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PERIODIC BOLT PLACEMENT IN STEEL STRUCTURES FOR GUIDED DAMAGE DETECTION

LU ZHANG, DIDEM OZEVIN, and GORKEM OKUDAN

Civil and Materials Engineering, University of Illinois at Chicago, Chicago, USA

Connections form the weakest link in structural systems. Bolted connections are especially susceptible to stress corrosion cracking due to stress-riser points at the bolt edges and the intrusion of water between plates leading to galvanic corrosion. Bolts are conventionally placed based on minimum and maximum spacing requirements guided by American Institute of Steel Construction. Unfortunately, the detectability of crack and corrosion is currently not a design variable. In this study, bolts are placed in periodic pattern such that they exhibit unique frequency response. The periodic placement allows modeling only unit cell in the shape of hexagon with periodic boundary conditions to obtain the frequency response. When damage occurs, the periodic pattern is broken, and the frequency response behavior changes. The influence of crack to vibration modes is numerically modeled, and the damage detection ability with unique bolt placement is demonstrated. It is shown that the spatial distribution of bolt can assist the damage detection ability, which should be considered as a criterion in the design of bolted connections.

Keywords: Frequency response, Crack detection, Corrosion detection, Spatial distribution, Periodic pattern, Failure.

1 INTRODUCTION

Welded or bolted connections are usually considered as the weakest elements in structural systems that impact the performance and the resistance to normal service as well as extreme events. For seismic regions, bolted connections are preferred over welded connections as welds are brittle and do not have good energy dissipation mechanism to reduce the dynamic load. The design of bolted connections is based on strength limit states depending on loading (axial, shear or combined). Once number of bolts is determined, they are placed based on minimum and maximum spacing requirements of American Institute of Steel Construction (AISC). The distance between centers of standard, oversized, or slotted holes shall not be less than 2 2/3 times the nominal diameter of bolt while it is preferred to use 3 times the nominal diameter of bolt. The longitudinal spacing between bolts shall not exceed 24 times the thickness of the thinner part or 12 in for painted members or unpainted members not subjected to corrosion, or 14 times of the thickness of the thinner part or 7 in for unpainted members of weathering steel subjected to atmospheric corrosion. The purpose of maximum spacing is to prevent water intrusion between layers and provide good contact. The purpose of minimum spacing is to facilitate construction.

In this paper, the concept of “inspectability” will be considered as another design variable such that the presence of corrosion, hidden cracking and stress increase can be detected at the earliest state. Typical inspection methods to assess the presence of damage in bolted connections are visual inspection, ultrasonics, vibration analysis, and fiber optic sensing (Ryan *et al.* 2012, Fu 2005, Graybeal *et al.* 2002, Hong-Nan *et al.* 2004 and Fritzen 2005). Visual inspection fails as there may be hidden defects. With current design practice, the performance of ultrasonics and vibration methods is limited due to unstructured bolt distribution as shown in Figure 1(a).

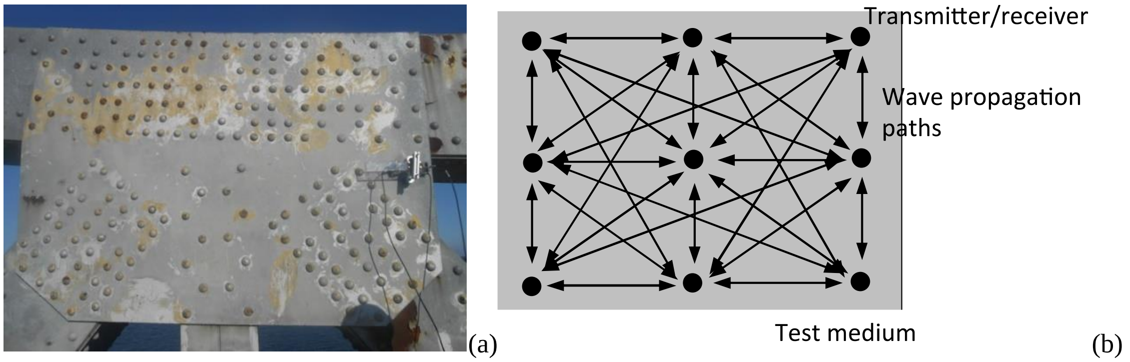


Figure 1. (a) Typical bolt placement in steel bridges and (b) an example of guided wave UT on plate-like structure.

2 GUIDED WAVE ULTRASONICS IN PERIODIC PERFORATED PLATED

Ultrasonic Testing (UT) is an active nondestructive evaluation method based on exciting structural systems by a transmitter and analyzing the received waveform. This is a high frequency dynamic method. In bulk ultrasonics, frequencies above 1 MHz are selected; however, the method is limited spatial resolution. To inspect larger volumes, lower frequencies are selected such that guided waves are generated in plate-like structures.

2.1 Guided Wave Ultrasonic Testing

Guided wave ultrasonic testing is applied to structures with bonded media such as plates. Multiple wave modes are generated due to reflections and refractions at boundaries leading to multi-modal and dispersive waves as opposed to single mode and non-dispersive bulky waves (Mitra and Gopalakrishnan 2016). Figure 1(b) shows an array of transmitter/receiver placed on plate-like structure and wave propagation paths. The transducers are typically made of piezoelectric material with reciprocal property functioning as transmitter and receiver. Therefore, the same transducers in the array are used as either transmitter or receiver. Using the waveforms recorded through multiple wave paths, damage location, type and size are measured by applying signal processing methods to the received signals. Figure 2 shows two examples of waveforms recorded from pristine condition (no damage) and damage condition. Various information such as arrival times of multiple wave modes, phase shift, amplitude and energy changes is utilized to assess the damage of structure. The method is successful in plain plates without bolts. However, when bolts are placed between the paths of transmitter and receivers, ultrasonic waves scatter, which complicates the measurement process. Therefore, bolts should be placed strategically such that their effect on ultrasonic waves is known at the design stage.

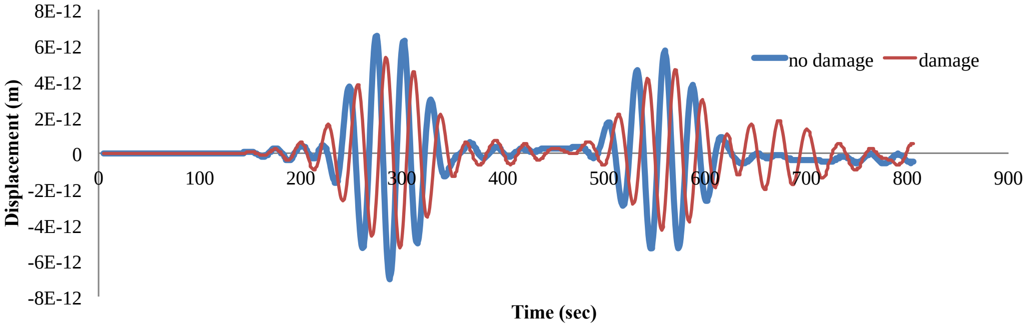


Figure 2. Typical guided wave ultrasonic signal.

2.2 Periodic Perforated Geometries

In recent studies on periodic structures, it is recognized that structures with periodic design have unique effective mechanical properties due to geometric pattern rather than constituents. Metamaterials and phononic crystal (PC) structures are of growing interest due to their ability to manipulate and control the propagation of elastic waves in ways that are not possible in conventional materials. Elastic metamaterials are artificial composite, man-made periodic systems creating new responses through physical constraints in the constituent materials (Craster and Guenneau 2013). The superior property of the acoustic metamaterial is attributed to its engineered geometry and artificially induced inhomogeneity (Pai 2010). The periodicity or the lattice constant, and composite behavior of resonating unit cells control the scattering of elastic waves, as a consequence, the wave properties (e.g., energy, direction). The metamaterial medium exhibits band gaps, or frequency ranges with negative modulus for acoustic waves that cannot propagate into the medium (Lee *et al.* 2009). The band gap of the metamaterial can be controlled by the contrast of elastic constants, the filling fraction and the lattice (i.e., periodicity) of the constructed element, and the thickness of the base plate (Hou *et al.* 2004, Charles *et al.* 2006). In this paper, the bolts are placed periodically to exhibit unique frequency response, which is influenced by the presence of damage such that single measurement becomes sufficient to change from the pristine state of the connection.

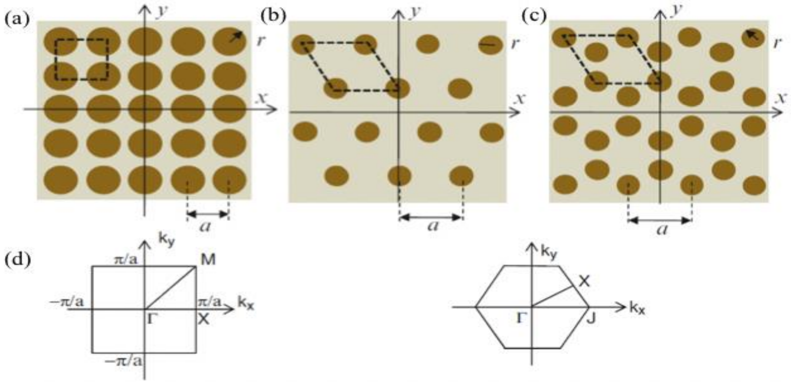


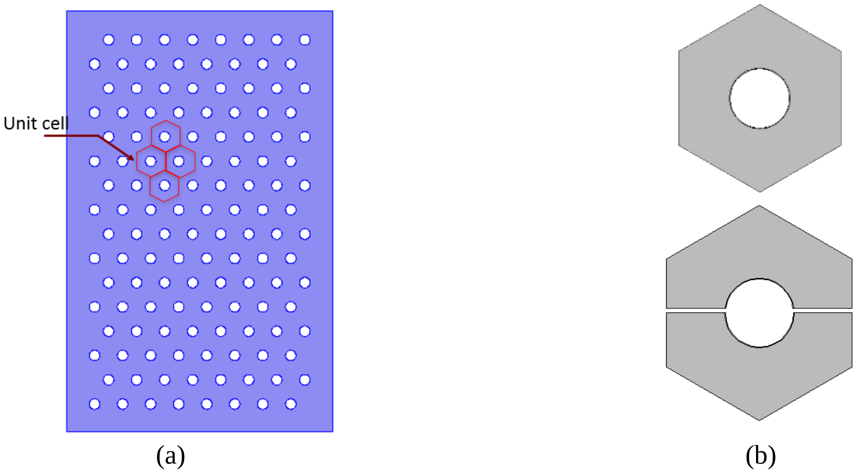
Figure 3. Three binary composite metamaterial designs, (a) square lattice, (b) hexagonal lattice, (c) honeycomb lattice and (d) first Irreducible Brillouin zone (IBZ) (Pennec and Djafari-Rouhani 2016).

3 NUMERICAL ASSESSMENT OF DAMAGE IN HONEYCOMB PLACED BOLTS

Binary composite materials are defined as steel-air and hexagonal placement of unit cells is considered. Figure 3 shows examples of binary composite materials in square, hexagonal and honeycomb lattice. Considering the effective placement of bolts with minimum spacing, hexagonal placement and the influence of crack on vibration modes are studied.

3.1 Numerical Models

When the gusset plate is subjected to loading, crack may initiate perpendicular to the loading direction. The studied gusset plate with and without crack is shown in in Figure 4(a). The bolt layout with the gusset has a repeated pattern; therefore, the edges of base plates are defined using the Bloch-Floquet (periodic) boundary condition. One unit cell is sufficient for creating the dispersion curve, which represents the solution of entire structure such that changes in wave modes due to the presence of damage can be detected with minimum effort. The unit cell models with and without crack are built. Then, the transmission analysis is conducted to simulate guided wave ultrasonics. The models are built using COMSOL Multiphysics Software. The typical gusset with the bolted connection is selected. The schematic of periodic unit cell is shown in Figure 4(b). The bolt units are arranged periodically in a hexagonal lattice. The diameter of the bolt is 5/8 inch, the spacing between each bolt is 2 2/3 times of its diameters, and the thickness of gusset is 3/8 inch.



(a) (b)

Figure 4. (a) The gusset plate model and (b) the unit cells with and without crack.

3.2 Results

The influence of presence of crack on the wave propagation within the periodic structure is studied. The fundamental frequency is the main concern since it has largest contribution to the structural response. The dispersion relations between frequency and wave number is calculated for the ten lowest bands from 0 to 80 kHz and plotted in Figure 5. The changes in the dispersion curve occur, mostly in the high frequency range. In addition, the band gap (no vibration occurs) of the crack case moves to the frequency range of 34.5-37.7 kHz. The width of band gap increases from 1.6 kHz to 3.2 kHz. The mode shape within the band gap of pristine gusset plate is shown in the figure. If that particular wave mode is excited with the guided wave ultrasonics, it is expected that the ultrasonic amplitude will decay with the presence of crack due to the formation of band gap.

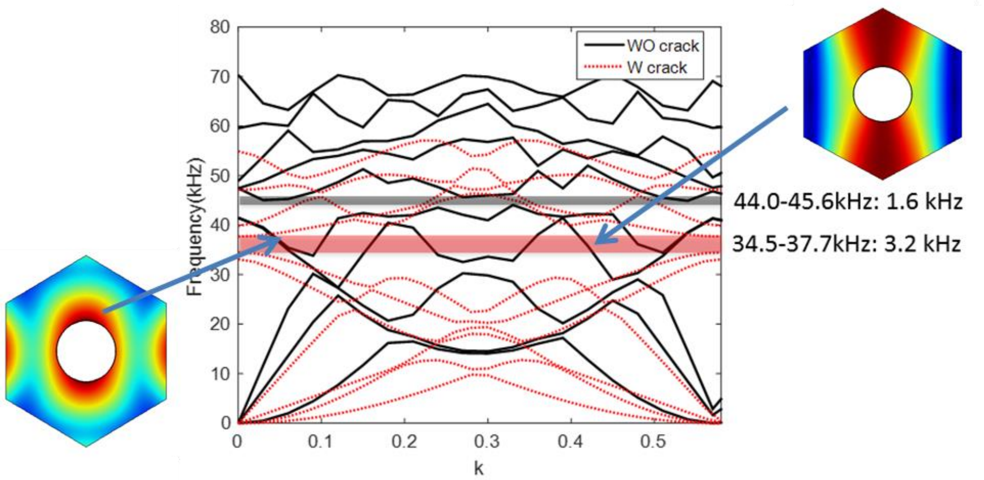
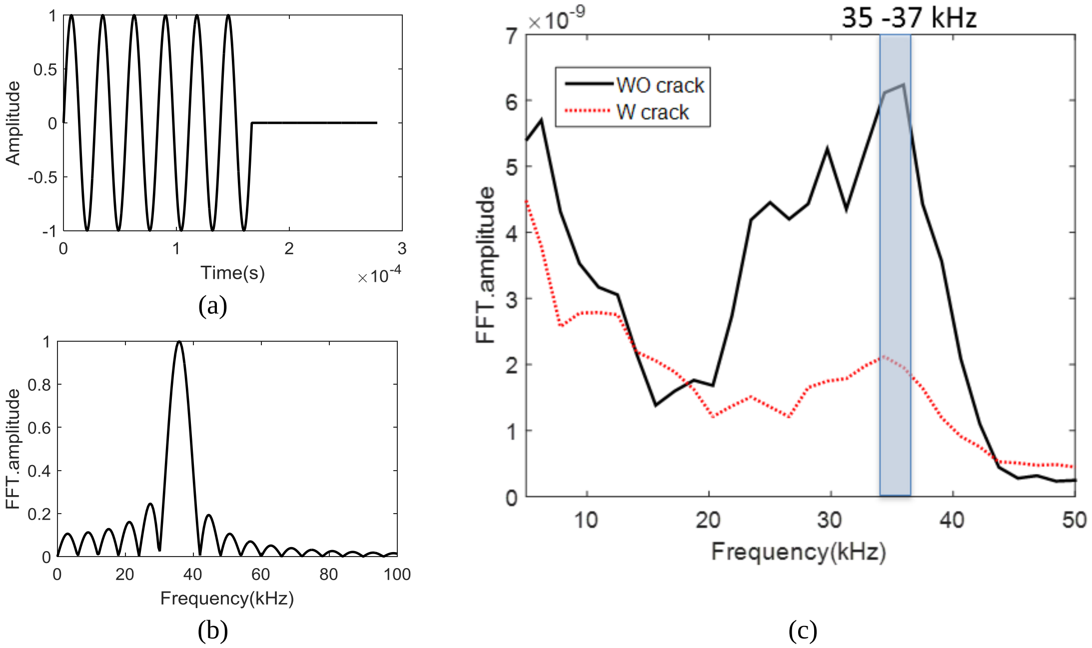


Figure 5. The dispersion curve with and without crack indicating two mode shapes of pristine case within the band gap of cracked case.

To demonstrate the influence of crack to guided wave ultrasonics, the transmission analysis is conducted using the entire gusset plate (Figure 4(a)) within the bandgap of the cracked plate. The excitation signal is selected as 6-cycle sine wave with 36 kHz excitation, and applied to the edge



(a)

(b)

(c)

Figure 6. The transmission model result (a) excitation signal in time domain (b) excitation signal in frequency domain, (c) the spectra responses without (WO) and with (W) crack.

of plate. The displacement response at the other edge is extracted from the model. The displacement histories without and with crack are shown in Figure 6. Significant reduction in amplitude is observed, which verifies the unit cell mode.

4 CONCLUSIONS

In this paper, a novel nondestructive evaluation method for detecting the crack of bolt connections is proposed by taking advantage of periodic pattern of bolt layout. The typical gusset plate with repeated hexagonal placement of bolts is studied. The band gap is observed due to the repeated bolt pattern and crack. The presence of crack significantly changes the periodicity of bolt layout, leading the change of vibration and ultrasonic wave propagation, which can be used for identifying the crack. The concept of 'inspectability' within design is verified numerical results, which will be validated with experimental results as future work.

Acknowledgments

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