the past 20 years, there have been many bridge collapse accidents caused by cable failure in the world, which have brought great economic losses to the whole society. Therefore, it is very important to develop simple and efficient non-destructive testing (NDT) and structural monitoring methods for multi-wire cables.

Structural health monitoring methods based on the overall behavior of structure has been widely used to detect abnormal changes in cable-supported bridges *(Cho, S. et al. 2010)*. However, those methods are generally not effective to detect local damage. Common non-destructive testing methods using magnetic leakage *(Ando, Y. 2021)*, impedance *(Min, J. et al. 2012)*, and eddy current *(Damhuji, R. et al. 2016)* techniques have their own limitations in terms of damage types, detection accuracy, detection range, and detection efficiency. Ultrasonic guided wave methods are promising non-destructive testing methods that offer advantages such as point-by-point detection, wide detection range, and high detection accuracy *(Zhang, P. et al. 2018.)*. They are highly efficient in detecting slender components such as pipelines, railways, and bridge cables *(Saidha, E., Naik, G. N., and Gopalkrishnan, S. 2016, Wu, J. et al. 2018, Zhang, X. et al. 2017, Tang, Z. et al. 2024)*.

For the detection of wire breakages in multi-wire cables, the amplitude variation of echo signals is a simple and intuitive damage indicator. Additionally, there are methods based on dispersion compensation *(Legg, M. et al. 2015)*, discrete wavelet transforms *(Rizzo, P. and Di Scalea, F. L. 2006)*, but these methods cannot achieve precise damage quantification. This study proposes a damage localization and severity assessment method based on the time-of-flight information and energy transmission coefficient, which can accurately evaluate the wire breakage location and severity. A numerical simulation study is presented for the wire breakage detection on a cable with multiple wires, whereas an experimental validation is currently in progress.

2. WAVE DISPERSION ANALYSIS

2.1. Semi-analytical finite element method

The semi-analytical finite element (SAFE) method has been utilized to calculate the wave dispersion curves of a cable with 37 parallel wires. This method combines the advantages of both analytical and finite element methods. The cross-section of the waveguide structure in the *x-y* plane is discretized into finite element meshes, and a spatio-temporal harmonic function $e^{i(kz-\omega t)}$ is employed to represent the wave propagation along the axial (z) direction. This approach simplifies of the wave propagation model and improves computational efficiency. In the Cartesian coordinate system, the displacement $\{u(x,y,z,t)\}$ of the guided wave can be approximately expressed as Eq. (1), where $i=\sqrt{-1}$, k is the wave number, and $\omega = 2\pi f$ is the angular frequency.

$$\{u(x,y,z,t)\} = \begin{Bmatrix} u_x(x,y) \\ u_y(x,y) \\ u_z(x,y) \end{Bmatrix} e^{i(kz-wt)} \tag{1}$$

2. 2. Wave dispersion curves

The detailed parameters of the cable are listed in Table 1. The cross-section is divided into a triangular mesh, comprising a total of 909 nodes and 1480 elements (as in Figure 1). The contact conditions between the wires are considered as rigid. The computed dispersion curves are shown in Figure 2. It can be observed that the number of propagating modes increases at the higher frequency. In the low-frequency range, the number of wave modes is relatively fewer, which is suitable to select the excitation frequency. In this study, 25 kHz is selected as the excitation frequency, at which a small number of modes exist including longitudinal L (0,1), flexural F (0,1), and torsional T (0,1) modes, as shown in Figure 2. The mode shapes at 25kHz is shown in Figure 3, and L (0,1) mode is chosen as the excitation mode due to the relatively uniform energy distribution in the cross section, which results in a group wave velocity of 4975m/s at 25 kHz.

Table 1 Parameters of a cable with 37 parallel wires

Wire diameter (mm)	Young's modulus (GPa)	Poisson ratio	Density (kg/m^3)
7	210	0.3	7850

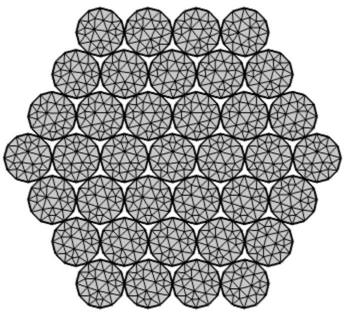


Figure 1 SAFE mesh of the cross section

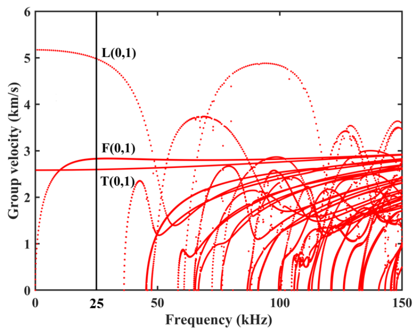
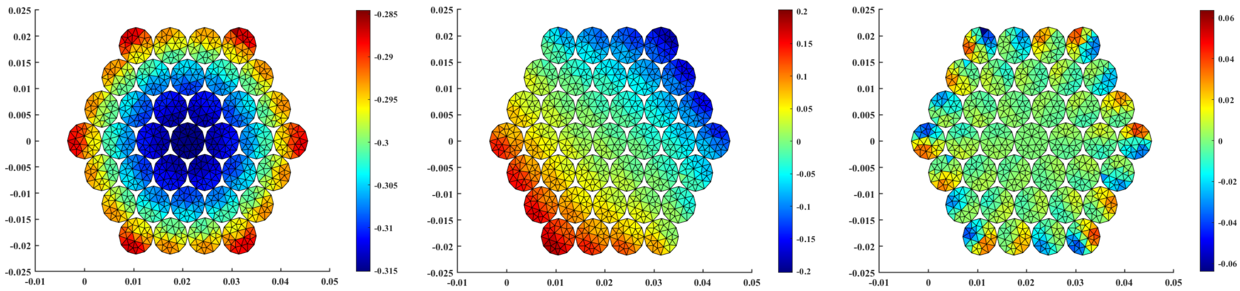


Figure 2 Dispersion curves of a cable with 37 parallel wires



(a) L (0,1) mode (b) F (0,1) mode (c) T (0,1) mode

Figure 3 Mode shapes at 25kHz

3. METHODS OF DAMAGE LOCALIZATION AND SEVERITY ESTIMATION

A method for cable damage localization and severity estimation is proposed based on the time-of-flight information and energy transmission coefficient, which consists of four main steps:

Step I: Calculation of Wavelet coefficients

Wavelet coefficients at the exciting frequency are obtained by applying continuous wavelet transform (CWT) to the received echo signal, which can be expressed by Eq. (2)

$$W(a,\tau)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}x(t)\psi(\frac{t-\tau}{a})dt \tag{2}$$

where $W(a,\tau)$ is the wavelet coefficient, $x(t)$ is the received signal, a represents the wavelet scale factor which is inversely proportional to its center frequency, τ is the time delay, and $\psi(t)$ is the mother-wavelet function which is taken as Morlet wavelet in this study.

Step II: Determination of energy attenuation coefficient

Energy attenuation coefficient is estimated under the intact condition, which is the rate of energy attenuation of the guided waves along the *z*-direction of the cable. This coefficient is related to the structural characteristics of the cable, material damping, excitation frequency, and friction between multi-wires *(Schaal, C., Bischoff, S. and Gaul, L. 2016)*. Assuming the initial energy of the excitation signal is E_0 and the energy of the direct incoming wave at a propagation distance of d is E_d, the energy attenuation can be expressed as Eq. (3), where the energy attenuation coefficient (β) can be obtained as Eq. (4) and the wave energy E can be obtained using Eq. (5) with t_1 and t_2 being the start and end times of the wave packet.

$$E_d = E_0 e^{-\beta d} \tag{3}$$

$$\beta = (\ln E_0 - \ln E_d)/d \tag{4}$$

$$E = \int_{t_1}^{t_2} |W(a,\tau)|\, dt \tag{5}$$

Step III: Wave velocity measurement and damage location estimation

The time interval between the maximum amplitude of two wave packets is defined as the time of flight between the wave packets (ToF), from which the wave velocity can be determined. The wave velocity and ToF of the echo signals from the damage are used to locate the damage.

Step IV: Damage severity estimation

The energy transmission coefficient α at the location of broken wires can be defined as Eq. (6), which is related to the cross-section areas before and after wire breakage. Therefore, the energy transmission coefficient can be used as an index for the severity of wire breakage. In Eq. (6), E^{Inc} represents the energy of the incoming wave, and E^{Trans} denotes the energy transmitted through the point of the wire breakage. The energy reflected at the broken wire E^{Refl} can be obtained as Eq. (7).

$$\alpha = E^{Trans} / E^{Inc} \tag{6}$$

$$E^{Refl} = (1-\alpha)E^{Inc} \tag{7}$$

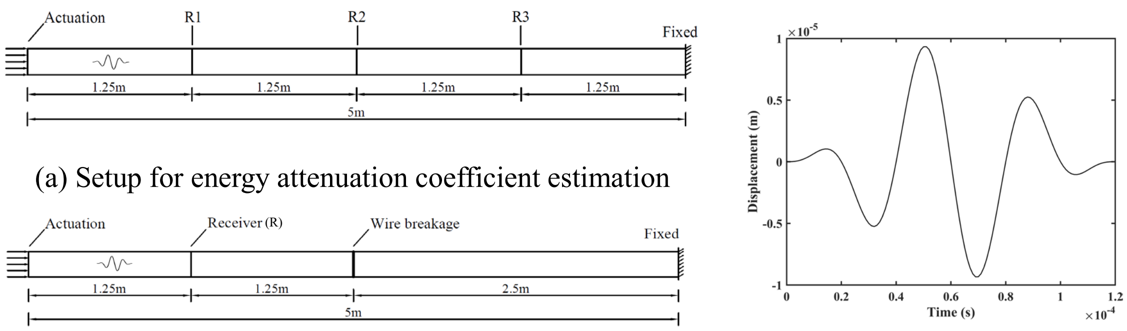
4. NUMERICAL STUDY FOR WIRE BREAKAGE DETECTION

4.1. Setup of guided wave actuation and receiving

The length of the example cable is 5m, and the cross section is the same as in Figure 1. For the energy attenuation coefficient estimation, three observation points are set at the centers of the cross-sections at distances of 1.25m, 2.5m, and 3.75m from the actuation face (the left end of the cable). For the wire breakage detection, an observation point (R) is placed at 1.25m from the actuation point, while the breakage location is at 2.5m from the actuation point as shown in Figure 4(b). The actuation signal $f(t)$ is a sine wave with 3 cycles modulated by a Hanning window with a center frequency of 25kHz, which can be described as Eq. (8) and Figure 4(c)

$$f(t) = A(1-\cos(\frac{2\pi f_c t}{3}))\sin(2\pi f_c t) \tag{8}$$

where A is the amplitude of the excitation signal, and f_c is the center frequency of the signal.



(b) Setup for wire breakage detection (c) Actuation signal

Figure 4 Setups of guided wave actuation and receiving

4.2. FE model for a multi-wire cable and wire-breakage

An FE model of a cable with 37 parallel wires cable model is established for the guided wave analysis in ABAQUS, and the material and geometric parameters are shown in the Table 1. The contact condition between the steel wires is assumed to be rigid. Hexahedral eight-node elements are used for the FE meshing. To effectively capture the propagation of guided waves at the target frequency, it was recommended to have at least 20 nodes within a single wavelength *(Moser, F., Jacobs, L. J., and Qu, J. 1999.)*. Considering the excitation frequency of 25 kHz and the corresponding wave wavelength $(\lambda = v_L / f = 4975/25000 = 0.199m)$, the suggested element size is obtained as 0.010m $(\Delta L_{\max} = \lambda / 19)$. In this model, the axial element length is set to 0.01m, while the circumferential element length for each wire is set to 0.0015m, and Figure 5 illustrates the FE mesh. The right end is modeled as fixed, while the left end is subjected to guided wave signals along the axial direction by nodal displacements. Figure 6 shows cases with 1, 3, and 5 broken wires occurred on the edge and at the center of the cable, the width of the breakages are taken as 1cm.

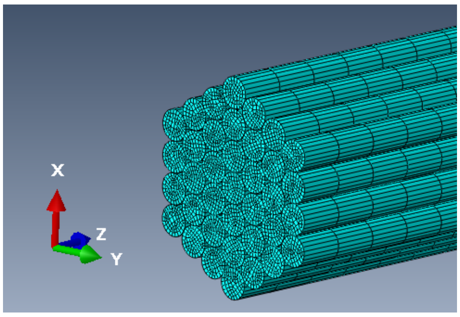
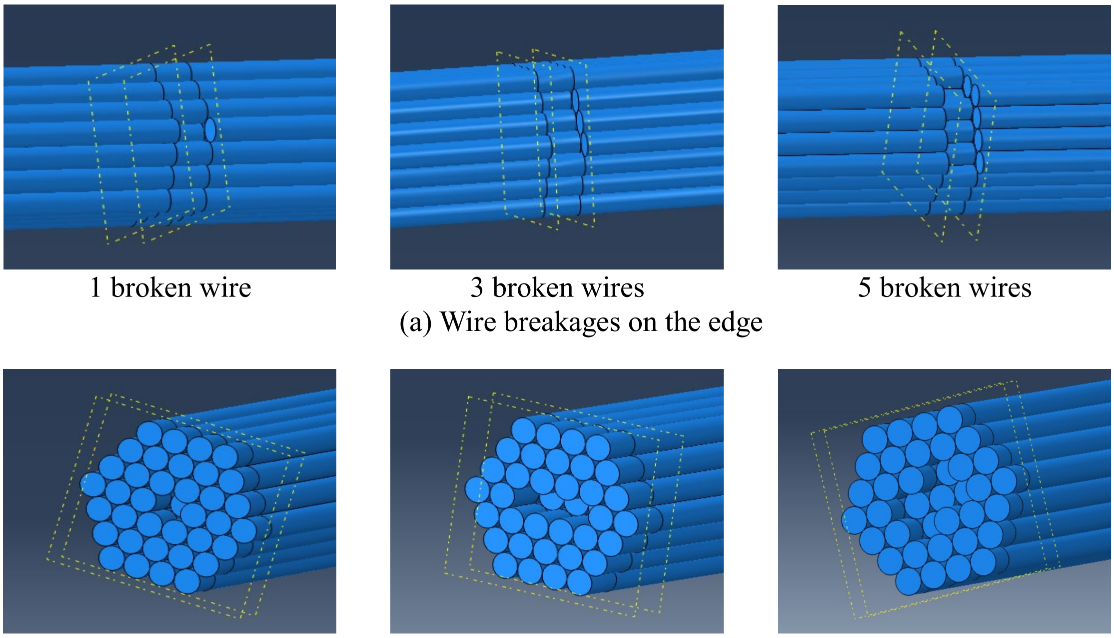


Figure 5 Meshing schematic diagram



1 broken wire | 3 broken wires | 5 broken wires

(a) Wire breakages on the edge

1 broken wire | 3 broken wires | 5 broken wires

(b) Wire breakages on the center

Figure 6 Simulation of various wire breakages at 2.5m from the left end

5. DETECTING RESULTS

5.1. Energy attenuation coefficient

Figure 7 illustrates the guided wave signals obtained at the three observation points (in Figure 4(a)). The first three wave packets represent the direct incoming waves, while the latter three represent the wave reflected from the right end. Wavelet coefficients are extracted at the excitation frequency (25kHz). The energy of the direct waves incoming and reflected wave from the right end are calculated at each observation point. Then the energy attenuation coefficient is determined in Eq. (4). Figure 8 illustrates the wavelet coefficient of the guided wave signals in Figure 7. Figure 9 presents the results of the linear fitting for the energy attenuation coefficients, resulting in $\beta = 0.019$. The coefficient of determination is 0.9585.

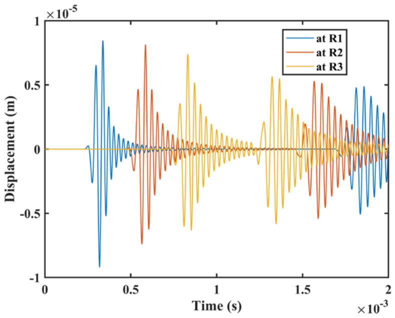


Figure 7 Guided wave signals at 3 points (R1, R2, R3)

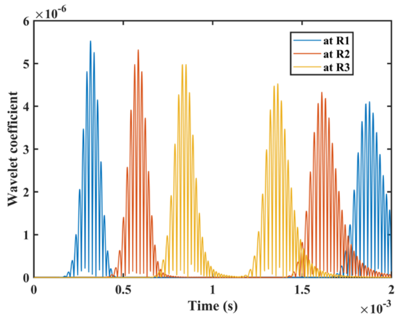


Figure 8 Wavelet coefficients of signals at R1, R2, R3 at 25kHz

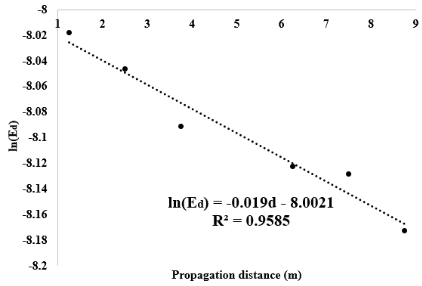
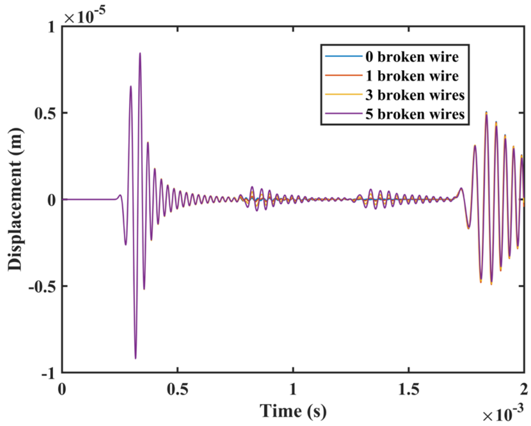


Figure 9 Energy attenuation coefficient fitting results

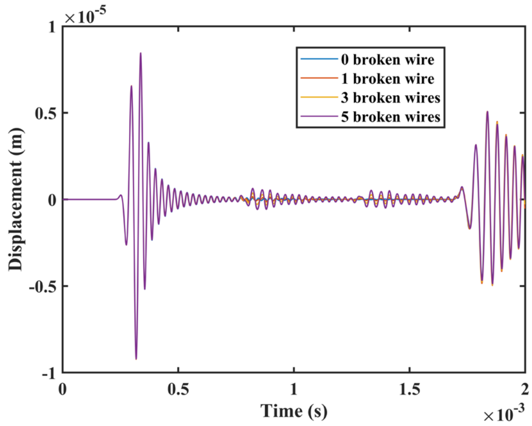
5.2. Wire breakage localization estimation

The first two wave packets in Figure 8 are used to calculate the wave velocity, which is determined as 4864 m/s that is slightly smaller than the SAFE result 4975 m/s by 5%.

Figures 10(a) and (b) illustrate the guided wave signals at the observation point (R in Figure 4(b)), where broken wires are positioned at on the edge or at the center in the cross-section. Each curve in Figure10 has four wave packets. The first represents the direct incoming wave, the second is the reflected echo at the damage, the third is the damage echo signal that is reflected again on the left end, and the fourth represents the transmitted wave at the damage and reflected on the right end. Wavelet coefficients are extracted at the excitation frequency, and shown in Figures 11(a) and (b). The damage localizations using the above information are shown in Table 2, the ToF between two wave packets is considered and the damage location is the distance from the actuation point (left end of the cable). Excellent agreement can be found with the true locations with errors less than 3.0%.

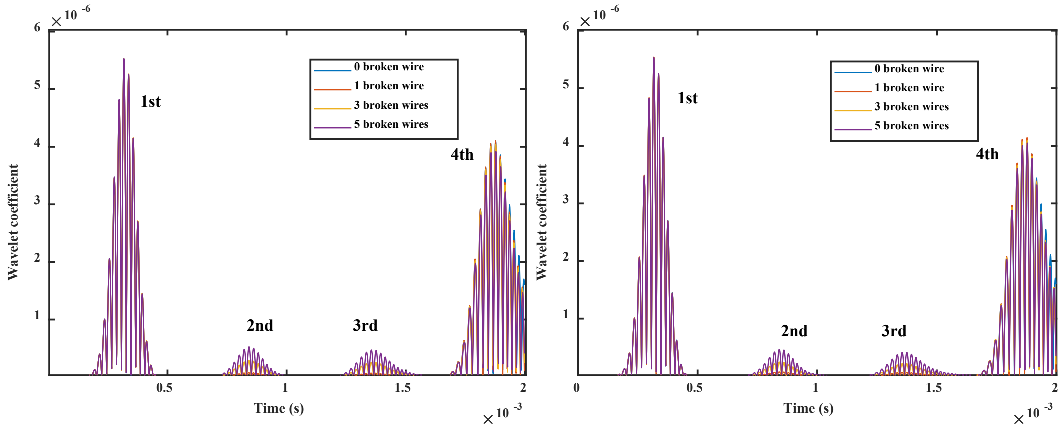


(a) Broken wires on the edge



(b) Broken wires at the center

Figure 10 Guided wave signals under different number of broken wires



(c) Broken wires on the edge (d) Broken wires at the center

Figure 11 Wavelet coefficients of guided wave signals under various number of broken wires

Table 2 Wire breakage localization results

Case	Wave packets considered	ToF (ms)	Estimate damage location (m)	Exact damage location (m)	Error (%)
Broken wires on the edge	1st - 2nd	0.525	2.53	2.5	1.20
	1st - 3rd	1.057	2.57	2.5	2.80
Broken wires at the center	1st - 2nd	0.523	2.52	2.5	0.80
	1st - 3rd	1.037	2.51	2.5	0.40

5.3. Wire breakage severity estimation

In Figure 11, the echo signals from the broken wires increase with the increasing number of broken wires. The energy levels of the first two reflection wave packets are used to estimate the wire breakage severity. Based on Eq. (3)-(7) and Figure 4(b), the relationship between the wave energy levels of the incoming wave to the receiver (E_R^{Inc}) and the reflected wave from the damage measured at the receiver (E_R^{Refl}) can be obtained as in Eq. (9), from which the wave energy transmission coefficient (α) can be determined:

$$E_R^{Refl} / E_R^{Inc} = (1-\alpha)e^{-2\beta\Delta} \tag{9}$$

where β is the wave energy attenuation coefficient and Δ is the distance between the receiver (R) and the damage location. Table 3 shows the estimated wire breakage severities, which show that the proposed energy transmission coefficient method can estimate a small degree of wire breakage very well, and the maximum error is less than 4%.

Table 3 Wire breakage estimation results by proposed method

Case	Number of broken wires	Estimated α	Remaining area	Error (%)
Broken wires on the edge	1	0.983	0.973	1.03
	3	0.937	0.919	1.96
	5	0.885	0.865	2.31
Broken wires at the center	1	0.984	0.973	1.13
	3	0.946	0.919	2.94
	5	0.898	0.865	3.82

6. CONCIUDING REMARKS

In this study, a guided wave method was presented to evaluate location and severity of the wire breakage in a cable with multiple wires. The SAFE-based wave dispersion analysis provides a good reference for the selection of the excitation frequency and the estimation of the wave velocity. The time-of-flight information of the wave packet reflected from the damage and energy transmission coefficient based on the continuous wavelet transform are proposed for damage localization and severity estimation, respectively. An ABAQUS finite element model for the example cable with multiple parallel steel wires is established to verify the proposed method. The results show that the proposed method can estimate locations and severities of the wire breakage very well with errors less than 3.0% and 4.0%, respectively. Currently a related experimental study is in process for the broken wire detection.

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REFERENCES

Ando, Y. 2021. Serial MTJ-based TMR sensors in bridge configuration for detection of fractured steel bar in magnetic flux leakage testing. *Sensors*, 21(2):668.

Cho, S. et al. 2010. Structural health monitoring of a cable-stayed bridge using wireless smart sensor technology: data analyses, *Smart Structures and Systems*, 6(5-6),461–480.

Damhuji, R. et al. 2016. Giant magnetoresistance sensors: a review on structures and non-destructive eddy current testing applications. *Sensors*, 16(3).

Legg, M. et al. 2015. Increased range of ultrasonic guided wave testing of overhead transmission line cables using dispersion compensation *Ultrasonics*, 62:35-45.

Moser, F., Jacobs, L. J., and Qu, J. 1999. Modeling elastic wave propagation in waveguides with the finite element method. *NDT & E International*, 32(4):225-234.

Min, J. et al. 2012. Impedance-based structural health monitoring incorporating neural network technique for identification of damage type and severity, *Engineering Structures*, 39:210–220.

Rizzo, P. and Di Scalea, F. L. 2006. Feature extraction for defect detection in strands by guided ultrasonic waves. *Structural Health Monitoring-An International Journal*, 5(3):297-308.

Schaal, C., Bischoff, S. and Gaul, L. 2016. Damage detection in multi-wire cables using guided ultrasonic waves. *Structural Health Monitoring-An International Journal*, 15(3):279-288.

Tang, Z. et al. 2024. Guided wave-based cable damage detection using wave energy transmission and reflection. *Structural Control and Health Monitoring*, 28(5).

Saidha, E., Naik, G. N. and Gopalkrishnan, S. 2016. An experimental investigation of a smart laminated composite beam with a magneto-strictive patch for health monitoring applications, *Structural Health Monitoring: An International Journal*, 2,273–292.

Wu, J. et al. 2018. Ultrasonic guided wave based switch rail monitoring using independent component analysis, *Measurement Science and Technology*, 29(11).

Zhang, P. et al. 2018. Ultrasonic guided wave approach incorporating SAFE for detecting wire breakage in bridge cable. *Smart Structures and Systems*, 22(4):481-493.

Zhang, X. et al. 2017. Scattering of torsional flexural guided waves from circular holes and Crack-like defects in hollow cylinders, *NDT & E International*, 89 (7),56–66.