SMAR 2019 – Fifth Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2019

Detection of bolt loosening through Ultrasonic imaging

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ABSTRACT: Maintaining adequate bolt torque levels is imperative to ensure the integrity of bolted structures. While in operation, the strength of bolted joints is affected due to structural vibration induced bolt loosening. This article reports a non-destructive methodology to detect bolt loosening. An ultrasonic wave based methodology has been used in this study. Piezo electric ceramic patches have been used for the transmission and reception of ultrasonic signals. The investigation of a single bolted joint steel plates tightened at different torque levels have been undertaken in this study. Ultrasonic waves are excited on the steel plate and its interaction with the bolted interface (plate to plate) has been investigated. It is observed that the strength of reflected signal from the bolted interface varies with the level of bolt tightening. These reflected signals are used as inputs for a newly developed imaging algorithm. It is observed that the developed images clearly discerned the loosened bolt from the tightened one. This proposed method is reference free and has potential for the monitoring of a multi-bolt structure non-invasively.

KEYWORDS: Bolted joints, bolt loosening, ultrasonics, imaging, non-destructive evaluation

1 INTRODUCTION

Bolted structures are important in addressing the problems in sustainable infrastructural development. Bolted joints facilitate easy unfastening of structural members for recycling of structural components once their intended use is over. However, it is crucial to maintain the appropriate bolt tightening levels throughout the service life of the structure. Bolt loosening due to structural vibration during their operation is a very common but a dangerous issue if goes unnoticed. The load capacity of the bolted joints depends on the quality of the bolt tightening provided during their installation. Insufficient clamping force/ preload is a prime reason for bolted joint failure (Kim and Hong 2009). Therefore, there is a need of technologies which can efficiently estimate the level of bolt tightening.

A common technique to estimate bolt tightening is to measure the strain in the bolt using standard strain gauges fitted inside the body. This method has been used by Ahn et al. (Ahn et al. 2016) to measure the loss in clamping force due to corrosion induced bolt damage. However, installation of strain gauges in multi-bolt structure can become an extra cost issue and gauges might require regular replacement if goes bad. Wave based techniques can be an alternative to avoid the instrumentation maintenance issues. Ultrasonic methodology has been utilized to estimate the axial loads in bolts (Johnson, Holt, and Cunningham 1986; Kim and Hong 2009). The underlying principle of these studies relies on the fact the propagating ultrasonic wave velocity is dependent on the bolt axial stress. Other than ultrasonic velocity, time of flight and phase detection measurements were also used to determine the bolt axial load (Jhang et al. 2006). Wang et al. (Wang et al. 2013) utilized ultrasonic transmission measurement to identify the change in the clamping force with bolt loosening. Above mentioned methods are useful but are not very practical to use when it comes to estimate the instant condition of the bolted joints. In these methods, comparison with some baseline information of the joint is needed.

In order to eliminate the constraint of having a baseline information, researchers have utilized the generation of harmonics due to bolt loosening (Amerini and Meo 2011; Zhang et al. 2017). It has been reported in these studies that bolt loosening results in a clapping phenomenon at the bolted interface when ultrasonic waves propagates through it. However, there is always a possibility of instrument related higher harmonics which needs to be taken care of. For a low density and thin plates (< 3mm) this phenomenon might hold true but for thicker and higher density material plates these wave induced clapping might not be significant. Also, it is possible that bolt loosening induced higher harmonics might not be significantly higher than instrument related higher harmonics which are always present in the system even for the fully tightened bolt condition.

Imaging techniques are handy in overcoming the above mentioned issues with monitoring the bolt loosening situations. This can give reliable results if developed and understood properly. However imaging techniques have been used efficiently in monitoring the conditions of structural components (Schickert 2005; Yan, Royer Jr, and Rose 2010) but only few articles (Martinez et al. 2012) are available when it comes to detection of bolt loosening through imaging. In this study, we have explored the potential of imaging technique to monitor the condition of a bolted joint at different tightening levels.

The structure of the paper is as follows: 1) Specimen fabrication 2) discussion on imaging algorithm principle 3) experimental set up 4) results and discussions 5) conclusion 6) Future scopes.

2 SPECIMEN FABRICATION

Two identical steel plates of dimensions 400 mm x 100 mm x 5 mm were cut from a sheet of mild steel. Both the plates are bolted with an M16 fully thread bolt. To demonstrate the effect of bolt loosening on the load capacity of the joint, we performed destructive tensile testing on the specimens tightened at 100 Nm (fully tightened) and 40 Nm (tight enough that it could not be untightened without torque wrench). Figure 1a shows the stress strain characteristics of the two specimens. It is evident that load capacity of the joint almost reduced to half with bolt loosening. Figure 1b shows that the failure mode of the specimen changed from plate shear with bolt intact to bolt shear with plates intact with bolt loosening. Therefore, it is emphasized to timely monitor the level of bolt torque levels in order to avoid catastrophic failures.

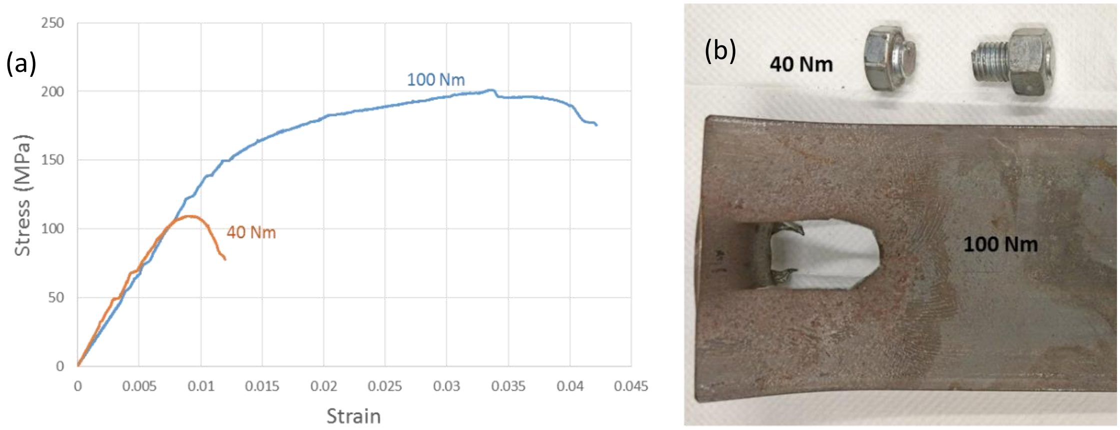

Figure 1: (a) Stress-strain behaviour of bolted joint at 100 Nm and 40 Nm (b) failure of specimens at 40 Nm and 100 Nm bolt torque (Jay Kumar Shah 2019)

3 IMAGING PRINCIPLE

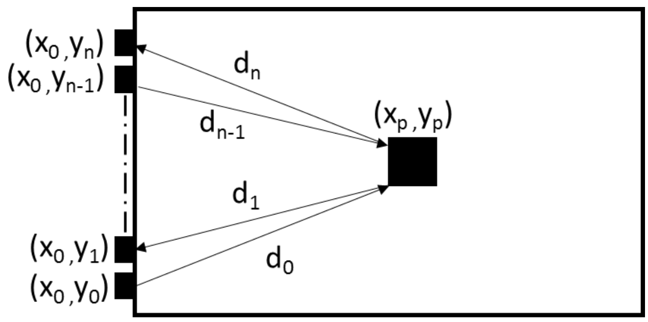

Figure 2: Schematic diagram for imaging principle

Figure demonstrates the underlying principle of the imaging technique. Transducers in pairs located at positions x_{n-1}, y_{n-1} and x_n, y_n (n = 1 to N) acts as transmitter and receiver. It can be understood from the figure that the reflection from a particular pixel located at x_p, y_p is received by transducer after the excited waves travelled the distance $d_{n-1} + d_n$. The corresponding time 't' at which the reflection comes from a specific pixel can be calculated using the following equation 1:

$$t = \frac{(d_{n-1} + d_n)}{c} = \frac{\sqrt{(x_0 - x_p)^2 + (y_n - y_p)^2} + \sqrt{(x_0 - x_p)^2 + (y_{n-1} - y_p)^2}}{c} \qquad (1)$$

where c is the velocity of the wave travelling in the medium, which can be found experimentally. Intensities of the reflected signals recorded at different transducer locations are plotted in order to get an image of the medium. The locations of mismatched medium properties become a source of wave scattering resulting in the high lightening of that particular region in the developed image. In our study, c was found to be ~3200 m/s corresponding to the S-wave velocity in the mild steel. This value was indirectly calculated from the time of arrival of first peak received at the receiver location when the wave propagated in a straight line in between two points (300 mm apart) on the same plate.

4 EXPERIMENTAL PLAN

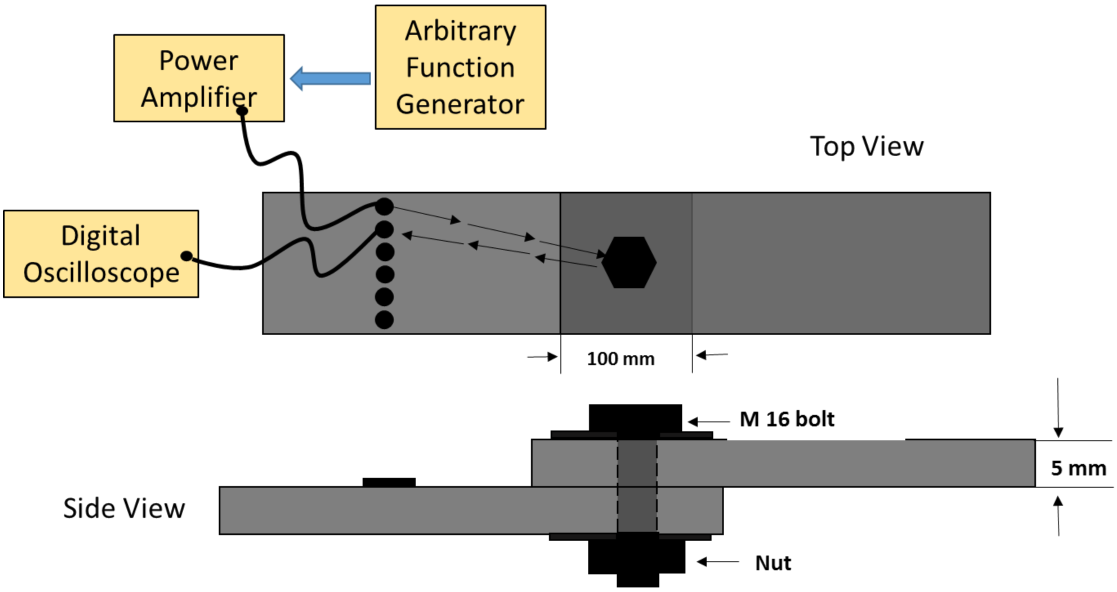

Figure 3: Top and side view of the planned experimental investigation

Ultrasonic waves are excited on one plate of the specimen as shown in figure 3 (top view) using securely bonded piezoelectric ceramic patches. It is to be noticed that the placement of the patches are at the same level as the interface between the plates (side view). In tied together data collection approach, one patch at a time acts an exciter and the neighbouring one acts as a receiver. It is necessary to cleverly choose the distance of patches from the bolted interface in such a way that the reflections from the boundaries (unwanted information) do not come at the same time as the reflection from the interfacial regions. This can also be done by using an efficient combination of signal frequency and the distance. However, high frequencies lose more energy for the same propagation distance. In this way, reflected signals from the interface are recorded along the width of the plate. The recorded reflection data is then fed as the input for the developed imaging algorithm.

5 RESULTS AND DISCUSSIONS

To validate the effectiveness of the imaging technique single plate with a bolt hole has been imaged. Five cycles of a 200 kHz sinusoidal signal has been used as the form of excitation. Figure 4 shows the developed image along with the schematic of the specimen. The reflections from the location of the bolt hole are quite evident in the developed image. The location of the reflection exactly matches with the location of the bolt hole. The colour bar showed in the imaging figures represents the normalized signal amplitudes. Positive and negative values represent the compression and rarefaction components of the recorded wave. Hence, this result validates the logic of developed imaging algorithm.

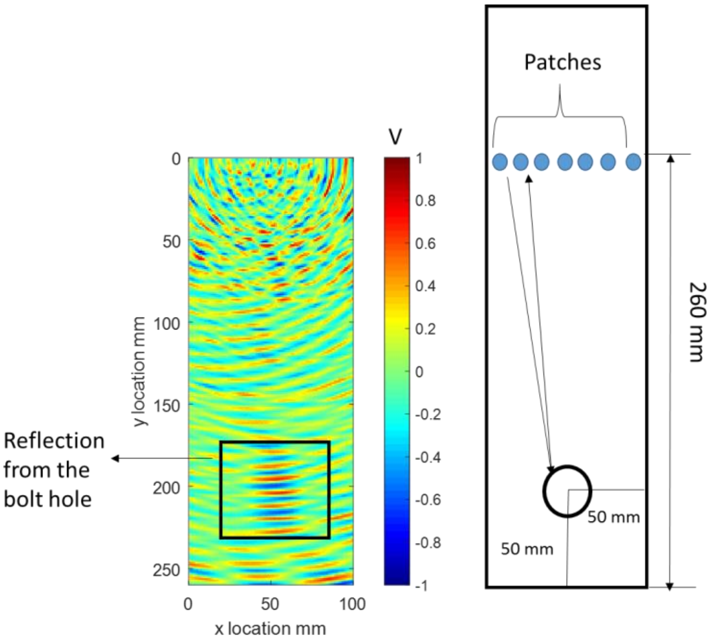

Figure 4: Developed image of a single plate with bolt hole

Further, we have repeated the same experiment on the bolted specimen tightened at 100 Nm and 40 Nm. Figure 5 shows the developed images for each case. It is clearly evident from the images of 100 Nm that there is no significant local reflection from the overlapped region (160 mm to 260 mm) as can be seen in figure 5a. However with the bolt loosening, considerable reflection starts appearing from location of the bolthole (figure 5b).

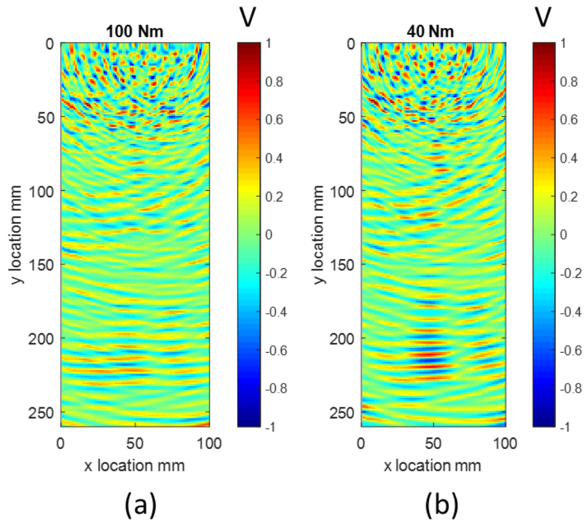

Figure 5: Images of bolted plates at (a) 100 Nm and (b) 40 Nm bolt tightening

It is known strength of a bolted joint depends on the level of contact between two plates. It can be argued that even machined plates do not have perfectly smooth surfaces at microscopic scale. The contact between plates would have undulations as shown in figure 6a. From the conclusion of Wang's work (Wang et al. 2013), it is quite evident that ultrasonic measurements can be used to discern the loosely bolted joint from a tightened joint. Wang et al. deduced their conclusions based on the strength transmitted wave energy across the interfaces which varies with the bolt torques.

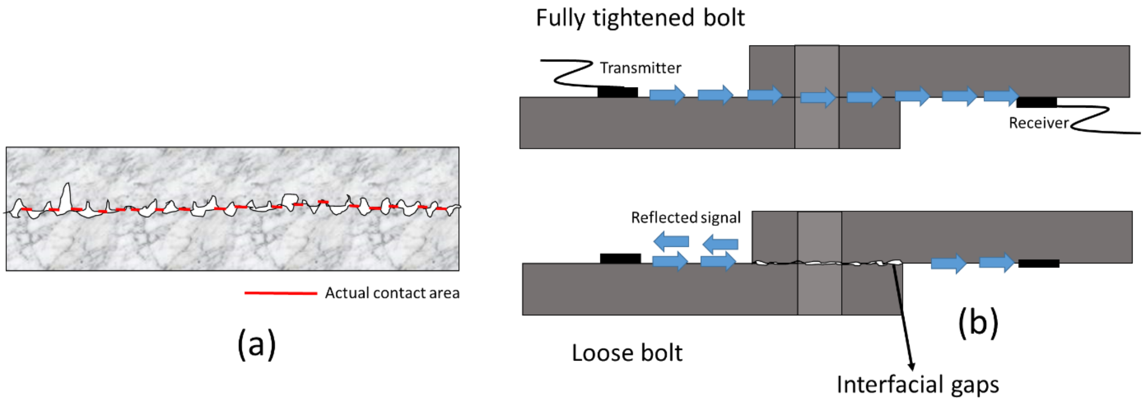

Figure 6: (a) Microscopic gaps at the plates interface (b) wave propagation in fully tightened loosely bolted specimen

In our study, we utilized the complement of Wang et al. idea that with loosening reflection from the interface between bolted plates can be utilized in an imaging technique to identify the bolt loosening. With the bolt tightening microscopic gaps between the plates becomes negligible hence the two plates becomes a continuous medium ideally. This is the case with 100 Nm bolt tightening, where barely visible reflections from the interface (160 mm to 260 mm) are uniformly distributed along the width of the specimen as shown in the figure 5a. These are clear indications of the possibility non-contact areas between the plates due to microscopic gaps.

However, with bolt loosening, there is decrease in the area of contact between the plates. This represents the situation in 40 Nm bolt tightening case. In this case, there is a clear shift of reflected energy towards the location of the bolthole as shown in figure 5b. It can be argued from the principle of elastic wave propagation, major source of reflections in a medium are the locations where there is a significant acoustic impedance mismatch. For loose bolted plates, chances of wave interaction with the bolthole increases and hence there is a significant increase in the reflection from the bolthole region. The benefit of this monitoring approach is that it is reference free.

6 CONCLUDING REMARKS

The paper reports an experimental investigation based imaging technique to detect bolt loosening. A single lap joint tightened at 100 Nm (fully tightened) and 40 Nm (tight enough that it cannot be loosened without torque wrench) bolt torque are investigated. Piezoelectric patches have been used to excite and receive ultrasonic signals. It is established that bolt loosening results in increase in interfacial gap between the bolted plates resulting in the reflection of ultrasonic signal from the bolthole region. The developed images clearly discerned the fully tightened bolt with loosely tightened bolt. Thus, the study shows that the reported ultrasonic based imaging method has the potential to detect loose bolts in a multi-bolt structure as well. The prosed method is baseline free and can be used to estimate the instant condition of the bolted joint.

7 FUTURE SCOPES

In the reported work, the scope of investigation was limited to a single joint specimen. Further extension of this work on intermediate bolt torque levels and multi-bolt structure is underway and will be reported in future.

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