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Publication Date

2014-03-09

DOI

10.1117/12.2045024

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Monitoring Bolt Torque Levels through Signal Processing of Full-Field Ultrasonic Data

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ABSTRACT

Using full-field ultrasonic guided wave data can provide a wealth of information on the state of a structure through a detailed characterization of its wave propagation properties. However, the need for appropriate feature selection and quantified metrics for making rigorous assessments of the structural state is in no way lessened by the density of information. In this study, a simple steel bolted connection with two bolts is monitored for bolt loosening. The full-field data were acquired using a scanning-laser-generated ultrasound system with a single surface-mounted sensor. Such laser systems have many advantages that make them attractive for nondestructive evaluation, including their high-speed, high spatial resolution, and the ability to scan large areas of in-service structures. In order to characterize the relationship between bolt torque and the resulting wavefield in this specimen, the bolt torque in each of the bolts is independently varied from fully tightened to fully loosened in several steps. First, qualitative observations about the changes in the wavefield are presented. Next, an approach to quantifying the wave transmission through the bolted joint is discussed. Finally, a method of monitoring the bolt torque using the ultrasonic data is demonstrated.

Keywords: Bolted Connections, Ultrasonic Guided Waves, Scanning Laser Excitation, Damage Detection

1. INTRODUCTION

Scanning laser ultrasound systems have the capability of producing a very high spatial density of data for rapid inspection of structures.[1,2] In this study, a system using laser scanning to generate ultrasonic guided waves is applied to characterize the full-field response of a steel bolted joint. In addition to characterizing the wavefield, approaches to monitoring the bolt torque through the guided wave interaction are explored.

The particular bolted elements used in this study have been used previously as a testbed for sparse array guided wave SHM techniques.[3] As such, using the full-field capabilities of the laser system to characterize the wave propagation is useful for its application to future studies on the testbed.

2. EXPERIMENTAL PROCEDURE / METHODOLOGY

2.1 Laser-scanning procedure

To collect full-field guided wave data, a laser scanning technique has been developed previously.[4] This technique utilizes a Q-switched pulsed laser to generate guided waves at the point where the laser beam impinges on the structure's surface. A two-dimensional scanning mirror is then used to direct the beam to different locations on the structure. The excited waves are then received at a separate, surface-mounted piezoelectric sensor. By raster scanning the laser over a region of the structure, a complete set of waveforms characterizing the response of that region to guided waves is obtained. If linearity holds, elastodynamic reciprocity implies that the responses collected at a single point from excitation at all of the scanning points is equivalent to the response at each scanning point if the wave had been

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generated at the receiver. In this way, the response of the structure to guided wave excitation can be acquired and very intuitively visualized.

2.2 Bolted joint specimen

The test article chosen for study here is a simple steel bolted lap joint. Two elements measuring 2 inches (5.1cm) in width and 1/8 inch (3.2 mm) in thickness overlap for a 2 inch (5.1 cm) region. The elements are connected by two ¼-inch-diameter (6.4 mm) bolts positioned asymmetrically as shown in Figure 1.

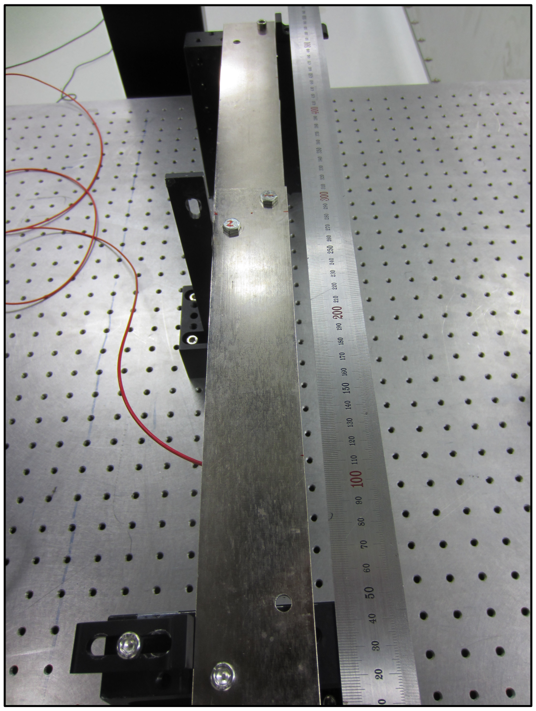

Figure 1 - Bolted joint assembled for laser scanning. Note that the laser is mounted above the plates facing down.

The sensor location is not visible in the figure (since the sensor is on the reverse side so as not to block the laser's line of sight), but its approximate location is indicated by the cable protruding from the left side of the plate. The bolt farther from the sensor side has been designated Bolt 1, and the closer bolt designated Bolt 2.

2.3 Test protocol

To characterize the full wavefield around the bolted joint, a scan area of 350 by 55 mm was established, centered on the joint. The scan area was chosen to be slightly larger in dimension than the plates so that the entire area of the plates would be captured. In post-processing, the points where the laser did not hit the specimen were removed from the analysis. The raster scanning was conducted with a grid spacing of 0.5 mm with a repetition rate of 100 Hz. The PZT sensor recorded 2000 data points over a 150 µs window (a sampling rate of 13.3 MHz). Because guided waves are not excited at all of those frequencies, however, the resulting waveforms were bandpass filtered from 50-500 kHz.

In order to evaluate the effectiveness of the laser-scanning procedure to monitoring bolt torque level, a series of tests was carried out, varying the torque at each step. A summary of the tests (in the order in which they were conducted) is presented in Table 1.

Table 1 - Test protocol

Test Number	Bolt 1 Torque (kgf-cm)	Bolt 1 Torque Code	Bolt 2 Torque (kgf-cm)	Bolt 2 Torque Code
1	0	0	0	0

2	120	3	120	3
3	0	0	120	3
4	40	1	120	3
5	80	2	120	3
6	120	3	120	3
7	120	3	0	0
8	120	3	40	1
9	120	3	80	2
10	120	3	120	3
11-20	Repeat tests 1-10			
21-30	Repeat tests 1-10			

As detailed in Table 1, four levels of bolt torque were chosen from fully loosened to 120 kgf-cm in 40 kgf-cm increments. The effect of these varying torque levels on the guided wave propagation was then investigated.

3. BOLT TORQUE MONITORING

3.1 Qualitative evaluation

First, it is useful to inspect some representative figures of wave interaction with joint in tightened and loosened configurations. Each of the following figures shows the wavefield at three time points for the given trial. The first time point is early, showing the PZT location, the wavefield propagating out circularly, and then setting up nearly planar wavefields moving along the element.

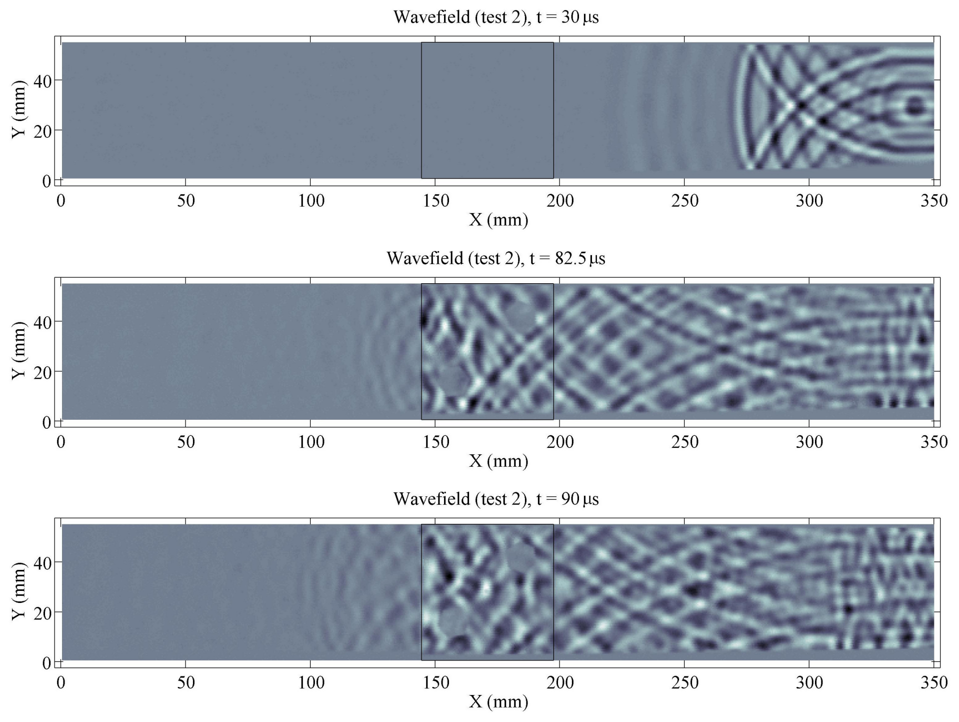

Figure 2 - Representative images of the wavefield for test 2, both bolts fully tightened

The first noticeable characteristic of the wave propagation is that there are two clearly distinguishable modes – the fundamental symmetric (S0) and anti-symmetric (A0) modes. The S0 is noticeably faster, traveling approximately 4,200 m/s compared to the 2,950 m/s of the A0 mode. However, the A0 mode produces a substantially higher amplitude response, which may be a result of either the characteristics of the laser excitation or of the surface-mounted PZT receiver. In every trial, the amplitude of the S0 mode wavefront is lost beneath the noise floor on the other side of the bolted joint, indicating that virtually no energy of that mode is able to transmit through the joint. Therefore, while higher modes have been shown to be useful in other studies,[5] this study assumes effectively single-mode propagation and focuses on the A0 mode.

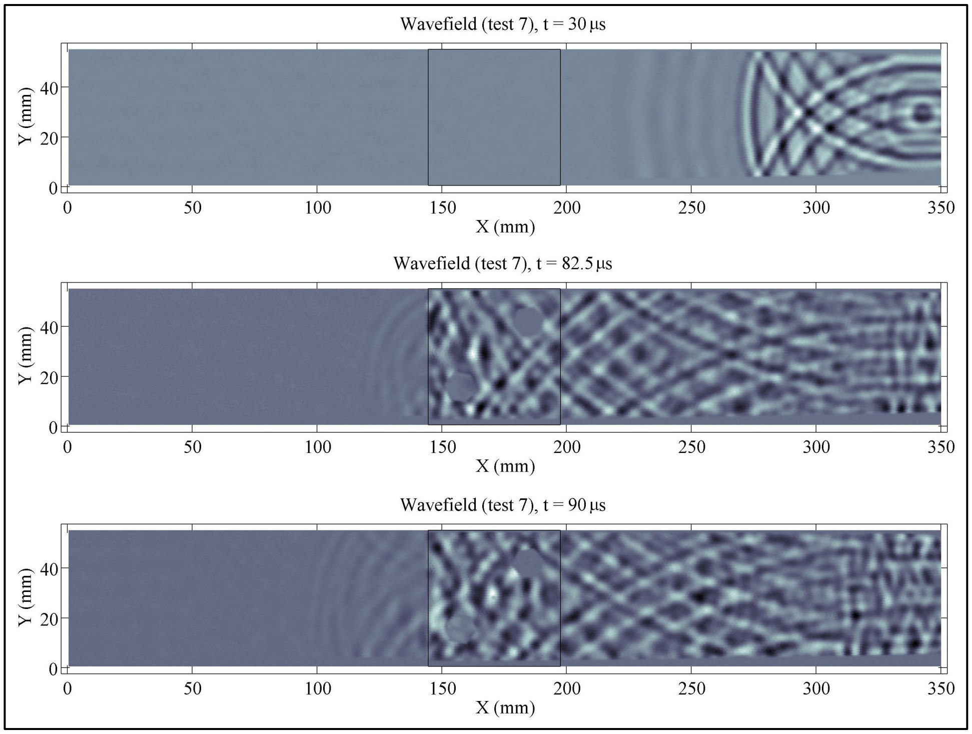

Figure 3 - Representative images of the wavefield for test 7, bolt 1 fully tightened and bolt 2 fully loosened

Figure 3 gives the corresponding results for test 7, for which bolt 1 was fully tightened and bolt 2 was fully loosened. In the figures, bolt 1 is on the lower left. The first time point is included again to show how similar the actuation was in each of the trials – there are no noticeable differences in the wave pattern in any of the four trials presented. However, for test 7 the wavefield on the other side of the bolted joint is skewed substantially. Most of the energy seems to be propagating radially out from the one bolt that is still tightened, in contrast to the symmetric propagation observed in test 2.

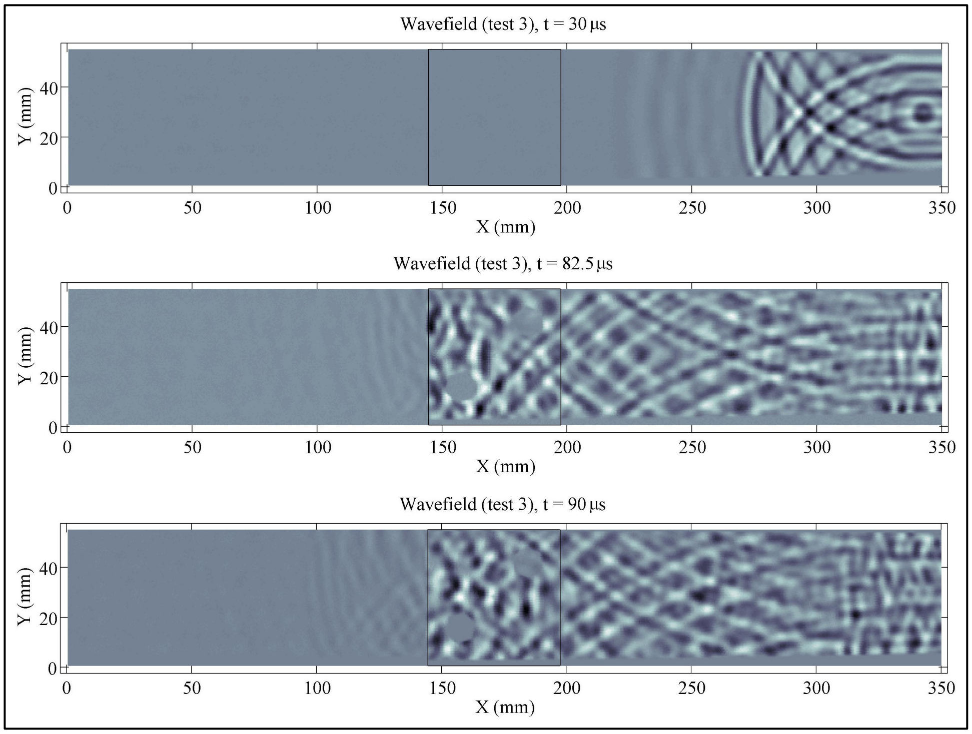

Figure 4 - Representative images of the wavefield for test 3, bolt 2 fully tightened, bolt 1 fully loosened

Figure 4 presents results for test 3, where the situation is now opposite the previous situation. Bolt 2 is fully tightened and bolt 1 is fully loosened, but because the scan is conducted from the top, it is more difficult to see that the propagation in the second element is radiating from bolt 2. The waves must travel further to be observable, and by that time they are closer to the planar front observed in the far field.

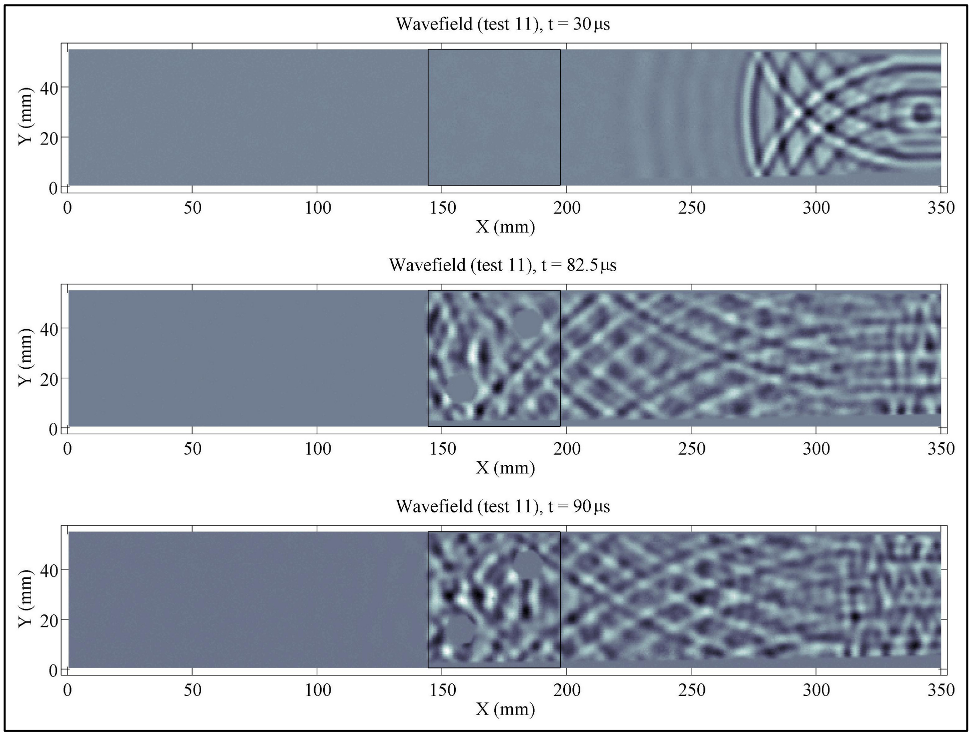

Figure 5 - Representative images of the wavefield for test 11, both bolts fully loosened

Finally, Figure 5 shows the results for test 11, where both bolts are fully loosened. In this case, almost no ultrasonic energy is able to propagate through the connection, as would be expected.

3.2 Wave-joint interaction – energy

In order to provide a better characterization of the interaction of the guided waves with the bolted joint, the ratio of incident energy transmitted through the joint is estimated. Figure 6 shows the geometry of the specimen and designates the rectangular regions over which an average energy is calculated. The boxes on the left are after the wave propagates through the joint and those on the right are an equal distance before it. The regions are further split into halves to see whether bolt loosening on one side or the other will produce a change in energy on the corresponding side. The energy estimate is also windowed in time to correspond with the arrival of the A0 waves at the locations. After the joint, the window starts at 82.5 μs and end at 90 μs (the same time points used in the previous figures). Before the joint, the window is 45-52.5 μs.

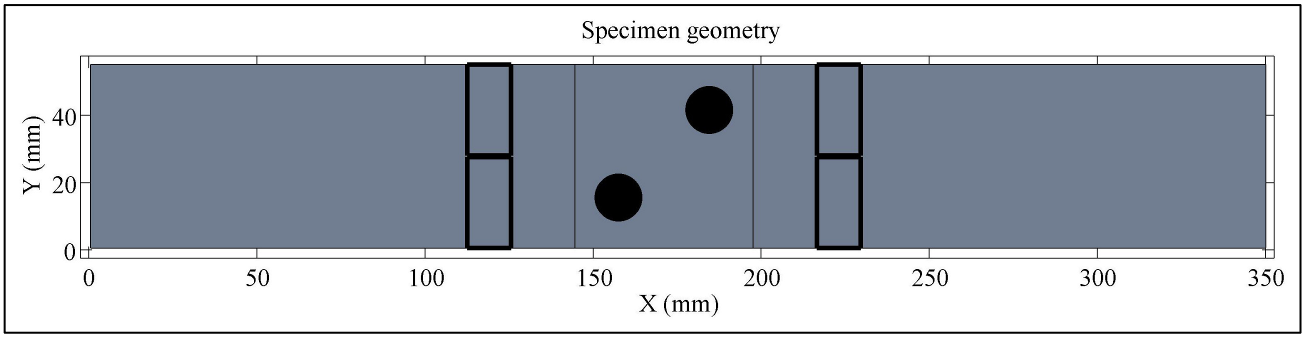

Figure 6 - Regions used to calculate energy ratios (shown with bolt positions)

Using these windows, the average root-mean-square (RMS) energy can be calculated before and after the joint and used to construct a ratio of energy transmitted. The results for each bolt torque condition are presented in Figure 7, considering both halves separately and the combined results. The ratio of energy transmitted through the bolted joint with both bolts fully tightened is approximately 0.16, or 16%. Note that this value includes a slight amount of natural attenuation that the wave would undergo propagating in a continuous plate, but it is not necessary to explicitly compensate for the effect in this study.

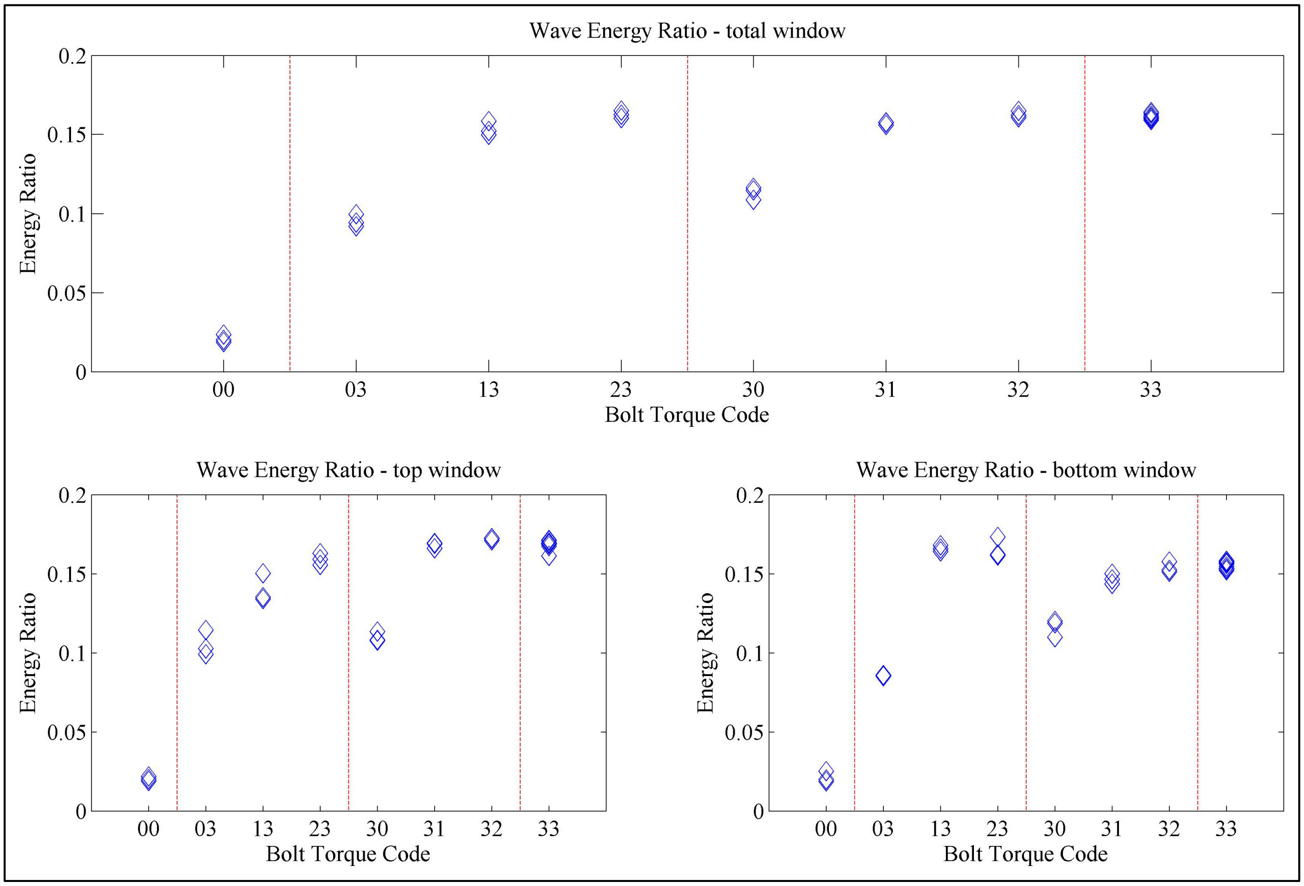

Figure 7 - Wave energy ratios by bolt torque code. Top: total window. Bottom left: top window (bolt 2). Bottom right: bottom window (bolt 1).

The energy ratio across the bolted joint is also a quantified metric that may provide information on the current torque levels. Figure 7 certainly shows a dramatic difference between the 33 case (fully tightened) and the cases where a bolt is fully loose (00, 03 and 30). There is also a positive correlation between energy ratio and torque level, as each successive level tends to raise the energy ratio. However, there does not generally seem to be a substantial enough difference between torque levels 1-3 to distinguish those cases accurately.

A more direct demonstration of this phenomenon is given in Figure 8. In this case, the RMS energy is computed on the area representing the bolt head. In principle, the higher the torque value, the better transmission the guided wave will have from the elements into the bolt itself. In fact, a fully loosened bolt shows almost no energy in the bolt head. There is also a positive trend in the energy with torque level. However, the variation is such that a positive identification would be impossible. With more data, it might be possible to construct a probabilistic assessment of the most likely torque value for a given energy value.

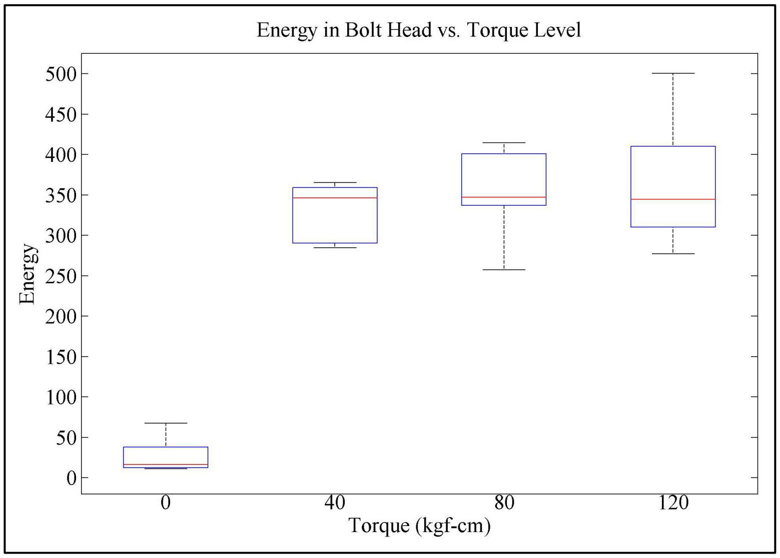

Figure 8 – Box and whisker plot of bolt head energy vs. torque level (whiskers represent extrema)

3.3 Symmetry metrics

Another possible type of metric for monitoring the health of the bolted joint is related to the previous observation that when one bolt is loosened, the wavefield close to the joint becomes asymmetric and roughly propagates radially outwards from the bolt that is fully torqued. The symmetry across the axis along which the wave is propagating can be calculated by taking a line of points across the width of the plate and applying equation (1). Calling the vector of points **x**, the pseudocode is as follows:

$$\text{degree of symmetry} = \frac{\text{dot}(\mathbf{x}, \text{flipdim}(\mathbf{x}))}{\text{dot}(\mathbf{x}, \mathbf{x})} \tag{1}$$

where dot() is the inner product and flipdim() reverses the order of the elements. Note that the degree of symmetry will fall between 0 and 1, with 1 being perfectly symmetric.

The results from applying the symmetry metric to the data for each torque level are given in Figure 9. Again, all cases with a fully loosened bolt are easily identified, and there is an upward trend in symmetry for higher torque levels. Note that the cases where bolt 1 is loosened perform substantially better, as was observed in the qualitative analysis section. Two out of the three 13 trials produced values low enough to distinguish from the higher torque cases. However, there is too much variability in the fully tightened cases to conclusively separate the other torque levels.

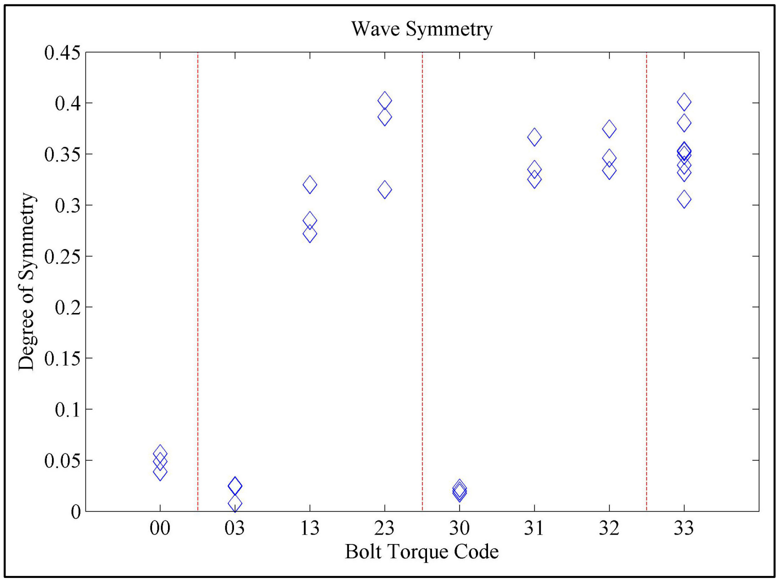

Figure 9 - Degree of symmetry vs. bolt torque

4. CONCLUSIONS

A detailed experimental look at the interaction of ultrasonic guided waves with a metallic bolted joint has been presented. The structure of the wavefield was interpreted qualitatively as the torque levels in each bolt were varied. Finally, quantitative methods for assessing bolt torque were proposed. However, with all processing techniques it was difficult to distinguish bolt torque levels 2 and 3, and also to some extent levels 1 and 3. This is most likely due to improper selection of the bolt torque levels for the test – there is simply not enough difference in the contact condition between the plates to be detectable with guided waves. However, the analysis presented here demonstrates that scanning laser systems can monitor for bolt loosening damage and provides characterization of the guided wave interaction with a bolted joint.

ACKNOWLEDGMENTS

This work was supported under grant #UG110097JD of the Agency for Defense Development in Korea by the Leading Foreign Research Institute Recruitment Program (2011-0030065) through the National Research Foundation of Korea, funded by the Ministry of Education, Science, and Technology (Korea). It was also supported by the National Science Foundation through a Graduate Research Fellowship (Colin Haynes). The authors gratefully acknowledge the assistance of the members of the Smart Structures Lab at Chonbuk National University, especially See Yen Chong and Jae Kyeong Jang, for help with the experimental testing.

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