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TITLE: Detection of Bolt Load Loss Using Frequency Domain Techniques

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ABSTRACT

Use of frequency domain techniques is investigated to determine the bolt load loss in hybrid metal composite connections. Hybrid composite/metal connections are susceptible to bolt load changes due to viscoelastic creep and/or environmental effects such as temperature and humidity. A proof-of-concept model was created consisting of a fiber reinforced composite panel bolted to a steel frame. A PZT actuator bonded to the center of the composite panel was used to provide controlled vibration input. The response of the plate was measured using either shear accelerometers or dynamic strain sensors located at the four corners of the composite panel. The effect of changing the load on an instrumented bolt was evaluated using three different monitoring techniques including (a) low frequency modal analysis, (b) high frequency transfer functions between the actuator and sensors and (c) high frequency transmittance functions between pairs of sensors. Experiments demonstrate that the transmittance function approach shows the most promise.

INTRODUCTION

The effort summarized in this paper focuses upon real time detection of bolt load changes in connections for hybrid composite/metal structures. Often, bolted connections are critical to the function of the structure and their failure may have high associated repair costs, or may endanger lives. An accurate assessment of structural integrity depends on a proper evaluation of both the global structural response and the condition of the connections and interfaces. Accordingly, one must perform a thorough investigation into the mechanics of the connections and interfaces of the structure. Real time monitoring of connection integrity is an important challenge.

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The development of structural health monitoring and damage detection systems is the focus of much current research. Monitoring systems can be used to substantially reduce maintenance costs or to prevent catastrophes. In developing a damage detection system the objectives need to be clearly defined so that an optimum and robust detection scheme is the outcome. Global damage will produce large structural changes that can be detected by analyzing the lower vibration frequencies. This is often done in conjunction with numerical models of the structure. Localized damage mechanisms such as delamitation in composites, bolt loosening and cracking may be difficult to detect using the lower structural modes. Techniques that excite and analyze the higher frequencies are typically more robust when the detection of local structural changes or damage is the goal.

There are numerous structural health monitoring techniques currently available for detection of structural damage. However, there has not been much research on the structural health monitoring of bolt load loss in hybrid connections, although techniques developed from other methods reported in the literature may be applicable to this problem. To address this issue, a proof-of-concept test bed was developed that consists of a square plate made of E-glass/vinyl ester composite. The hybrid connection was formed by bolting this plate to a steel frame using steel bolts, including an instrumented bolt. Several interrogation techniques were employed and compared including: 1) low frequency modal analysis; 2) high frequency transfer functions and 3) high frequency transmittance functions. Each of these techniques used a piezoelectric actuator bonded to the panel to deliver a characterized disturbance in a controlled manner. The technique using transmittance functions to evaluate changes in bolt tensioning level shows the most promise.

METHODS OF DAMAGE DETECTION

The fundamental premise behind vibration-based damage detection techniques is that changes in the physical properties of a system will alter a system's modal properties. Thus changes in mass, damping, and stiffness of a system should lead to measurable changes in the system's dynamic properties, such as the natural frequencies, mode shapes and damping. The vibration based structural health monitoring techniques discussed herein are methods using frequency domain calculations including transfer functions and transmittance functions.

Comprehensive literature reviews on the subject of structural health monitoring can be found in references [1]-[3]. The use of statistical analysis procedure and statistical pattern recognition was applied to a vibration based damage detection scheme by Fugate et al. [4]. A passive control technique using piezoelectric materials was used to detect damage by Lew and Juang [5]. In this method, the natural frequencies of a system are identified to detect damage in a closed loop system. A system's damping almost always increases when a virtual passive controller is added. Todd et al. [6] used chaotic input signatures and a state-space method for damage detection. A novel feature called the local attractor variance ratio was developed using chaos theory. They showed how a properly tuned chaotic excitation could be used to robustly detect structural changes.

Salawu [7] presented a review of various investigations on the effects of structural damage on natural frequencies. Many damage location methods use changes in resonant frequencies because frequency measurements can be quickly conducted and are often reliable. However changes in ambient conditions such as temperature and moisture can cause significant frequency changes in composite materials, and findings suggest that detection of damage using frequency measurements might be unreliable when the damage is located at regions of low stress. Similar results were presented by Kessler et al. [8] where the frequency response method was found to be reliable for detecting damage in simple composite structures, but information about damage type, size, location and orientation could not be obtained. Another investigation by Zak et al. [9] showed good agreement between experimental and numerical calculations of the first three bending natural frequencies of a delaminated composite beam. Kuo and Jayasuriya [10] used transfer functions to determine the extent of joint loosening in automobile vehicle frames with high mileage. The method was successful as presented in the paper, but did not give specifics for frequency ranges investigated and what type of frequency response functions were utilized.

Transmittance functions are similar to the FRF's and are derived as the complex ratio between Fourier transforms of a response point and a reference point on a structure. The transmittance function between two response points, a and b, can be written as:

$$T_{ab}(f) = \frac{G_{ab}(f)}{G_{bb}(f)} \tag{1}$$

The motivation for using transmittance functions is that excitation does not need to be measured; therefore, changes in the structure due to the environmental effects (temperature and moisture) are partly cancelled [11,12]. Also, the cross-spectral density used in transmittance functions is a measure of the linearity between two response points on the structure and can detect local damage by propagation changes (phase delay and amplitude modulation) in the structural response. Since the cross-spectral density function is the Fourier transform of the cross-correlation function, it represents the frequency domain characterization of the similarity of the magnitude and phase of two signals, e.g. of two nearby response points on the structure. Hence, if used in the correct frequency range, it can accurately detect damage over small distances on a structure. Furthermore, measured transmittance data inherit certain advantages over modal data. Firstly, transmittance functions have few sources for computing error, except the minimal error from the numerical Fast Fourier Transform. Secondly, they carry complete information on the dynamic behavior of the test structure, in terms of both the vibration modes and the damping, at many frequency points, including those away from the response of the structure.

Damage Detection Approaches Using a Damage Index

A damage index can be used to quantify the change in dynamic properties of a structure in a potentially "damaged" state compared to a baseline "healthy" state. The damage index, Dij, quantifies the aggregate change of the frequency response function or transmittance functions across a given frequency range in terms of a scalar value. This scalar quantification eliminates the need to store the complete time history and/or spectral data when data storage limitations are of concern. The damage index (Dij), defined over a frequency range of f1 to f2 is given as:

$$D_{ij} = \frac{\int_{f_1}^{f_2} \left| Q_{ij}^{h}(f) - Q_{ij}^{d}(f) \right| df}{\int_{f_1}^{f_2} \left| Q_{ij}^{h}(f) \right| df} \tag{2}$$

Here $Q_{ij}^{h}(f)$ represents either the frequency response function, $H_{ij}^{h}(f)$, of response point, i, relative to force, j, or the transmittance function, $T_{ij}^{h}(f)$, of response point, i, relative to response point, j in a healthy state and $Q_{ij}^{d}(f)$ represents the damaged state. A matrix of damage indices are computed for the system whose size is equal to the number of response points measured. This matrix can be interpreted based upon the phenomenon being measured. In the case of bolt loosening on a structural system the desired outcome is to quantify the change in damage index relative to bolt torque. Of course other phenomenon may also change the structure, which can bias the estimate. The study presented in this paper is an assessment of the feasibility of several methods in detection of bolt load loss.

EXPERIMENTAL TESTING

As a test bed for the study, a composite plate and steel frame apparatus were designed and fabricated. The test article consists of a 622 mm (24.5-inch) square Eglass/vinyl ester composite plate drilled at its perimeter and bolted to a steel frame with sixteen 12.7 mm (½-inch) diameter steel bolts as shown in Figure 1. The composite plate was a 6.35 mm (¼ inch) thick Eglass/vinyl ester composite. It consisted of eight layers of Brunswick Technologies Inc. (BTI) 0/90 Eglass knit fabric (BTI CM-2408) in a symmetric lay-up, [(0/90)4]S. The matrix material is a Dow Derakane 8084 resin infused at the University of Maine Crosby Laboratory, using a Vacuum Assisted Resin Transfer Molding (VARTM) process. Sixteen 14.3 mm (9/16 in.) holes were drilled around the plate perimeter to match the bolt pattern of the steel picture frame.

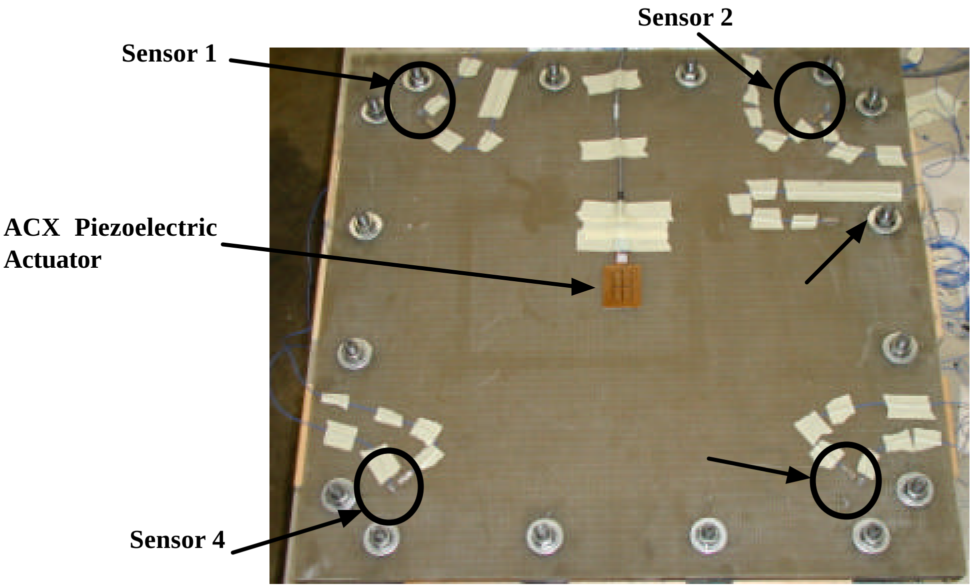
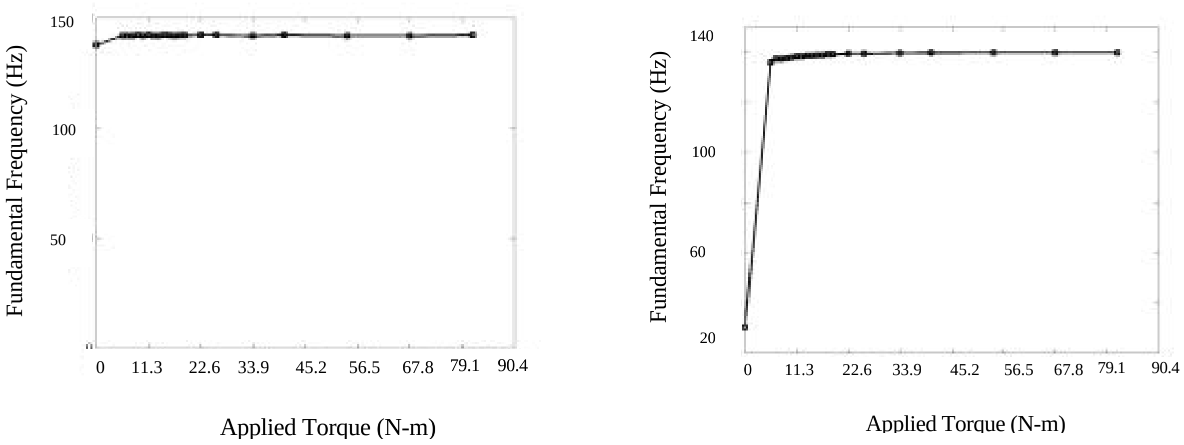


Figure 1. Layout of plate with bolted hybrid connection with PZT.

Detection of Bolt Loosening Using Fundamental Frequency

As a baseline, an attempt was made to detect bolt loosening using fundamental frequency information. This study was conducted two ways; namely 1) with the torque in only one bolt being reduced with the other bolts left at full level (720 in-lbs); and 2) with the torque in all bolts reduced by the same amount. The results of the study a single loosened bolt is presented in Figure 2a. It is observed that a change in the tension of one bolt around the perimeter of the plate does not significantly change the fundamental frequency of the plate, expect for a slight decrease in frequency when the bolt is completely loose. Results of the more dramatic case where all of the bolts are loosened to the same load level is presented in Figure 2b. Again, it is observed that a change in the tension of all the bolts does not significantly change the fundamental frequency of the plate, expect for the case when all of the bolts are completely loose.



a) One bolt loosened

b) All bolts loosened

Figure 2. Changes in Fundamental Frequency

Detection Using the Transfer Function Method

The potential for using transfer function information to detect bolt loosening is presented in this section. Various bands of input frequency, with a 4 KHz bandwidth, were analyzed for their effectiveness. During these tests, all of the bolts were torqued to a level of 81.3 N-m (720 in-lbs) and a change in torque was applied to the instrumented bolt only. One sensor was placed directly next to the instrumented bolt and another sensor was placed directly on the other side of the plate away from the loosened bolt. Both the ICP accelerometers and dynamic strain sensors were employed to determine which sensor produced better results. The bolt torque was incrementally varied, for the instrumented bolt, in the same manner as described in the previous section. It was observed that the chirp signal in the band from 13-17 kHz resulted in the most sensitive response.

Figure 3 shows an example frequency response functions using the shear accelerometer signals for the sensors next to the loosened bolt. The plot shows the response measured on the decibel scale relative to the PZT actuator input signal as a function of both the loosened bolt load and frequency range investigated. The figure shows that the transfer functions, in the band of 13-17 kHz, change significantly as the bolt load is reduced. Plots of the damage index for this case is shown in Figure 4 for an accelerometer placed near to and far from the instrumented bolt. Inspection of the damage index plots show an increasing change in the damage index as the bolt is loosened. However, the damage index plots do not show significant dependence on the location of the sensors relative to the loosened bolt. The transfer function plots change as the bolt load varies, and thus the damage index changes. The results do show that there is a change in the dynamic characteristics of the system with a bolt loosening, and that the sensitivity to the changes are different depending on the input frequency range and what type of sensor is used.

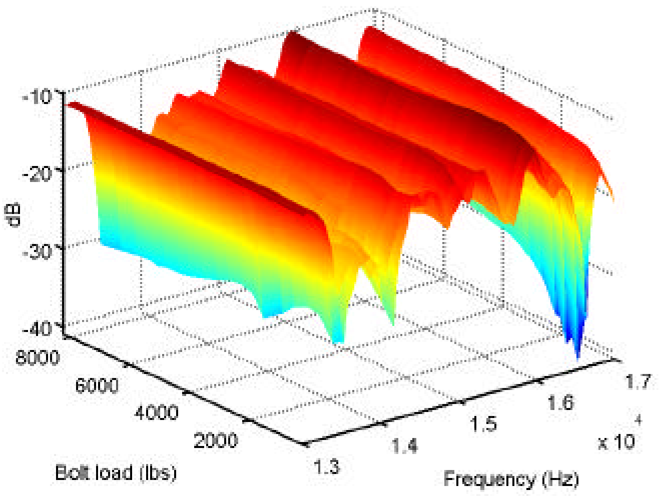


Figure 3. FRF Using accelerometers near the bolt

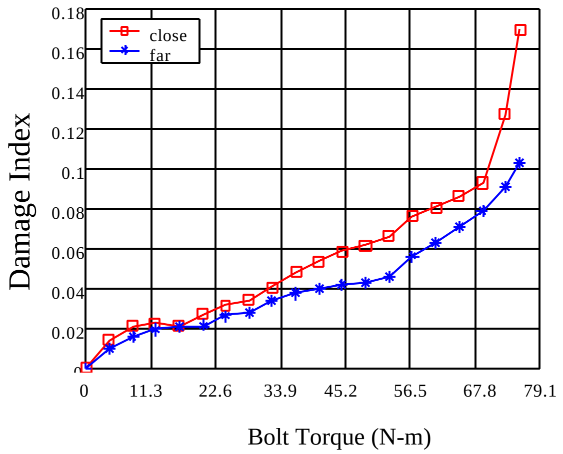


Figure 4. Loosening indicator for frequency response function test with accelerometers

Detection Using the Transmittance Function Method

Transmittance testing procedures are similar to the procedures using transfer functions. For the transmittance tests, the response in the frequency domain of two sensors is compared with each other, in contrast to estimating transfer functions where the response of the sensor is compared to the excitation signal. Thus, for the transmittance testing, sensor A was connected to input channel 1 and sensor B was connected to reference channel 2 of the Siglab hardware, thus the transmittance function A with respect to B (TAB) was calculated using this configuration according to Eqn. (1). Tests were conduced by incrementally loosening a single bolt as described previously. Switch boxes were employed to facilitate a quick change of sensors so that multiple transmittance functions could be recorded easily.

Transmittance function estimates were made in the frequency range from 0 Hz to 20 KHz, which was divided into a series of subranges with a 2 KHz bandwidth. The various analysis bandwidths were investigated so to determine the best range in which to detect bolt loosening for this particular structure. The use of smaller bandwidths allows for a higher frequency resolution than would be possible if the damage estimates were taken over the entire 0-20 kHz range. Responses of strain sensors were compared to accelerometers and larger damage indices were found using the acceleration as the measurand. The frequency band from 7-9 KHz was observed to produce the most sensitivity of the damage index to bolt loosening. A sample transmittance function, T23, for this frequency range is presented in Figure 5. The healthy state is represented by a bolt torque of 81.3 N-m (720 in-lbs) and loosened state plotted correspond to torques of 61.0, 33.9 and 6.8 N-m (540, 300 and 60 in-lbs).

The damage index was computed for the loosened states and an increasing trend with bolt loosening is observed as shown in Figure 6. This figure includes a complete set of transmittance functions for input in the 7-9 KHz range noting that transmittance TAB is virtually equal to transmittance TBA due to the symmetry of the system and sensor placement. The horizontal axis in this figure is the decrease in torque of the instrumented bolt from its fully torqued level of 81.3 N-m (720 in-lbs). This set of parameters resulted in a worst case damage index of 1.4 when the bolt was loosened by 74.6 N-m (660 in-lbs) to 6.8 N-m (60 in-lbs). As a comparison, the frequency range from 18 to 20 KHz results in a damage index of 1.0 for the T23 response when the bolt is loosened to 6.8 N-m (60 in-lbs). The use of strain sensors in the range of 7-9 KHz resulted in a damage index of 0.6 for the same bolt loosening parameters. The damage levels for the transmittance function T23 was higher than all other reported transmittance functions in the 7 kHz to 9 kHz frequency range when using accelerometers as sensors. Also demonstrated in Figure 6 is that the damage index of sensors 2 and 3 was in all cases the largest of the four measured damage indices. It is noted that the bolt loosened lies between sensor 2 and 3.

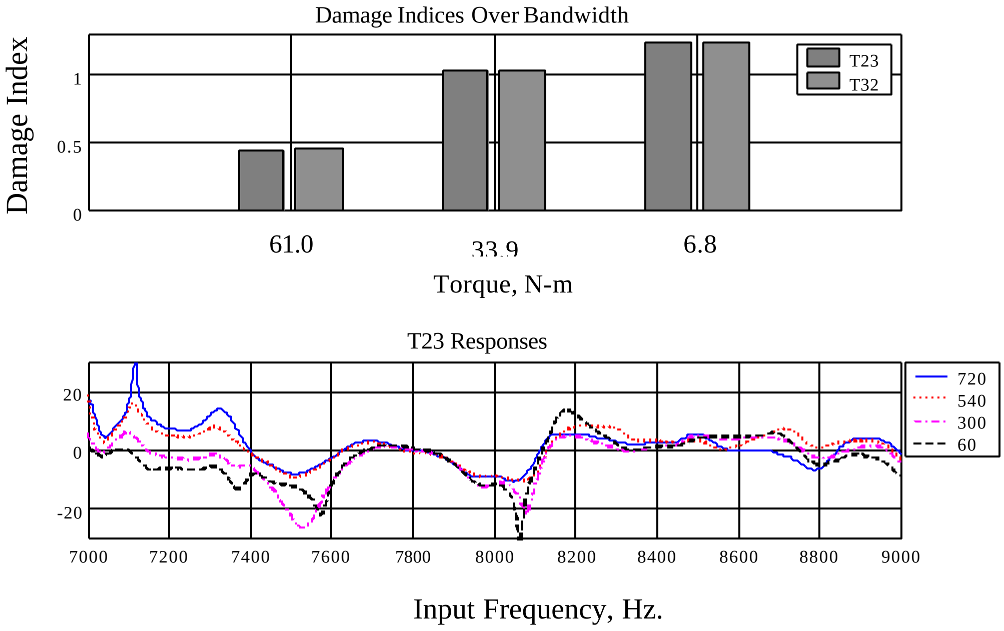


Figure 5. Transmittance function with accelerometers over 7-9 KHz range

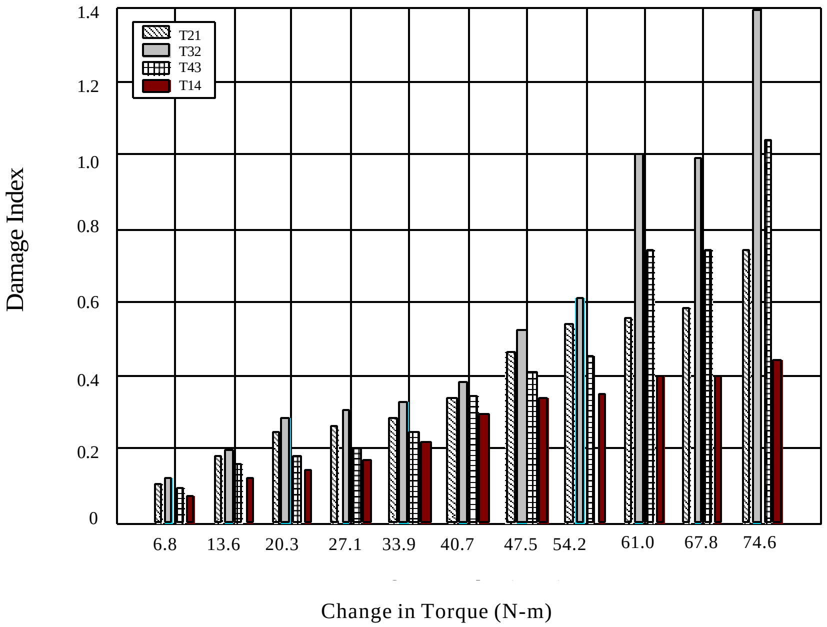


Figure 6. Damage index using transmittance function over 7-9 KHz Range

CONCLUSIONS

The research summarized in this paper focus on assessing several different frequency domain methods to assess loosening of bolted connections in hybrid metal/composite connections. The bolted connection is one of the most widely used in practice and loss of bolt load can occur due to viscoelastic creep of the composite material, thermal effects, moisture effects and vibrations. Methods attempted to monitor bolt load loss are under the umbrella of structural vibration analysis. Three different schemes were attempted which cover a large range of input vibration frequencies. The methods include: 1) assessing the change in fundamental mode properties; 2) assessing the change in transfer functions; and 3) assessing the change in transmittance functions. A proof-of-concept model was created consisting of a steel frame and an E-glass/vinyl ester composite panel that was bolted to the frame using sixteen bolts. Controlled vibration input was provided to the panel using a piezoelectric actuator bonded to the composite panel at its center.

The technique using fundamental mode properties was only able to detect changes in bolt load only when all of the sixteen bolts on the panel were loose. It is also observed that a change in the load of a single bolt does not significantly change the fundamental frequency of the plate, expect for the case when it is completely loose.

Use of transfer functions to detect bolt loosening shows some promise. Various bands of input frequency from 0 to 20 kHz. were analyzed for their effectiveness with a bandwidth of 4 kHz. It was observed that the band from 13-17 kHz was the most sensitive. Change in frequency response function were quantified using a damage index that compares the current state to a healthy baseline state. Observed in testing was an increasing change in the damage index as the bolt is loosened. The damage index plots do not show significant dependence on the location of the sensors relative to the loosened bolt. The results do show that there is a change in the dynamic characteristics of the system with a bolt loosening, and that the sensitivity to the changes are different depending on the input frequency range and what type of sensor is used.

Transmittance function estimates were made in the frequency range from 0 Hz to 20 KHz, which was divided into a series of subranges with a 2 KHz bandwidth. The frequency band from 7-9 KHz was observed to produce the most sensitivity of the damage index to bolt loosening. An increasing trend in damage index with bolt loosening is observed with the worst case being 1.4 with the bolt loosing 92% of its original preload. A bolt load loss of only 8% was reliably detected and resulted in a damage index of 0.16. Strain sensors resulted in a lower damage index of 0.6 for the same bolt loosening parameters. The damage levels for the transmittance function T23 was higher than all other reported transmittance functions in the 7 kHz to 9 kHz frequency range when using accelerometers as sensors. Also demonstrated is that the damage index of sensors 2 and 3 was in all cases the largest of the four measured damage indices. It is noted that the bolt loosened lies between sensor 2 and 3.

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