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Identification of Local Debonding in Bolted Panels Using Nonlinear Pseudo-forces

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ABSTRACT

Bolt looseness can occur subject to long-term structural service. With this concern of structural integrity and safety, there is a huge demand to identify bolt-looseness-caused local debonding in connected structural components such as bolted panels. With the aid of non-contact laser scanning, transverse operating deflection shapes (ODSs) of a bolted panel can be measured with high spatial resolutions. Perturbation to the linear transverse dynamic equilibrium of the panel can be regarded as the linear pseudo-force (LPF), which is applied to the debonding region only and vanishes at undamaged locations. However, nonlinearities caused by contact of debonding interfaces during vibrations are not taken into consideration in the LPF model. As a consequence, only linear damage features can be contained in the LPFs which are established on linear ODSs, leading to incompleteness of damage features. Addressing this problem, this study establishes a nonlinear pseudo-force (NPF) model from the nonlinear transverse motion of equation of a beam-type bi-layer panel model with local debonding. Superior to LPFs, NPFs can extract linear and nonlinear damage features from linear and nonlinear ODSs, respectively. Similar to LPFs, NPFs concentrate in the debonding regions to form local peaks. Therefore, the NPF can be utilized as an ideal nonlinear indicator for the identification of local debonding in bolted panels. The applicability of the NPF is experimentally validated by identifying width-through debonding in a steel panel connected by bolts, whose ODSs at linear and nonlinear (higher) harmonics are acquired through non-contact laser scanning measurement. Experimental results reveal that the NPF can extract complete linear and nonlinear damage features, and hence has a higher-dimensional capacity for identifying local debonding in connected structural components such as bolted panels, whose occurrence, location, and size can be graphically characterized.

Keywords: bolted panel, local debonding identification, nonlinear harmonics, nonlinear ODS, nonlinear pseudo-force, laser scanning measurement

1. INTRODUCTION

Bolts are widely used to connect structural components such as bolted panels. However, bolt looseness can occur after long-term service, which can cause local debonding, and thence jeopardize the integrity and safety of the connected structural components. With this concern, it is of significance to identify bolt-looseness-caused local debonding in bolted panels.

Taking advantage of contact-caused nonlinearities in vibrations, identification of debonding or delamination using nonlinear vibration responses has been attracting increasing attention [1]. According to the "constrained mode", debonded layers are not allowed to separate during vibration and always have identical transverse vibration deflections; in contrast, the "free mode" allows the debonded layers to separate but cannot prevent them from penetrating into each other [2]. Superior to the two aforementioned debonding modes, the recently proposed "breathing mode" [3-7] allows debonded layers to contact and separate, whereby the breathing-like opening-closing motion of local debonding is produced, as observed earlier in the experiment [8]. The contact behavior between debonding interfaces occurs when "breathing" debonding closes and vanishes when "breathing" debonding opens, whereby nonlinear harmonics such as higher and sideband harmonics can be produced. Since this phenomenon was first reported in 1966 [9], nonlinear harmonics have been increasingly utilized as nonlinear indicators of debonding or delamination during recent decades.

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In 1998, a new nonlinearity called contact acoustic nonlinearity (CAN) was observed, caused by normal stress in contact (nonbounded) interfaces for "clapping" and "rubbing" vibration patterns, whereby nonlinear harmonics could be produced [10]. In 2000, the concept of nonlinear elastic wave spectroscopy (NEWS) associated with delamination-induced higher and sideband harmonics was established [11,12]. Solodov et al. [13] proposed the theory that CAN is assumed to be concerned with stiffness asymmetry, forming a "bimodular" model: due to the weakening of the contact between the surfaces, the compression elasticity is higher than that for tensile stress. Van Den Abeele et al. [11] proposed the theory of nonlinear mesoscopic elasticity to explain nonlinear behavior, in which a simplified one-dimensional model with a nonlinear stress-strain relationship is used. Lim et al. [14] assumed that the displacement response of a delaminated laminate is a linear combination of linear and nonlinear harmonics. Force components at corresponding frequencies were considered to produce such displacement components. A similar hypothesis [15,16] holds that linear vibrations are linearly produced by external excitations, whereas nonlinear vibrations are produced by nonlinear forces in delamination. Solodov [10] used ultrasonic waves propagating on interfaces to exhibit the CAN, whereby several nonlinear non-destructive testing (NDT) modes were proposed for the detection of small fractured defects that were almost "invisible" by linear NDT techniques. Through observation of the occurrence of higher and sideband harmonics in the response spectrum subject to coupled vibro-acoustic excitation, NEWS techniques were widely developed to manifest the occurrence of delamination [11,12,17,18].

In the recent decade, the concept of linear pseudo-force (LPF) was developed to represent damage-induced perturbation to a linear equation of motion, which can be regarded as an equivalent "force" applied to the damage region [19]. Consider a bolted panel with bolt-looseness-caused local debonding, whose bending stiffness is reduced at the debonding region. The occurrence and location of the debonding can be indicated by identifying the distribution of a pointwise LPF which is established on a pointwise linear operating deflection shape (ODS) because the LPF theoretically exists in the debonding region only and vanishes at undamaged locations [20]. However, nonlinearities caused by contact behaviors of debonding interfaces during vibrations cannot be taken into consideration in the LPF model. As a consequence, only linear damage features are contained in LPFs, leading to incompleteness of structural damage features. More recently, the concept of nonlinear pseudo-force (NPF) was inspired and extended by the LPF to expound the mechanism for generating nonlinear harmonics in "breathing" damage such as cracks [21] and delamination [22]. In this study, the NPF model is established from the nonlinear transverse motion of the equation of a beam-type bi-layer panel model with local debonding. Superior to LPFs, NPFs are capable of extracting linear and nonlinear damage features from linear and nonlinear ODSs, respectively. The capability of the NPF in identifying damage is experimentally validated on a bolted panel with local debonding caused by bolt looseness. The results reveal that the NPF has a higher-dimensional capacity for identifying local debonding in connected structural components such as a bolted panel, whose occurrence, location, and size can be graphically characterized.

2. NONLINEAR PSEUDO-FORCE GENERATED BY LOCAL DEBONDING

Considering a beam-type bi-layer panel model with uniform material and cross-section is subjected to a transverse excitation $f(x,t)$, whose equation of transverse motion can be expressed as

$$EI\frac{\partial^4 w(x,t)}{\partial x^4}+\rho A\frac{\partial^2 w(x,t)}{\partial t^2}+c\frac{\partial w(x,t)}{\partial t}=f(x,t), \tag{1}$$

where $w(x,t)$ is the transverse displacement with time t and abscissa x along the panel length, E is the Young's modulus, ρ is the material density, c is the damping coefficient, I and A are the inertia moment and area of the cross-section, respectively. Assuming that the panel bears a local through-width debonding that spans from x_1 to x_2 along its length. The inertia moment of the cross-section in the debonding region can be represented as

$$I(x,t)=\begin{cases} I^I & x\in[0,x_1)\cap(x_2,l] \\ I^C(1-\eta(t)) & x\in[x_1,x_2] \end{cases}, \tag{2}$$

where l is the panel length and $\eta(t)$ denotes the time-varying coefficient to quantify the debonding-induced periodical reduction in I (superscripts I, C, and O denote intact, totally closed, and totally open statuses of the panel elements, respectively):

$$\eta(t)=\frac{1}{2}(1-\frac{I^O}{I^C})(1+\cos\omega_B t), \tag{3}$$

in which ω_B denotes the "breathing" frequency of the opening-closing motion of the debonding. In the authors' previous study [20], ω_B was numerically proved to be the excitation frequency ω. By substituting Eq. (2) to Eq. (1), one has

$$EI^I\frac{\partial^4 w(x,t)}{\partial x^4}+\rho A\frac{\partial^2 w(x,t)}{\partial t^2}+c\frac{\partial w(x,t)}{\partial t}=f(x,t)+f_{NPF}(x,t), \tag{4}$$

where debonding-induced perturbation to Eq. (1) is arranged to the right side of Eq. (4) and written as f_{NPF}:

$$f_{NPF}(x,t)=\begin{cases}0 & x\in[0,x_1)\cap(x_2,l]\\ (I^I-I^C(1-\eta(t)))\dfrac{\partial^4 w(x,t)}{\partial x^4} & x\in[x_1,x_2]\end{cases}, \tag{5}$$

which is equivalently regarded as a nonlinear pseudo-force applied to the debonding region of the panel under virtual intact status. Note that f_{NPF} appears at damaged locations only and vanishes at the undamaged locations.

Due to the opening-closing motion of the debonding, the steady-state displacement of the panel is assumed to be composed of linear ($m=1$) and nonlinear ($m=2,3,...,M$, M is the number of the observed harmonics) harmonics with corresponding ODSs $W_m(x,t)$ and phases ϕ_m:

$$w(x,t)=\sum_{m=1}^{M}W_m(x)e^{-\mathrm{i}(m\omega t+\phi_m)}. \tag{6}$$

By substituting Eq. (6) to Eq. (5), the amplitude of f_{NPF}, denoted as $F_{NPF}(x)$, can be decomposed into components F_{NPF}^m ($m=1,2,...,M$) associated with the corresponding harmonics:

$$F_{NPF}(x)=\begin{cases}0 & x\in[0,x_1)\cap(x_2,l]\\ \sum_{m=1}^{M}F_{NPF}^m(x) & x\in[x_1,x_2]\end{cases}, \tag{7}$$

where F_{NPF}^m is expressed as

$$F_{NPF}^m(x)=(I^I-I^C(1-\eta(t)))\frac{\partial^4 W_m(x)}{\partial x^4}e^{-\mathrm{i}(m\omega t+\phi_m)}. \tag{8}$$

In that situation, for the panel elements bearing no external excitations where $f(x,t)=0$, a set of equations can be established:

$$EI\frac{\mathrm{d}^4 W_m(x)}{\mathrm{d}x^4}-\rho Am^2\omega^2 W_m(x)-\mathrm{i}\,cm\omega W_m(x)=F_{NPF}^m(x). \tag{9}$$

As depicted by Equation (9), linear equilibrium that is built on the linear ODS when $m=1$ and nonlinear equilibriums that are built on the corresponding nonlinear ODSs when $m=2,3,...,M$. It is noteworthy that Eq. (9) degenerates into the linear equation of motion when m merely equals to 1; in that situation, only the LPF is generated from the linear ODS. Relying on the expression of F_{NPF}^m in Eq. (9), a family of DIs is established:

$$DI_m(x)=\left|\frac{F_{NPF}^m(x)}{\max F_{NPF}^m(x)}\right|. \tag{10}$$

As all NPF components theoretically appear at the debonding region only and vanish at undamaged locations, $DI_m(x)$ built on the NPF components are ideal indicators to manifest the occurrence of local debonding and characterize its location and size. For the integration purposes, a hybrid NPF-based DI $DI^*(x)$ is established by fusing all $DI_m(x)$:

$$DI^*(x) = \frac{1}{M}\sum_{m=1}^{M} DI_m(x). \tag{11}$$

Superior to the existing LPF-based DI that can only extract linear damage features, the hybrid NPF-based DI proposed in this study is capable of extracting both linear and nonlinear damage features for the identification of local debonding.

3. EXPERIMENTAL VALIDATION

The experimental setup and specimen are shown in Figure 1. A bi-layer steel panel is manufactured by bolting two mono-layer panels with thicknesses of 1 mm and 3 mm. The length and width of the bolted panel are 500 mm and 100 mm, respectively. The panel is fixed at one of its ends as a cantilever beam. A local width-through debonding is made by removing all 12 bolts at that section, as shown in the zoomed-in view (also see Figure 1). An electromagnetic shaker is attached to the panel, by which the single-tone harmonic force is generated to excite the panel in the transverse direction. Simultaneously, an SLV is used to measure the steady-state transverse velocity responses of the panel. A piece of reflection tape is pasted along the beam length, spanning 15 mm to 495 mm from the fixed end of the beam, on which 121 measurement points are uniformed distributed. The local debonding spans from 240 mm to 325 mm along the measurement line. In the dimensionless coordinate of the measurement line, the two edges of the debonding region are located at $\zeta = 0.5$ and $\zeta = 0.677$.

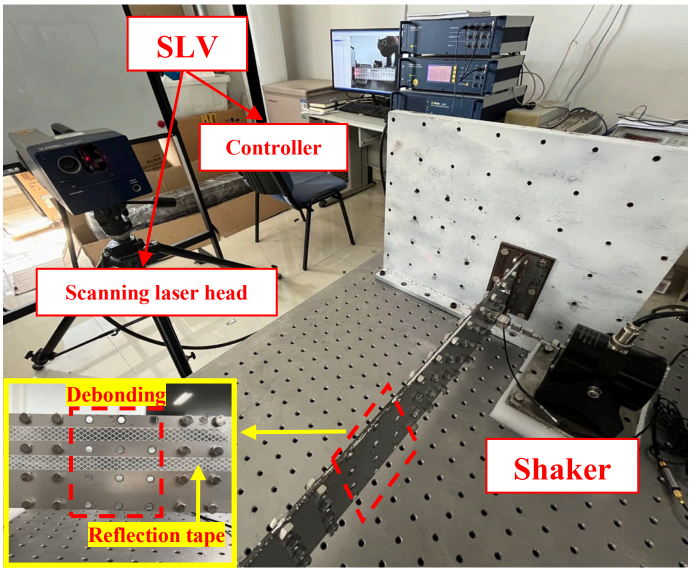
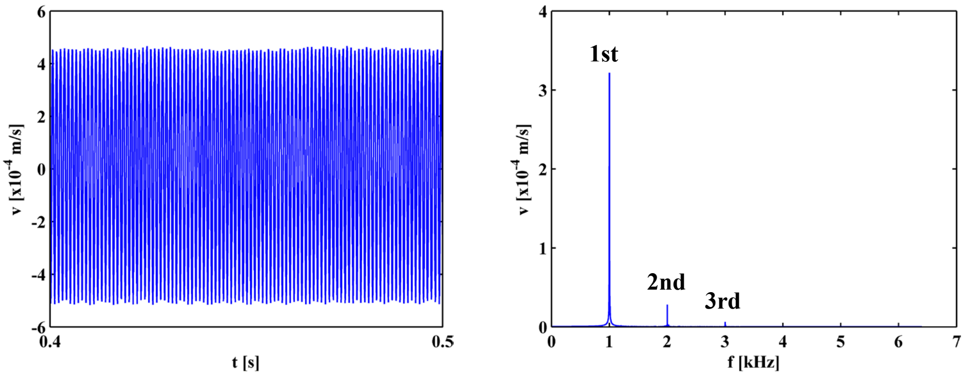


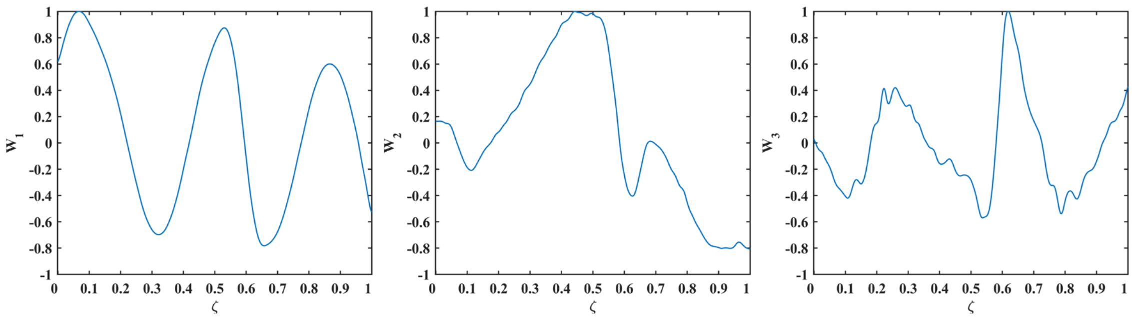
Figure 1. Experimental specimen and setup: a bi-layer bolted panel with debonding and an SLV.

The excitation frequency is arbitrarily selected to be 1 kHz. When the panel undergoes steady-state vibration at that frequency, the SLV pointwisely scans the beam along the measurement line to acquire the velocities at each measurement point. The sampling frequency of the laser measurement is 12800 Hz with 6400 fast Fourier transform (FFT) lines. Figure 2(a) shows the steady-state velocity of the panel at the center of the debonding region, the frequency spectrum of which is obtained by the FFT and shown in Figure 2(b). In addition to the linear harmonic at the excitation frequency (1 kHz), the higher harmonics at twice and triple excitation frequencies (2 kHz and 3 kHz) appear to indicate the nonlinearity in the vibration response. The 1st, 2nd, and 3rd ODSs associated with the 1st, 2nd, and 3rd harmonics are shown in Figure 3(a), (b), and (c), respectively. It can be seen in Figure 3 that although the 1st linear ODS $W_1(x)$ seems much smoother than the 2nd and 3rd nonlinear ODSs $W_2(x)$ and $W_3(x)$, none of them has noticeable local changes at the debonding location. By Eqs. (9) and (10), the corresponding DIs are obtained and shown in Figure 4(a), (b), and (c), respectively. It can be seen in Figure 4 that all DIs concentrate in the debonding region and almost vanish at undamaged locations. The sharply-rising peak in each DI well corresponds to the actual debonding region whose location is between red lines. The hybrid DI is calculated by Eq. (11) and shown in Figure 5, in which the identified debonding region spans from about 0.5 to 0.68, in good agreement with the actual debonding whose edges are indicated by two red lines at $\zeta = 0.5$ and $\zeta = 0.677$. Therefore, the NPF-based DI proposed in this study is capable of extracting both linear and nonlinear damage features for the identification of local debonding in the bolted panel.



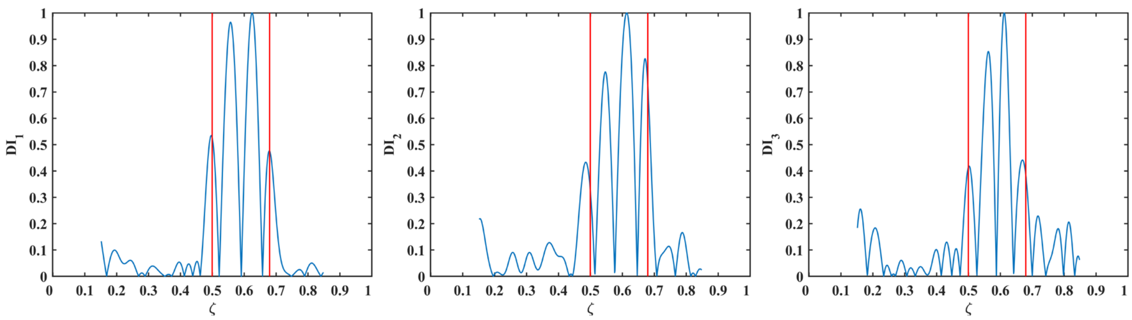
(a) (b)

Figure 2. (a) Velocity of the beam at the center of the debonding section and (b) its frequency spectrum.



(a) (b) (c)

Figure 3. The (a) 1st, (b) 2nd, and (c) 3rd ODSs.



(a) (b) (c)

Figure 4. DIs associated with the (a) 1st, (b) 2nd, and (c) 3rd ODSs (actual debonding edges are marked in red lines).

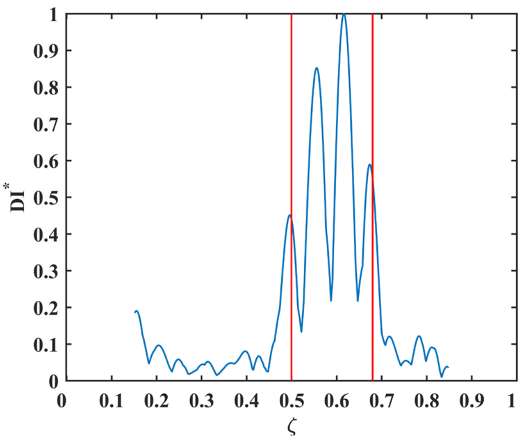


Figure 5. Hybrid DI with actual debonding edges marked in red lines.

4. CONCLUSIONS

Nonlinear harmonics have been widely utilized for manifesting the occurrence of local debonding in connected structural components such as bolt panels. Addressing the challenge of locating local debonding in connected structures, the concept of NPF is formulated from the nonlinear transverse motion of equation and acts as a nonlinear indicator of local debonding. Superior to the existing LPFs that can only extract linear damage features from linear ODSs, NPFs can extract complete linear and nonlinear damage features from linear and nonlinear ODSs. An experiment is implemented on a bolted steel panel with width-through debonding caused by local bolt looseness, whose linear and nonlinear ODSs are acquired using an SLV. Experimental results validate the applicability of the NPF in graphically characterizing the occurrence, location, and size of the debonding. Therefore, superior to the LPF, the NPF has a higher-dimensional capacity for identifying local debonding in connected structural components such as bolted panels.

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