Effects of fastener load on wave propagation through lap joint

Jingjing Bao*, Victor Giurgiutiu

Mechanical Engineering Dept., Univ. of South Carolina, 300 Main St., Columbia, SC 29208

ABSTRACT

Experimental results on the propagation of guided waves through a bolted joint under various bolt load values are presented. Piezoelectric wafer active sensor (PWAS) transducers are used for the generation and reception of the guided waves. Two specimen types are used, a strip lap joint and a plate lap joint. The signals measured under various bolt load values and frequency values are studied in order to identify relevant features that change drastically with bolt load. We found that some of the signals, especially those at S0 tuning frequency of 320 kHz, were very much simplified by the change from strip to plate conditions.

The main contribution of this paper to the advancement of the state of the art consists in highlighting the need for removing the confounding effects of the strip side reflections on the correct interpretation of guided wave changes as they travel through a lap joint with various fastener loads.

Keywords: bolted lap joint, guided wave, wave propagation, bolt loosening, bolt load

1. INTRODUCTION

Evaluation and monitoring lap joint integrity is important for structural health monitoring (SHM). In a friction type bolted lap joint, the fasteners create clamping force upon the joint members, and the resulting friction between the contacting surfaces prevents joint slip. Loosen fasteners lead to reduction of clamping force, and compromise the structural integrity. Hence, fastener loading condition evaluation and monitoring need to be addressed for SHM applications.

In this paper, some preliminary results from experimental study on wave propagation through bolt lap joint are presented. Two specimens were constructed for the tests: (a) lap joint of two aluminum strips, and (b) lap joint of two aluminum plates. Piezoelectric wafer active sensors (PWAS) transducers were used to generate and receive ultrasonic propagating waves in the specimens. Observations of wave propagation patterns at different fastener loading level are described and discussed.

1. EXPERIMENTS

We constructed a number of experiments to study the propagation of guided waves through a lap joint with fasteners. Figure 1 presents a typical setup consisting of two strips jointed by two nut-and-bolt fasteners. The load in the fasteners is controlled by the torque applied to the nut-bolt pair. In order to ensure precise application of the load, we also used washer-type load cells ("bolt sensors") inserted under the head of the bolts.

The guided waves were generated with surface mounted PWAS transducers glued to the surface of strips. One PWAS transmitter was placed 2.375 inches ahead of the joint; one PWAS receiver was placed 2.375 inches after the joint. Modulated interrogative waves of various frequencies were generated by the T-PWAS, and received by the R-PWAS. The waves generated by the T-PWAS in the first strip had to travel through the bolted joint into the second strip in order to be picked up by the R-PWAS. It is apparent that a tighter joint would transmit waves better than a looser joint and, for this reason, we varied the tightness of the joint by varying the load measured in the bolts. For each joint tightness condition, we measured all the wave propagation situations and compared the results.

* baoj@mailbox.sc.edu; phone 1 803 777-0619; fax 1 803 777-0619; www.me.sc.edu/research/lamss/

The experiments performed on the large plates indicated that the removal of boundary reflections has cleaned up the received signal to a large degree, but not completely. A number of extraneous signals still remained, and we believe that they are due to the scattering of the incoming waves from the bolt holes combined with partial transmission through the joint. In addition, the incoming waves would be reflected at the edge of the first half-plate and sent backwards towards the bolt holes and then scattered forward into the second half plate through the joint. The experimental setup and the results from these two experiments are presented next.

In this section, we present the experiments performed on the strip lap joint specimen. First we discuss the experimental setup; next, we discuss the wave propagation results.

The strip lap joint specimen is constructed with 6061-T6 aluminum strips. Two 11 in. x 2 in. strips of 1/16 in. thick 6061-T6 aluminum strips are used as joint members. Two holes are drilled on each strip for 1/4 in. bolt fasteners. The diameter of the bolt hole is 0.265 in. The two strips have an overlap of 1 in. giving a total surface contact area of 1 in. x 2 in. The two bolts are placed 1 in. from center to center, symmetric to the center line of the strips. The geometry and setup of the specimen are shown in Figure 1.

We also use two bolt sensors (Omega LC901) to directly measure the clamping force. The bolt sensors are capable of measuring force up to 2000 lbf, with an accuracy of $\pm 3.5\%$ full scale output. A calibration experiment was performed separately to evaluate the relation between the applied torque and the actual load in the bolted joint. Figure 2 shows this relationship which resembles close enough a linear dependency.

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Figure 2 Calibration of the applied torque vs. bolted joint load measured with the bolt sensors.

The modulated interrogative waves were generated by the transmitter PWAS excited with tone-burst signals of various carrier frequencies. Hanning windowed 3.5-count sine signals generated by an arbitrary function generator with a repetition rate of 10 Hz were used. The signal amplitude was 20 Vpp. During each experiment, a carrier frequency scan was carried out between 100 kHz and 500 kHz with 10 kHz step.

The receiver PWAS was connected to a digital oscilloscope for collection of the output voltage signal. The sampling rate was 25 MHz, and total 5000 data points were collected over a 200 μ s time interval. Figure 3 shows the actual experimental setup.

Figure 3 Strip lap joint specimen experimental setup

Table 1 bolt load values and frequencies used in the strip lap joint experiments

		Frequencies: from 100 kHz through 500 kHz in 10 kHz steps				
Load values		100 kHz	110 kHz	...	490 kHz	500 kHz
	Hand tight	X	X	X	X	X
	10 lb-in	X	X	X	X	X
	20 lb-in	X	X	X	X	X
	24 lb-in	X	X	X	X	X

Strip lap joint specimen experimental results

During the strip lap joint experiment, we collected 164 wave signals corresponding to the combinations of bolt loads and frequencies shown in Table 1. The processing of such a large amount of wave data posed considerable challenges. We developed a special LabVIEW program and a graphical user interface (GUI) to facilitate the manipulation of data in order to extract meaning out of the wave signals.

Figure 4 Strip lap joint specimen signal at different bolt torque loading values. Excitation signal frequency is 320 kHz

As an illustration, Figure 4 presents the receiver PWAS signals at 320 kHz for various bolt torque loading values from hand tight up to 24 lb-in. The signal length is 200 μ s throughout. One notices that the amplitude of the signal increases with the bolt load up to 20 lb-in; however, the higher load of 24 lb-in resulted in decreased amplitude. At lower bolt loads, we can see clearly wave packets whereas at higher bolt loads, the wave packets start to merge and at the highest bolt load, a continuous signal seems to appear.

Another example of the received signal at lower frequency of 100 kHz is given in Figure 5. The signal presents different behavior. The maximum signal amplitude was obtained at 10 lb-in torque, and the main wave packet is much stronger than other secondary wave packets. At higher torque loads, multiple wave packets appear, and the main wave packet seems to be splitting into two smaller wave packets. It worth noting that at 100 kHz excitation frequency, the first arrived wave packet amplitude is very low compare with the main wave packet; whereas at 320 kHz excitation frequency, the first arrived wave packet amplitude is much higher. This can be explained by the wave tuning effect, that at 100 kHz, the S0 mode is not tuned, while for the 320 kHz is the optimum frequency for S0 mode transmission.

Figure 6 shows aggregated signal plots for four bolt load values. Each of these plots was obtained by converting the instantaneous signal values into color scale, and stacking all the signals according to their frequency. The same time basis is used for all the signals. These plots show how the dominant wave packets change as the bolt load increases. However, the image seems to be too rich in contents to be easily interpreted. The content richness is due to the multiple reflections from the strip sides that are mixed into the forward wave signal. These difficulties in signal interpretation prompted us to perform experiments on large plates that do not have same issues with side reflections from the boundaries, as discussed next.

Figure 5 Strip lap joint specimen signal at different bolt torque loading values. Excitation frequency is 100 kHz

Figure 6 Strip lap joint specimen aggregated signal plots at different bolt torque loadings

1.2 Experiments on the plate lap joint specimen

In this section, we present the experiments performed on the plate lap joint specimen. First we discuss the experimental setup; next, we discuss the wave propagation results.

Plate lap joint specimen experimental setup

We constructed a second experiment using large plates to reduce the interferences from boundary reflections. In order to keep the two experiments as similar as possible, we instrumented the plate joint with only two fasteners placed identically as in the strip joint. The specimen was constructed with two 24 in.x48 in.x1/16 in. 6061-T6 aluminum plates. The geometry and setup of the specimen are shown in Figure 7. The actual experimental setup is shown in Figure 8.

Figure 7 Geometry and setup of bolted lap joint specimen constructed with two aluminum plates

Plate lap joint specimen experimental results

During the plate lap joint experiment, we collected 492 wave signals corresponding to the combinations of bolt loads and frequencies shown in Table 2. Again, our special LabVIEW program was used for manipulation of data in order to extract meaning out of the wave signals.

Figure 8 Plate lap joint specimen experimental setup

We choose wave signals of frequency 320 kHz and 100 kHz to compare those from strip lap joint experiment, shown in Figure 9 and Figure 10.

Figure 9 presents the receiver PWAS signals at 320 kHz for various bolt torque loading values from hand tight up to 24 lb-in. The signal length is 200 μ s throughout. It's apparent that each wave signals has several high amplitude wave packets that are grouped together, and arrived first. The amplitude of the rest part of the wave signal is much lower than the first arriving wave packet group. In comparison to the strip lap joint experimental results, these wave signals seem to

be much cleaner. Nonetheless, we can see more wave packets when higher torque was applied to the bolts. Similar to the results from strip lap joint experiment, the amplitude of the signal increases with the bolt load up to 20 lb-in, and at higher load of 24 lb-in the amplitude decreases.

Table 2 bolt load values and frequencies used in the plate lap joint experiments

		Frequencies: from 100 kHz through 500 kHz in 10 kHz steps				
Load values		100 kHz	110 kHz	...	490 kHz	500 kHz
	Hand tight	X	X	X	X	X
	3.3 lb-in	X	X	X	X	X
	5 lb-in	X	X	X	X	X
	7 lb-in	X	X	X	X	X
	10 lb-in	X	X	X	X	X
	14 lb-in	X	X	X	X	X
	17 lb-in	X	X	X	X	X
	20 lb-in	X	X	X	X	X
	22 lb-in	X	X	X	X	X
	24 lb-in	X	X	X	X	X
	27 lb-in	X	X	X	X	X
	30 lb-in	X	X	X	X	X

For lower frequency of 100 kHz, as shown in Figure 10, the signal presents different behavior. The maximum signal amplitude was actually obtained at hand tight condition, which was unexpected. Multiple low amplitude wave packets spread over the 200 μ s time frame, and the wave packets are not very well defined.

Figure 9 Plate lap joint specimen signal at different bolt torque loadings values. Excitation frequency 320 kHz

It is also very clear that the amplitude of wave signals from plate lap joint experiments is significantly lower than those from the strip lap joint experiments. For example, at 320 kHz frequency and 20 lb-in torque load condition, the maximum signal amplitude from plate lap joint experiment is ± 60 mV; whereas ± 20 mV was detected from the strip lap joint experiment. This may be due to the circumferential spreading of the wave energy in the plate following the $1/r$ law, which is inhibited in the strip by the multiple reflections at the strip boundaries.

Figure 10 Plate lap joint specimen signal at different bolt torque loadings values. Excitation frequency 100 kHz

Figure 11 shows aggregated signal plots for four bolt load values. Each of these plots was obtained by converting the instantaneous signal values into color scale, and stacking all the signals according to their frequency. The same time basis is used for all the signals. These plots show how the dominant wave packets change as the bolt load increases. These plots are easier to interpret than the plots of Figure 6 because the number of wave packets has been reduced by the use of a large plate specimen. Hence, it is apparent in Figure 11 that certain areas in the plots grow in amplitude as the bolt load increases. These signal areas are marked by red ovals in Figure 11.

Figure 11 Plate lap joint specimen aggregated signal plots at different bolt torque loadings

2. DISCUSSION

In this section, we will try to understand the experimental results presented in previous sections in comparison with the nonlinear finite element simulations. Before starting the discussion of our own results, we will present a brief review of the state of the art in assessing the bolt lap joint condition as a function of bolt load levels using piezoelectric transducers and guided waves propagation through the bolt.

Yang and Chang¹ developed an attenuation-based diagnostic method to detection of bolt loosening in carbon-carbon (C-C) thermal protection system (TPS) panels. The C-C TPS panel was bolted to C/SiC standoff brackets, and the brackets were then bolted to the metallic base structure. PZT (lead zirconate titanate)-embedded sensor washer was developed to create a sensor network. The sensor washers were installed under the head of the bolts connecting the brackets and the base structure. Prototype tests were performed in the laboratory for various loosening conditions of the bolts connecting C-C panel and standoff brackets bolt and the bolts connecting brackets and the base structure. For each combination of panel and bracket loosening, the sensor signals are retrieved and processed into the features energy and SDC, and based on the extracted features the torque levels in the bracket are evaluated collectively to generate two variables: panel torque (T_p) and bracket torque (T_b). It was found during the verification tests that the attenuation-based diagnostic method was capable of locating a loosened bracket and identifying whether the panel-bracket bolt or the bracket-base structure bolt was loosened.

Zagrai et al.² studied lap joint integrity using acousto-elastic method to relate the bolt torque loading with the elastic wave propagation delay. Two 12 in.x2 in.x0.08 in. 2024 aluminum beams were connected by two 3/8-16 3/8-16, grade 8, hex flange, 1 inch steel screws with accompanying 3/8-16 UNC flange nuts to form the lap joint. Piezoelectric transducers (7mm diameter, 0.2 mm thick disk) made with APC 850 piezoceramic material were used to perform pitch-catch experiments. Torque load of 10 ft-lbs to 50 ft-lbs with 10 ft-lbs step were applied to the bolts during the experiments. The wave propagation delay were found to be varying from 0.1 μs to 0.6 μs . Data analysis showed linear dependence of the arrival time on the applied torque.

Coelho et al.³ used a classification algorithm based on support vector machines to detect fatigue crack growth, and also to classify the amount of torque in the bolt of interest. Clayton et al.⁴ explored the feature extraction from guided ultrasonic waves to detect the bolt loosening.

Doyle et al.⁵ proposed models using thermal conductance and guided-wave resistance across lap joint interfaces. Finite element package (ABAQUS) was used to model a lap joint specimen. Simplified 3D model of the two lap joint member strips were created with brick elements (C3D8R0). The bolt loading was converted to pressure loading to be applied on partition matching the profile of the bolt washer on the real specimen. The PWAS transmitters were substituted with circular through-all partition on the surface of one plate where the exciting sensor was bonded. Excitation was simulated as a surface traction load where the vector was defined to be radially directed away from the center. The receiving PWAS was not modeled; instead, a data point was assigned at the center of the receiving PWAS. Figure 12 shows the finite element model and the actual specimen.

Figure 12 Modeled and experimental lap joint specimen used by Doyle et al.⁵

In the simulation, 5 Nm and 10 Nm torque loadings were converted to 2000 N/m² and 4000 N/m² pressure loading on the partition surrounding the bolt hole. It was expected to see the wave slow down as load increases and attenuation as pressure increases. However, analysis on the recorded wave signal from both torque loads did not show discernible variation between the two loads. Figure 13 shows the change in waveforms seen in FEM modeling and experimental results.

Figure 13 Experimental and numerical variation in Lamb waves at 5 N-m and 10 N-m, reported by Doyle et al.⁵

Above mentioned methods sense variation in wave parameters, such as energy, velocity, frequency components, and feature of wave to detect the condition change in bolted lap joint. When wave propagate through lap joint interface, wave transmission, reflection, mode conversion, and damping happen across the lap joint interface. Finite element models are normally created to simulate the bolt joint using contact analysis. However, the contact model requires prior experience for defining the contact pairs and proper calculation parameters such as contact stiffness, friction, etc. Although the correlation between bolt loading value and lap joint clamping force was previously studied by other authors^{6,7}, accurate model is not readily available. Hence, thorough experimental study is necessary to obtain more knowledge about effects of fastener loading on wave propagation through bolted lap joint.

In our work, we have found additional issues that we are not mentioned by previous investigators. In particular, we found that the strip like specimens used by most investigators (and also by ourselves) do not represent well the actual physical condition encountered in practice, e.g. in the joining of aircraft skins. The use of narrow strips to construct bolted joint specimen has the disadvantage that it introduces additional signals from the reflections of the guided waves at the strip side boundaries. Our subsequent experiments on large plates have demonstrated that the signals transmitted through the bolted lap joint are much cleaner, especially at higher frequencies where S₀ guided waves are predominant. Although the signals were somehow cleaned up, some additional wave also appeared beside the fundamental S₀ and A₀ wave packets. These additional waves are believed to be due to scattering from the bolt holes.

3. CONCLUSIONS

This paper has presented experimental results on the propagation of guided waves through a bolted joint under various bolt load values. Piezoelectric wafer active sensor (PWAS) transducers were used for the generation and reception of the guided waves. Two specimen types were used, a strip lap joint and a plate lap joint. The signals measured under various bolt load values and frequency values were studied in order to identify relevant features that change drastically with bolt load.

It was found that the interpretation of the bolt load effects on wave transmission through lap joint interface is very challenging, and is insufficiently understood. A review of the state of the art revealed that several other authors have studied this topic without finding a definitive interpretation of the relation between signal changes and bolt load. Some wave signal features, such as energy, velocity, frequency components, etc. were considered with a certain degree of success, but the interpretation of the wave physics phenomenon taken place in the lap joint at various load values is still not fully understood. A detailed finite element model performed by Doyle et al.⁴ included in the analysis the local pressure created by the bolt head and washer onto the strips, but could not reproduce the drastic changes observed experimentally in the waveform.

This paper has presented a set of carefully conducted experiments aimed at clarifying some of the issues related to the effects of fastener load on guided wave propagation in a bolted lap joint. Our research started with a strip lap joint specimen since strip and beam specimens have been widely used for wave propagation experiments because of their simplicity. However, we found that the wave signals received after traveling through the joint are much more complicated than expected. We hypothesized that these signals are "polluted" by the multiple reflections from the strip side boundaries. These side reflections take place before and after the actual lap joint and mix with the forward traveling waves such that the resulting waves are very difficult to interpret. In order to remove this confounding effect, we constructed a large plate experiment in which we reproduced the same sensors installation and bolt joint configuration as in the narrow strip specimen. We found that some of the signals, especially those at S0 tuning frequency of 320 kHz, were very much simplified by the change from strip to plate conditions. Thus, our hypothesis was confirmed. Hence, it seems that the main contribution of this paper to the advancement of the state of the art consists in highlighting the need for removing the confounding effects of the strip side reflections on the correct interpretation of guided wave changes as they travel through a lap joint with various fastener loads.

Future work is needed to develop appropriate signal processing methods to extract relevant features from the guided wave signals that can be directly correlated with the bolt load values. In doing this, it would be of great assistance to have an efficient predictive modeling approach that can capture correctly the effect of bolt load onto the wave transmission through the lap joint. Friction, Hertzian contact, nonlinear effects, etc. need to be properly captured and described. These and other aspects will make object of future work.

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