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DETECTION OF FATIGUE DAMAGE IN SHEAR CONNECTIONS USING
ACOUSTIC WAVE PROPAGATION

By

Zichao Wang

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Civil Engineering

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2017

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This report has been approved in partial fulfillment of the requirements for the Degree of
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Abstract

Fatigue damage is an important concern in structural steel connections where frequent load reversals are expected. Detection of fatigue damage is typically done with infrequent visual inspections that are subjective and limited to surface features. A permanent embedded structural health monitoring (SHM) system could be helpful in detecting damage as it occurs. Current methods for detecting fatigue damage include inference of fatigue life expended through cycle counting from long-term strain measurement campaigns, and through short-term impedance measurements. The first approach has the advantage that it is relatively simple from an algorithmic point of view, but it is an indirect measure of damage, and it does require that strain gauges be present and operational to measure the entire strain history of the component in question. Impedance measurements from piezoelectric transducers (PZTs) bonded to the surface of the specimen can detect damage directly and do not require the use of historical data (though baseline health impedance signatures are needed for reference), but the processing of impedance data in this application can be difficult and subjective. In addition, many studies focused on impedance measurements for damage detection use overly simplified coupon geometries for experimental validation that do not capture the full complexity of a structural steel connection. In this study, an acoustic wave propagation method is proposed to detect fatigue damage in a bolted seated connection. A PZT located on the connected column measures the energy that propagates through the connection. Only the top angle for the connection (typically used for stability) is damaged in the study to allow multiple tests to be made with minimal specimen preparation. Signal processing methods including

matched filter to separate the input signal from the signal distortions are used to improve sensitivity of the approach. Features examined include energy transmitted through the connection and pole information associated with the signal residuals (error information) with only the latter being sensitive to fatigue damage.

1 Introduction

With the goal of immediate re-occupancy after earthquakes in Chile [1], where facilities are typically to respond elastically with ‘fully functional’ performance after large-scale earthquakes [2]. The serviceability of structures after seismic activities in the rest of the world is well beyond prediction. For steel framed structures in the United States, energy generated by an earthquake is primarily absorbed and dissipated by the plastic hinges formed at connections between beams and columns [3]. In other words, in order to prevent catastrophic brittle failure, permanent damage such as yielding will be introduced to structural components after seismic activities [4-8].

However, despite this is likely that connections between beams and columns have sufficient capacities to accommodate ductile and brittle failures; what really makes the infrastructure at potential risk is the fatigue failure induced by cumulative cyclic loading. Research accomplished by Haghani, et al [9], has demonstrated a significant number of fatigue-prone details in steel structures. Seemingly, most of the fatigue damage occurred at connections between beams and major load carrying members. Hence, it is of great importance to detect fatigue damages in the earlier stage.

Fatigue is a cumulative process introduced by repetitive action of much lower load that could barely rupture an object. It consists of three stages: crack initiation, propagation, and final fracture of the component [10]. Particularly for steel, under low-cycle fatigue (LCF) where it takes less than 10^4 loading cycles to break a component, micro-cracks along with plastic deformation will be first introduced at the highest stress concentration. Next, micro-cracks will become visible within a blink of an eye. As the number of loading cycle

increases, macro-cracks propagate, and will eventually rupture the component. A study related to LCF fatigue failure can be found in [11]. While between 10^4 and approximately 10^6 cycles, fracture triggered by cyclic loading can be diagnosed as high-cycle fatigue (HCF) damage. Unlike LCF, the crack initiation stage accounts for most of the fatigue process [12]. Related investigations have shown that in this failure mode, final fracture could occur rapidly following the development of macro-cracks [13-15]. Most importantly, without the indication of distinctive plastic deformation, detecting HCF damage would be nigh impossible with visual inspection under field condition, maybe...!

Yet, previous studies have specified that structural health monitoring (SHM) could make damage detection possible under field conditions. SHM is the process of measuring the dynamic response of a system and determining from these data the current state of the system's 'health' in near real time. Two state-of-art approaches have been implemented to SHM process. One is called *global approach*, which the system's dynamic responses under vibration will be monitored as damage accumulates [16-24]. While the other approach concentrates on the study of ultrasonic wave propagation where any characteristic change of the ultrasonic wave propagated across the structure, in comparison with baseline wave from healthy structures could reflect damage. This approached is defined as *local approach* [25-30].

Current methods for detecting fatigue damage involve long-term strain measurement campaigns [31-35], and short-term electromagnetic impedance measurements [36-40]. The first approach has an advantage in monitoring the global healthiness of the structure, but it needs the entire real time history of the component. Furthermore, the sensors

embedded in the structure require regular maintenance and calibration overtime. While the latter approach does not require historical data, technical difficulties still exist in this approach. Optimal location for the sensor placement entails excessive investigation. Along with the data processing that can be difficult and subjective. Most importantly, randomness associated with identifying the frequency of interest to the structure is well beyond control. What's more, it is been observed that overly simplified coupon geometries that do not capture the full complexity of a structure were often used. Hence, there is an urge in finding new techniques in health monitoring fatigue damages.

In this paper, steel shear connections are investigated under the acoustic wave propagation technique. This technique can be interpreted as the global approach of SHM. Previous work performed by Ng and Veidt [41] on the subject of damage detection in composite materials using Lamb wave based techniques, and work by Noh, et al [42]., involving structural damage diagnosis using wavelet-based damage-sensitive features, have shown the effectiveness of acoustic wave propagation damage detection algorithm. On the other hand, Morlet-wavelets is able to propagate through steel as longitudinal and shear waves of plane strain. Not only Morlet-wavelet has extraordinary performance in ultrasonic frequencies, which it is capable to minimize interferences such as noise and unexpected vibration during damage detection process, but also its damage-sensitive natures has been proven favorable under nonstationary motions [43].

What makes the Morlet-wavelet based technique even more promising is the introduction of Piezoelectric (PZT) transducers. Several experiments have witnessed the successful implementation of PZT transducers [44-47]. Piezoelectric material can generate electrical

charges when stimulated mechanically, while with the presence of electric fields, it can produce feedback with mechanical strains. Due to this special nature, PZT transducers can act as both actuators and sensors in health monitoring processes [48-49]. What's more, PZT transducers have little influence on the integrity of the host structure. Madhav and Soh [50] suggested that there are no restrictions on mass of the PZT and its adhesive to the host structure. As well as there is no limitation on the quantity of PZT transducers applied.

In order to carry out the test, only the top angle for the connection is damaged in the study to allow multiple tests to be made with minimal specimen preparation. The method presented herein consists of two subtopics and covers high-cycle fatigue behavior of shear connections. Primarily, in lieu of naturally fatigue damaged specimen, the top-and-seated angle of the connection was tested mechanically in a condition of cyclic transverse bending at the frequency of 5Hz without any mean stress effect. Fatigue properties for ASTM A36 steel was estimated based on stress-life method, the specimen was expected to rupture around 130,000 cycles at stress level of 33 ksi. The integrity of HCF damaged specimen was evaluated gradually as fatigue damage accumulated.

Similarly, LCF damage feature extraction was performed as a reference to the previous test. Instead of exerted stress to the specimen from the test machine, LCF damage was achieved manually by means of lever action and body weight of an adult. Identical data acquisition methods and signal processing approaches were applied in this part. Lastly, the bolt looseness of snug-tightened bolt connection was inspected. Snug-tightened condition was achieved by a full effort of a torque wrench. Bolt looseness was investigated respectively on the beam and the column. Clamping force was reduced gradually by half

turns of the nut until it was eventually unscrewed. Further results indicates that variation in bolt looseness level due to frequent removal of the top-and-seated angle from the connection did not influence the findings.

To avoid low frequency interference, morlet-wavelet was driven at the frequency of 249.118 kHz. A PZT located on a beam specimen excites one five-peak morlet-wavelet in to the connection and a PZT sensor located on the connected column measures the energy that propagates through the system. Nevertheless, interference could be still possible, despite the combination of morlet-wavelet and the PZT transducers is applied. Under certain circumstances, difficulties in characterizing damage features is one of the problems engineers need to tackle. For example, similar to echoing, the morlet-wavelet could easily resonance in the surface of the host structure. The echoes, on one hand consist of the original soundwave as well as the ricochet; the output morlet-wavelet on the other hand, is embedded with the known mother wavelet and error information. Hence, in the effort to extract the actual reflection of the system, matched-filter approach was applied. Matched filtering is a process for maximizing the signal-to-noise ratio (SNR) of a wavelet that is embedded in noise. If the input signal were a wavelet, then the maximum SNR at the output would occur when the filter has an impulse response that is the time-reverse of the input wavelet [51].

In addition, it is hypothesized that the residual output, which is the subtraction between match-filtered data and the raw output, could represent the error information of the system. Moreover, in comparison with baseline structure, as damages occur, the energy attenuation

level of the mother wavelet could be altered. What's more, as Swartz [52] suggested, the transfer function of the system can characterize physical damage by the migration of poles.

Thus, due to the special natural of PZT materials, the total absolute area under the time domain output residual could represent electrical energy (or strain energy), alterations in this value indicates variance in energy attenuation of the morlet-wavelet as damage progresses. Damage indexes can be created in regards to the total absolute area under the output residual at each fatigue stage in the time domain. Twenty groups of data were collected for each fatigue stage. The mean and norm for the total area for each fatigue stage could indicate the energy attenuation level. Yet, this approach seems insensitive to fatigue damage.

As an alternative, because the transfer function is well known for characterizing the physical properties of the system, it was hoped that this mathematical tool could identify the relationship between the input signal and the output residuals. The system's damping ratio is straightly related to the poles of the transfer function. When damage is introduced to the system, an increase in the damping ratio of the system is expected, and then the location of transfer function poles migrates. Under Laplace domain, the real part of the pole represents the system's natural frequency, while the imaginary part of the pole stands for the damping ratio. In summary, a twenty pole and one zero transfer function was created. The poles for this transfer function were monitored. Later results show that, as fatigue damage grew; pole migration was detected at the frequency of 6.25×10^9 rad/s. For each fatigue stage, the damping ratio was extracted from twenty sets of data. It was then

averaged in order to generate the damage indexes of this method. This method has been proven useful in detecting fatigue damage.

Presumably, unlike in high-cycle fatigue damage, the energy attenuation method will not be influenced by plastic deformation, various damages can be found in specimens damaged by low-cycle fatigue. Thus, further investigations are required on this assumption. What's more, since only the top-and-seated angle was damaged in this study, other components were not subjected to the same level as the angle had. Hence, this adverse effect definitely corrupted the acoustic wave propagation process. As a result, the investigation of LCF in this study only served as a reference in fatigue damage detection, so did the study on bolt looseness.

This report is organized as follows. Firstly, detailed illustration of experimental setup is demonstrated in Chapter 2 including HCF test, LCF test and the monitoring of bolt looseness. Besides, Chapter 2 also describes the methodologies implemented in this study. Next, results of this study can be found in Chapter 3. Lastly, Chapter 4 summarizes the conclusion and recommended future works based on this study.

2 Experimental Setup and Methodologies

2.1 Beam-to-Column Connection

The shear connection (Figure 2.1.1) involves of W14 x 61 column (Figure 2.1.2), W 12 x 36 beam (Figure 2.1.3), and an ASTM A36 L 4 x 3 x ¼ top-and-seated angle (Figure 2.1.4). Only the top angle for the connection, which typically used for stability, was of great interest in this study allowing multiple tests to be made with minimal specimen preparation. Due to this reason, detailed drawings for other components in the connection will not be provided. Hardware for this connection include ¾ in. diameter ASTM A325 Type I Grade 5 Structural Bolts; as well as the corresponding F435-I hardened washers and ASTM A563 nuts. Under snug-tightened condition, those components conclude the shear connection.

Figure 2.1.1 Shear Connection Assembly

Figure 2.1.2 Shear Connection: Column and PZT Actuator Location, in.

Figure 2.1.3 Shear Connection: Beam and PZT Actuator Location, in.

Figure 2.1.4 Shear Connection: ASTM A36 L 4 x 3 x $\frac{1}{4}$ Top-and-Seated Angle

2.2 Fatigue Property Estimation

Fatigue damage is a common failure mode for metals. Metals subjected to axial; flexural; torsional; or a combination of these types of forces, could be damaged by loadings within the design limits due to cyclic effect. ASTM defines fatigue strength, as the value of stress at which failure occurs after certain cycles, and fatigue limit, as the limiting value of stress at which failure occurs as fatigue life becomes very large [53]. Typically, for steel, finite life region is around 10^6 cycles.

Since the 1800s, the stress-based approach has become the standard fatigue analysis method. This method is referred as the stress-life (S-N) approach. In this approach, fatigue property of a component is characterized in the relationship of stress and the associated fatigue life. In general, it has been observed that as the stress level increases the fatigue life in log scale decreases [54].

To estimate fatigue property for ASTM A36 L 4 x 3 x $\frac{1}{4}$ angle, stress-life approach was applied in this study. To begin with, fatigue strength at 10^3 and 10^6 were estimated. Since this study only emphasize on the detection of fatigue damage, a precise fatigue property estimation was not a significant consideration, as long the specimen was not subjected to plastic deformation. Hence, it is logical to assume the beam leg of the angle as a cantilever beam (**Error! Reference source not found.**) due to similarities in their geometry and behaviors under flexural loading.

Figure 2.2.1 Section Property for ASTM A36 L 4 x 3 x $\frac{1}{4}$ Angle

Table 2.2.1 Section Properties for ASTM A36 Angle	
Section Properties	
Width, in.	8
Height, in.	0.25
Moment of Inertia, in ⁴	0.0104
Length of Beam, in.	3.375
Length from Point of Load to Free End, in.	1.5
Hole Diameter, in.	0.75
Yield Strength, ksi	36
Ultimate Tensile Strength, ksi	58
Young's Modulus, ksi	29,000

Section properties for this angle is illustrated in Table 2.2.1. According to [12], the bending fatigue strength at 10^3 for all types of material is estimated as 90 percent of the ultimate strength. Consequently, the fatigue strength for steel at 10^3 cycles is estimated as 52.2 ksi. Fatigue strength at 10^6 cycles, on the other hand, was predicated as the multiplication of 0.5 to the ultimate tensile strength of steel and adjustment factors corresponding to Hot-Roll steel (0.76), which final rupture would occur at 10^6 cycles of constant loading at 25.56 ksi of bending stress. The result of Stress-life curve was plotted using linear interpolation in log scales. Figure 2.2.2 demonstrates the stress-life curve for ASTM A36 L 4 x 3 x 1/4 hot-rolled angle.

Figure 2.2.2 Stress-Life Curve ASTM A36 Hot-Rolled Steel

However, the stress-life approach has been accused insufficient in fatigue design, since this approach depends on a large number of testing and statistical analysis. What's more, material's geometry factors, size factors, surface finishing factors, and loading types should all be taken into consideration when estimating fatigue properties. Sophisticated

approaches have been developed since then, such as the strain-based fatigue analysis and the mean stress correction method. Nonetheless, the purpose of this study aimed to duplicate fatigue damage, stress-life method is proven capable of providing insights on fatigue properties.

2.3 High-Cycle Fatigue Test

High-Cycle Fatigue test offers an opportunity to replicate naturally occurred fatigue damage with little plastic deformation. The top-and-seated angle of the connection was tested mechanically in a condition of cyclic transverse bending at the frequency of 5Hz without any mean stress effect. This test was operated on Hydraulic MTS Machine at displacement control, according to the assumed cantilever beam modal; decisions of a ± 0.01 in. displacement representing 33 ksi of stress was made as the input parameter exerted to the beam leg of the angle. However, since the stress was dissipated by the hardware and other components in the assembly, the real input displacement was ± 0.1 in. Since at this parameter, expected reaction can be reached according to load cell reading. Final fracture of the specimen was expected to occur around 130,000 cycles. Further results have shown that this estimation was accurate.

Figure 2.3.1 Hydraulic MTS Test Machine

Figure 2.3.2 MTS Machine Load Cell

Figure 2.3.3 High-Cycle Fatigue Test Setup

Figure 2.3.1 through Figure 2.3.3 demonstrates the setup for this operation. Additional ASTM A36 L 5 x 5 X ½ angle serves as a jig connecting the lower part of the machine and the specimen. This connection jig was fastened to the machine, while ASTM A325 Type I bolts from the shear connection fastened the outstanding leg of the angle to the connection jig. Two steel rods were bolted together where the beam leg of the angle was sandwiched in between. Cyclic bending stress was subjected to the specimen by vertical displacement of the connection jig. Bending stress was mostly exerted to the outstanding leg of the angle. Nevertheless, in order to accelerate fatigue process, square notches were cut on both side of the beam leg with hacksaw in an effort to initiate fatigue cracks at the highest stress concentration. The result for this test can be found in Chapter 3.

2.4 Low-Cycle Fatigue Test

The goal of this operation was to duplicate fatigue damage under 10^2 cycles. Despite the fact that high-cycle fatigue damage is more devastating, health monitoring of low-cycle fatigue damage is of equal importance. Regardless of the MTS load cell is capable of withstanding loadings up to 10 metric tons, the abilities in withstanding fatigue damages for other components in the assembly are questionable. Hence, instead of conducting mechanical test on the MTS machine, the angle was damaged by means of lever action. As illustrated in Figure 2.4.1, a lumber pole modal was attached to the outstanding leg of the angle. This modal consists of two 7-feet 4 x 4 southern pine construction lumbers as levers, and two 4-inch 4 x 4 southern pine cubic transferring the bending stress from the lever to the angle. In addition, two 1-foot 2 x 4 southern pine boards sandwiching the components mentioned above from top and bottom in order to prevent shear failures. All lumber

components were connected with lag bolts. To fasten this modal to the outstanding leg of the angle, two 3/4 -10 grade 8 bolts were applied. The angle was then attached to a w 12 x 36 beam. To prevent uplift motion from happening, the beam was clamped to a 10-feet- w 10 x 35 beam.

Figure 2.4.1 Experimental Setup for Low-Cycle Fatigue Test

Since the lumber lever was long enough, the full body weight for an adult is sufficient to exert LCF damage to the outstanding leg of the angle. Because of the prying effect, the beam leg was also subjected to cyclic bending stress as well. Hence, plastic deformation can be found in both legs of the angle (Figure 2.4.2 and Figure 2.4.3). Unfortunately, due

to insufficient bracing, the outstanding leg of angle buckled during testing. Further improvements are needed for this setup.

Figure 2.4.2 LCF Test (a)

Figure 2.4.3 LCF Test (b)

2.5 Bolt Looseness

Constantly removing and replacing the top angle of the connection could introduce randomness to this study due to bolt looseness. However, results have been shown that acoustic wave propagation technique was not sensitive to this effect. Bolt looseness on each leg of the angle was investigated individually. RCSC defines the snug-tightened condition as “the tightness that is attained with a few impacts of an impact wrench or the full effort of an ironworker using an ordinary spud wrench to bring the piles into firm contact” [55]. For this operation, torque wrench was applied to keep the consistency of the testing. Bolts were fastened tightly initially and were loosened gradually by half turns until the nuts were completely unscrewed.

2.6 Data Acquisition

Data acquisition procedure includes the excitation of the system and data collection process. Acellent SMP-SP-1/4-20 PZT patches (Figure 2.6.1) were served as actuator and sensors. The actuator was glued to the center of the beam flange with epoxy glue, while the sensors were attached to the column flange, 2 in. above the fasteners connecting the angle and the column. The data acquisition network is demonstrated in Figure 2.6.2.

The beam-to-column connection with fatigue-damaged angles were excited with a five-peak morlet-wavelet at the frequency of 249.118 kHz and 1-volt peak-to-peak (Figure 2.6.3). Bolt looseness of the connection was also investigated under this approach. Agilent 33210A Function Generator served as the input source of the five-peak morlet-wavelet. Next, the signal was transmitted to Krohn-Hite Model 7500 Amplifier. Meanwhile, the

input signal was monitored by Agilent MSO 7014A Oscilloscope. 20-Db of gain was added to the input signal by the amplifier. This amplified signal was then propagated to PZT actuator attached to the beam flange of the connection. Electronic signal was converted to mechanical strain during this process and thus the connection was actuated. Morlet-wavelet was able to propagate through the whole connection. PZT sensors glued to the column picked up the reflected wavelet and feedback to oscilloscope. Sampling frequency for the oscilloscope was at 10^9 Hz to avoid aliasing. The oscilloscope output three channels, channel one monitored the input signal generated from the function generator, channel two and channel three examined the activities from the PZT sensors respectively. PZT sensor located on the left-hand side of the outstanding leg connected to channel two, and vice versa. Each data acquisition process was repeated twenty times for individual fatigue stage.

Figure 2.6.1 Acellent SMP-SP-1/4-20 PZT Patch

Figure 2.6.2 Data Acquisition Network

Figure 2.6.3 Five Peak Morlet-Wavelet

2.7 Signal Processing

This section covers the signal preprocessing procedure. Signal preprocessing was conducted in Matlab interface. Firstly, to avoid aliasing of the sampling process, sampling frequency was set at 10^9 Hz and 10,000 samples were collected for each operation. Raw time domain signals were normalized to the same amplitude and truncated to 4,096 samples for further filtering purposes. All signals were centered at the mid-span of the time domain in order to aid the calculation of output residuals.

Next, the extraction of reflected morlet-wavelet (which is the echo of the input signal received by PZT sensors) from the preprocessed output signal was performed. Matched-Filter was designed in this practice in Matlab interface. The theory behind Matched-filter was explained by Turin [56]. In this study, matched-filter was created with the timely reverse of input morlet-wavelet (Eq. 1), then convolution between the filter and the raw output was performed (Eq.2). Since this filter maximizes the signal-to-noise ratio, the algorithm was able to extract the reflected morlet-wavelet from noisy output data. The output data is believed to have three components, (1) reflected morlet-wavelet; (2) Noise induced from data acquisition process; and (3) Error information. With the reflection being extracted from the output data, the subtraction between raw output and the match-filtered output concludes the noise and error information (Eq.3). Because data acquisition process was performed under laboratory environment and the mother wavelet was driven at high frequency, it is logical to assume the noise components as white noise and remained constant throughout the test. Hence, the output residual between raw output and match-filtered output was able to represent error information introduced by fatigue damage.

However, it is common that digital filters used in the signal processing could corrupt the original time scale of the data. This problem was taken into the considering in matlab.

$$H(t) = Input(t - \tau) \quad (1)$$

$$y_{filtered(t)} = Output(t) * H(t) \quad (2)$$

$$y_{residual(t)} = Output(t) - y_{filtered(t)} \quad (3)$$

With output residuals being calculated, the physical identity of the connection can be extracted in both time domain and Laplace domain. Firstly, the total absolute area under the time domain output residual represents electrical energy (or strain energy due to the special nature of piezoelectric materials), alterations in this value indicates variance in energy attenuation of the morlet-wavelet as damage progresses. Thus, the output residual was able to identify the error information. Two damage indexes for each fatigue stage were created according to this error information in the time domain; they are demonstrated in Equation (4) and Equation (5) respectively.

$$DI = Mean(\int_0^T (|y_{residual(t)}|)) \quad (4)$$

$$DI_{norm} = Norm(\int_0^T (|y_{residual(t)}|)) \quad (5)$$

For each fatigue stage, the average and norm of the absolute value of output residual were founded and plotted in matlab representing the energy attenuation level. Nonetheless, later results illustrate that no significant trend was found in this technique.

Alternatively, in linear-time invariant systems, transfer function is one of the mathematical tools in characterizing the relationship between input signals and output signals in Laplace domain. Useful information can be extracted from the poles of the transfer function regarding to natural frequency (real part of the pole) and damping ratio (imaginary part of the pole) of the system. If the system is physically damaged, under the same mode, an increase in damping ratio is expected. As a result, in an effort to identify the relationship between the input signal and the error information, a 20 poles and 1 zero transfer function between output residual and input data were generated in Matlab System Identification ToolboxTM [57]. Yet, the output residual was dominated by the behavior of the wave at the morlet-wavelet driving frequency. To have a clear picture of the actual error information, the information embedded in low frequency should be removed. As can be seen in Figure 2.7.1, x-axis of the plot represents the frequency all the way up to the Nyquist frequency. Low frequency components were mostly clustered within one percent of the Nyquist frequency. Hence, a second-order Butterworth High-pass filter was applied to the output residual in matlab with a cut-off frequency at 10^6 Hz. Low frequency components were successfully removed (Figure 2.7.2). Similar to the energy attenuation method, time scaling issue after the implementation of digital filter has been fixed. Damage indexes were created based on the average-damping ratio from each fatigue stage (Eq. 6). This method has been proven sensitive to fatigue damage.

$$DI_{Transfer} = \text{Mean}(\text{Damping Ratio at each fatigue stage}) \quad (6)$$

Figure 2.7.1 Frequency Response of the High-Pass Filter vs Output Residual in Frequency Domain

Figure 2.7.2 Raw Output residual vs High-Pass Filtered Output Residual in Frequency Domain

3 Results and Discussion

3.1 High-Cycle Fatigue Damage

The fatigue testing undergoes with 123,000 loading cycles until the final fracture of the specimen has occurred. Illustrated in Table 3.1.1, significant milestones for the test can be seen. Up to 90,000 loading cycles, the reaction force from the load cell of the MTS machine was found stable, indicating little strength reduction of the specimen and thus during this period, no fatigue damage was initiated.

Figure 3.1.1 Crack Initiation at Left-Hand Side of the Beam Leg

At 120,000 cycles, an approximately 1/8 in. of crack has been developed at the left-hand side notch of the beam leg (Figure 3.1.1). The author could have missed this feature without a slow-motion camera. What's more, at this stage the initial crack has been developed towards the stress concentration. A 1/16 inch of crack was found at the end of this stage. (Figure 3.1.2).

Figure 3.1.2 Crack Propagation at the Left-Hand-Side of Beam Leg

Around 122,000 cycles, significant cracks in macro scale can be detected in the outstanding leg of the specimen. The crack was first developed at the left-hand-side cross-section of the specimen 9/16 in. from the root radius (Figure 3.1.3). It developed rapidly so that at the very end of test; there was a 2-7/8 in. of crack in the front side of the leg (Figure 3.1.4) as well as a 2-1/2 in. in the back (Figure 3.1.5). At this stage, little plastic deformation can be detected from the specimen (Figure 3.1.6). On the other hand, the cracks initiated from the notch of the beam leg propagated further, but not in a significant scale (Figure 3.1.7). It

was mainly because of the prying effect accelerated the fatigue process on the outstanding leg of the angle, which in comparison with the beam leg, the stress exerted to the outstanding leg was higher.

Figure 3.1.3 Crack Initiation at the Cross-Section of the Outstanding Leg

Figure 3.1.4 Crack Propagation in Front of the Outstanding Leg

Figure 3.1.5 Crack Propagation at the Back of the Outstanding Leg

Figure 3.1.6 No Plastic Deformation at 122,000 Cycles

Figure 3.1.7 Crack Propagation at the Notch

At approximately 122,500 cycles, crack at the outstanding leg developed into 3 in. on the front side (Figure 3.1.9) and 3-1/4 in. in the back (Figure 3.1.10). However, crack propagation process in the beam leg slowed down, with little crack length increments at this stage. No extra cracks were initiated. It is also worthwhile to state that, at this stage, fatigue cracks propagate in the fashion of intrusion and extrusion (Figure 3.1.8).

Figure 3.1.8 Fatigue Crack Behavior [12]

Figure 3.1.9 122,500 Cycle Crack Propagation at Front Side of Outstanding Leg

Figure 3.1.10 122,500 Cycle Crack Propagation at Back Side of Outstanding Leg

From 123,000 cycle to the final rapture of the specimen in the outstanding leg, crack initiated at the left-hand side of the outstanding leg developed. In addition, further fatigue crack was found initiated at the right-hand side of the outstanding leg. However, in comparison with the scale of the left-hand side of the outstanding leg, the crack located in the right-hand side of the leg was small but in substantial amount (Figure 3.1.11). At around 123,700 cycles, a significant strength reduction occurred. This phenomenon was detected from the sudden drop of reaction force from the MTS testing machine's load cell. Within an instant, immediate separation of the outstanding leg from the angle occurred. Cracks developed from both side of the leg united, which indicated a clear path of the stress concentration (Figure 3.1.12, Figure 3.1.13, and Figure 3.1.14).

Figure 3.1.11 122,500 Cycle Crack Propagation at Back Side of Outstanding Leg

Figure 3.1.12 Final Rapture Front Side of the Outstanding Leg

Figure 3.1.13 Final Rapture Back Side of the Outstanding Leg

Figure 3.1.14 Final Fracture

Table 3.1.1 Fatigue Stage and Crack Length, High-Cycle Fatigue Test

Number of Interval	Number of Loading Cycles	Crack Length, in.	Fatigue Stage
1	0	N/A	N/A
2	50,000	N/A	N/A
3	70,000	N/A	N/A
4	90,000	N/A	N/A
5	120,000	First visible crack	Crack Initiation
6	122,000	2-7/8 in.	Crack Propagation
7	122,500	3 in. (Front) & 3-1/4 in. (Back)	Crack Propagation
8	123,000	3-7/16 in. (Front) & 3-11/16 in. (Back)	Crack Propagation
9	123,500	3-3/4 in. (Front) & 4-3/16 in. (Back), Also, crack has initiated from the other side (2-3/4 in.)	Crack Propagation
10	123,700	Specimen ruptured	Fracture

3.2 Feature Extraction Energy Attenuation Method

In this section, damage indexes according to the mean and the norm of the output residual are plotted according to each fatigue stage. The x-axis of the plot represents fatigue stage mentioned in Table 3.1.1. Figure 3.2.1 through Figure 3.2.4 demonstrates the feature extraction process under energy attenuation method in time domain. While Figure 3.2.1 and Figure 3.2.2 illuminates DI at each fatigue stage, Figure 3.2.3 and Figure 3.2.4 illustrates DI_{norm} . In contrary to the expectations where the four plots ought to show a decreasing trend. The damage index did not trend up with the accumulation of fatigue damage, and the statistical distribution of the values was random.

Figure 3.2.1 DI HCF (a)

Figure 3.2.2 DI HCF (b)

Figure 3.2.3 DI_{norm} HCF (a)

Figure 3.2.4 DI_{norm} HCF(b)

3.3 Feature Extraction Transfer Function Algorithm

The damage feature used in the energy attenuation method was dominated by the behavior of the wave at the morlet-wavelet driving frequency. This behavior did not seem to be especially sensitive to the fatigue damage induced into the angle. It was expected that an alternative measure might be devised using the data collected at the various damage stages. Investigating the error residuals, the portion of the signal remaining after the carrier morlet-wavelet was (removed by the application of Matched filter) was proven sensitive.

To demonstrate the effect of pole migration clearly, one set of data was randomly chosen to begin with. This set of data represents the physical attributes of the shear connection at each fatigue stage. As can be seen from Figure 3.3.1 to Figure 3.3.3, pole migration was detected at the frequency of 6.25×10^9 rad/s. Although pole migration also occurred at other modes, this effect was due to the numerical artifacts generated from Matlab System Identification ToolboxTM, and thus was not meaningful for this study. Next, all damping ratio at this frequency was averaged. Damage indexes were created for each fatigue stage based on this value. Figure 3.3.4 illuminates the plot against the damage index and fatigue stage. Despite the fact that at fatigue stage seven (122,500 cycles), a decrease in damping ratio was observed; this plot, overall, has satisfied the assumption that damping ratio increases as damage accumulates. Hence, acoustic wave propagation processed with transfer function algorithm has been proven sensitive to high-cycle fatigue damage.

Figure 3.3.1 HCF Transfer Function Frequency Response

Figure 3.3.2 HCF Transfer Function Pole (a)

Figure 3.3.3 HCF Transfer Function Pole (b)

Figure 3.3.4 HCF Damage Index Transfer Function Damping Ratio

3.4 Low-Cycle Fatigue Damage

Low-cycle fatigue damage was exerted to the angle (Figure 3.4.1 through Figure 3.4.5). Plastic hinges were formed at both legs of the angle (Figure 3.4.6). Similar to HCF test, final fracture occurred at the outstanding leg, but the line of action was located at the holes. Instant crack initiation and plastic deformation was observed during this test, and crack propagation took most of the specimen's fatigue life. Strength reduction of the specimen was also encountered, less force were required to bend the specimen as test progressed. Table 3.3.1 demonstrates the fatigue stage for the angle during the test.

Figure 3.4.1 LCF Damage (a)

Figure 3.4.2 LCF Damage (b)

Figure 3.4.3 Figure 3.4.3 LCF Damage (c)

Figure 3.4.4 LCF Damage (d)

Figure 3.4.5 LCF Damage (e)

Figure 3.4.6 LCF Damage, Plastic Hinge in Comparison with Baseline Structure

Table 3.3.1 Fatigue Stage, Low-cycle Fatigue Test

Number of Interval	Number of Loading Cycles	Fatigue Stage
1	0	N/A
2	20	Crack Initiation
3	40	Crack Propagation
4	45	Crack Propagation
5	50	Crack Propagation
6	53	Final Rupture

3.5 Feature Extraction Energy Attenuation Method

As can be seen from Figure 3.5.1 through Figure 3.5.4, acoustic wave propagation technique was not sensitive to bolt looseness. The assumption of energy attenuation was not satisfied as neither plot demonstrate a decrease trend in energy attenuation level. Presumably, unlike little plastic information was subjected to high-cycle fatigue damaged specimen, energy attenuation method could be also sensitive to plastic deformations. Thus, further investigations are required on this assumption. What's more, since only the top-and-seated angle was damaged in this study, other components were not subjected to the same level as the angle had. Hence, this aversive effect definitely corrupted the acoustic wave propagation process. As a result, the investigation of LCF in this study only served as a reference in fatigue damage detection.

Figure 3.5.1 DI LCF (a)

Figure 3.5.2 DI LCF (b)

Figure 3.5.3 DI_{norm} LCF (a)

Figure 3.5.4 DI_{norm} HCF (b)

3.6 Feature Extraction Transfer Function Algorithm

Figure 3.6.1 through Figure 3.6.3 demonstrates the frequency response and pole migrations between the transfer functions of output residual and input signal. As can be seen in Figure 3.6.2 and Figure 3.6.3, pole migrates as damage increases. In comparison with HCF, pole migration for LCF was triggered at 5.65×10^9 rad/s. Damage Indexes were created based on this algorithm. A significant increase of the damping ratio was observed from fatigue stage 2 to fatigue stage 5.

Figure 3.6.1 LCF Transfer Function Frequency Response (a)

Figure 3.6.2 LCF Transfer Function Pole (a)

Figure 3.6.3 LCF Transfer Function Pole Enlarged (b)

Figure 3.6.4 LCF Transfer Function Damage Index

3.7 Bolt Looseness Investigation

The investigation of bolt looseness was carried out for each leg of the angle respectively. Fasteners were snug tightened initially; this stage was characterized as ‘healthy’ structure. Torque wrench was used to achieve snug-tight condition, 1,600 lb-in of torque was reached during this process. Next, fasteners were unscrewed gradually until the bolt nuts loosened completely. A 180-degree-turn was made at each subtest; the connection was then investigated with acoustic wave propagation approach. Since the column flange is thicker than the beam flange, it took 20 operations until the nut fall off from the connection; this action was titled as column leg in the plots. While 23 operations were made until, no clamping force can be observed between the leg and the beam flange; this action was defined as beam leg in the following plots.

3.8 Feature Extraction Energy Attenuation Method

Figure 3.8.1 through Figure 3.8.4 demonstrates the energy attenuation level as clamping force connecting the beam flange and the angle decreased. Little trend can be observed for this operation. Figure 3.8.5 through Figure 3.8.8 illustrates energy attenuation level of morlet-wavelet propagating through the column and outstanding leg of the angle. It has been proved that energy attenuation approach was not sensitive in bolt looseness detection.

Figure 3.8.1 DI Bolt Looseness Beam Leg (a)

Figure 3.8.2 DI Bolt Looseness Beam Leg (b)

Figure 3.8.3 DI_{norm} Bolt Looseness Beam Leg (a)

Figure 3.8.4 DI_{norm} Bolt Looseness Beam Leg (b)

Figure 3.8.5 DI Bolt Looseness Column Leg (a)

Figure 3.8.6 DI Bolt Looseness Column Leg (b)

Figure 3.8.7 DI_{norm} Bolt Looseness Column Leg (a)

Figure 3.8.8 DI_{norm} Bolt Looseness Column Leg (b)

3.9 Feature Extraction Transfer Function Algorithm

As can be found through Figure 3.9.1 through Figure 3.9.4 results have shown that this approach was not sensitive to bolt looseness. Figure 3.9.5 through Figure 3.9.8 has confirmed negative results between column flange and outstanding leg of angle. No significant pole migration was found.

Figure 3.9.1 Bolt Looseness Transfer Function Frequency Response Beam Leg (a)

Figure 3.9.2 Bolt Looseness Transfer Function Pole Beam Leg (a)

Figure 3.9.3 Bolt Looseness Transfer Function Frequency Response Beam Leg (b)

Figure 3.9.4 Bolt Looseness Transfer Function Pole Beam Leg (b)

Figure 3.9.5 Bolt Looseness Transfer Function Frequency Response Column Leg (a)

Figure 3.9.6 Bolt Looseness Transfer Function Pole Column Leg (a)

Figure 3.9.7 Bolt Looseness Transfer Function Frequency Response Column Leg (b)

Figure 3.9.8 Bolt Looseness Transfer Function Pole Column Leg (b)

4 Conclusion

In conclusion, transfer function pole migration method has been proven sensitive in detecting high-cycle fatigue damage in shear connections. This result was not influenced by constant removal of the angle from the connection due to bolt looseness. What's more, matched-filter technique is able to extract known signals from corrupted data. Under field conditions, this feature will definitely improve the accuracy in data acquisition process during structural health monitoring. Besides, the effect of pole migration was detected for LCF damaged specimen with transfer function algorithm, this method has been proven sensitive in detecting brittle failure.

Further works are necessary based on this study. Firstly, it would be helpful to set up a threshold-damping ratio between the 'healthy' and damaged components similar to the carbon monoxide detector equipped in every household. As a result, damage detection processes would be more efficient. Secondly, further research on optimal transfer function size is needed. Matlab interface is only capable of creating small-scale transfer function; it would be useful if a substantial sized transfer function were created. Thirdly, whether this method is sensitive to the location of the damage is also worthwhile to investigate. Lastly, despite the fact wireless sensor technologies were not applied in this study, it is the state-of-art data acquisition algorithm in structural health monitoring. Hence, the structural integrity of the whole structure can be monitored globally and proficiently.

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