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Acoustic emission monitoring of strengthened steel bridges: Inferring the mechanical behavior of post-installed shear connectors

Arvin Ebrahimkhanlou[1], Salvatore Salamone[1], Arash Ebrahimkhanlou[2], Amir Reza Ghiami Azad[2], Kerry Kreitman[3], Todd Helwig[1], Eric Williamson[1], Michael Engelhardt[1*]

[1] Ferguson Structural Engineering Laboratory (FSEL), Department of Civil Architectural and Environmental Engineering, The University of Texas at Austin, 10100 Burnet Rd, Bldg 177, Austin, TX 78758, USA
[2] School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran
[3] Pivot Engineers, 1000 Westbank Dr. Suite 5B, Austin, TX 78746, USA

ABSTRACT

This study proposes an acoustic emission (AE) monitoring approach for old steel bridges strengthened with post-installed shear connectors. In this strengthening method, cyclic traffic loads gradually fatigue the connectors and increase the bridge deflection at which the connectors engage in shear transfer. The key parameter that this study aims to estimate is how much the connectors need to slide before they engage in shear transfer. To estimate this parameter, this paper leverages the difference in AEs from shear connectors before and after they engage in shear transfer. Specifically, the b-value of AEs a k-mean clustering approach are used. To validate this novel approach, a full-scale, two-span steel girder with a concrete deck was used. The girder was strengthened with post-installed shear connectors and subjected to 20 cycles of sequential loads representing moving trucks. The results confirmed the effectiveness of the approach based on AE during the unloading of the girder.

Keyword: acoustic emission, structural health monitoring, large-scale testing, cyclic loads, post-installed shear connectors, steel structures, b-value, localization, k-means clustering

1. INTRODUCTION

Increased loads on aging transportation infrastructures have motivated their strengthening and structural health monitoring[1]. Some old steel bridges do not have any shear connector to facilitate steel-concrete composite action. In such bridges, installing shear connectors is a technique to increase the stiffness and load bearing capacity[2–5]. However, these post-installed shear connectors are subject to fatigue. The fatigue gradually decreases the effectiveness of the shear connectors and increases the deflection at which they engage in shear transfer. Since the strengthening increases expectations from bridges and thus their loads, without proper monitoring and maintenance, this gradual fatigue may eventually make the strengthened bridges unable to withstand the increased demand and cause unexpected failures. To overcome this limitation, this study proposes a novel AE monitoring approach. The proposed approach leverages the differences between mechanisms (e.g., friction, elastic deformation, plastic deformation, etc.) that generate AE events.

In the literature, AE has been used to estimate fatigue in steel bridges[6–9]. However, classifying AEs based on their source mechanisms is still a challenging task[10–13]. To overcome this challenge, several source characterization methods have been proposed[14–17]. Specifically, this paper focuses on b-value analysis, which was first introduced in seismology to characterize fault mechanisms causing earthquakes and later characterizing AE sources[18,19]. Then, the b-value is used to cluster AE events based on their source mechanisms. The goal is to detect when the source mechanism changes and based on that infer a change in the stiffness of shear connectors.

[*] **Emails:** arvinebr@utexas.edu, salamone@utexas.edu, arashkhanlou@ut.ac.ir, rghiami@ut.ac.ir, kreitman@pivotengineers.com, thelwig@mail.utexas.edu, ewilliamson@mail.utexas.edu, mde@mail.utexas.edu

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2. MECHANICAL BEHAVIOR OF POST-INSTALLED SHEAR CONNECTORS

Post-installed shear connectors have a bilinear mechanical behavior that consists of a low stiffness initial region followed by a stiff region (see Figure 1). In other words, shear connectors do not engage in shear transfer until a certain displacement (slip). As the connector wears off, the low stiffness region expands, and the connector tends to engage in shear transfer only under larger displacements. Therefore, the displacement at which the connector engages in shear transfer is an indicator of its fatigue stage. In terms of AE, shear connectors make different noises before and after the engagement. This is due to differences in the mechanisms that excites acoustic waves in each of the two regions. In the low stiffness region, friction is the main source of AE activity, whereas, in the stiff region, elastoplastic displacements are the main AE sources. To estimate the fatigue life of the shear connectors, this study leverages this difference and estimates the displacement (slip) at which the transition between the two regions occurs.

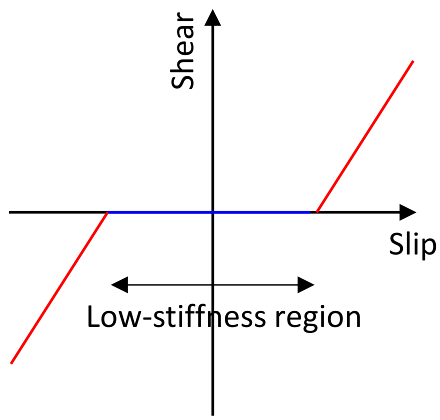

Figure 1. Mechanical behavior of a post-installed shear connector, the low-stiffness region expands as the connector wears.

3. PROPOSED AE MONITORING APPROACH

To estimate the width of the low-stiffness region in the behavior of shear connectors, this paper uses AE monitoring combined with slip measurement. Figure 2 shows the flowchart of the proposed approach. First, a linear source localization algorithm is used to identify AE of each shear connector. Then, the b-value of such AE events is calculated and used to cluster them. Specifically, k-mean clustering is used to divide AE events into two clusters: 1) AE in the low-stiffness region and 2) AE in the high-stiffness region. Finally, the length of the low-stiffness region is detected as the corresponding slip to the boundary of the two clusters.

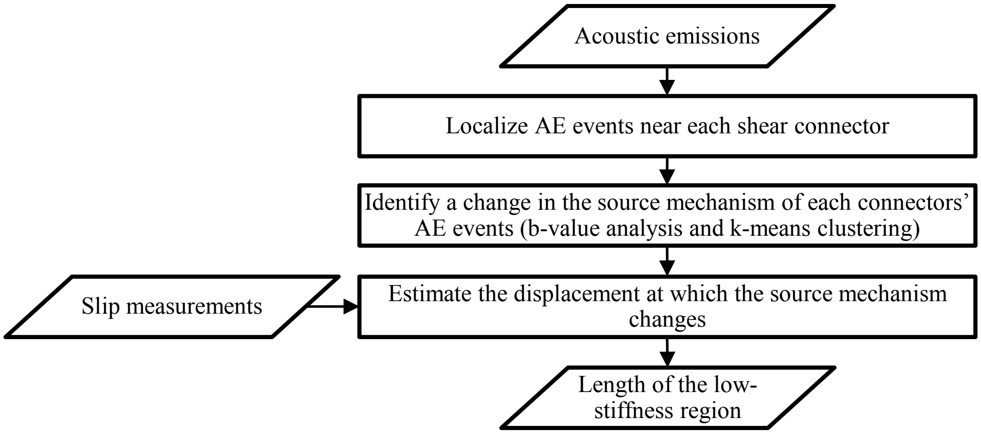

Figure 2. Flowchart of the proposed acoustic emission testing approach

3.1. Linear localization

In the literature of AE, several source localization algorithm have been proposed[20–24]. Linear localization is among the most simple localization methods that uses the time difference of arrival to two AE sensors to find the location of an AE event between the two sensors[10–12]:

$$x = x_1 + \frac{(x_2 - x_1) - v\Delta t}{2} \tag{1}$$

In this localization approach, the location of AE source x, is measured along the line connecting the two sensors located at x_1, and x_2, respectively. In this equation, v is the velocity of acoustic waves, and Δt is the time difference in the arrival of acoustic waves to the two sensors.

3.2. B-value analysis of acoustic emissions

The b-value analysis finds a relationship between the frequency of occurrence and the amplitude of AE events. Gutenberg–Richter[18] first introduced this relationship to characterize earthquakes based on their fault mechanisms. The following is the revised version of this equation for AE application:

$$\log_{10} \mathrm{n} = a - b\left(\frac{A_{\mathrm{dB}}}{20}\right) \tag{2}$$

In this equation, A_{dB} is amplitude in the decibels, and n is the number of AE events with amplitude A_{dB}. In addition, a and b are the intercept and the slop (b-value) of a line fitted to AE data[16].

3.3. K-means clustering

Clustering is the process of assigning similar data points to a group. K-means clustering is of the most common clustering technique[25]. To assign b-values $\mathbf{b} = \{b_1, b_2, ..., b_N\}$ into K clusters, $C_1, C_2, ..., C_K$, the k-means algorithm starts with random membership allocation (in this study, $K = 2$). Then, the memberships of iteratively re-allocated in such a way that the centers of the clusters, $\mu_1, \mu_2, ..., \mu_K$, minimize the following equation[25]:

$$E(\mu_1, \mu_2, ..., \mu_K) = \sum_{i=1}^{K} \sum_{x_j \in C_i} \left\| x_j - \mu_i \right\|^2 \tag{3}$$

where $\| \cdot \|^2$ is the Euclidian distance.

4. EXPERIMENT

To validate the proposed AE monitoring approach, a full-scale bridge girder was used (see Figure 3(a)). The specimen was a two-span steel girder[2]. The girder consisted of a W30x90 steel section with a minimum yield stress of 345 MPa (50ksi) and a 165 mm (6.5″) concrete deck with a nominal strength of 20.7 MPa (3 ksi). To facilitate composite action after casting the concrete, 40 shear connectors were installed in four groups from underneath the deck. The shear connectors were 22 mm (7/8″) threaded bars hold in drilled holes by epoxy. In each group, shear connectors were installed in pairs every 152 mm (6″) along the girder. Figure 3(b) shows shear connectors on the south span of the specimen. Each pair is numbered based on its distance from the north support of the girder in inches. More information about the specimen is available by the authors elsewhere[2].

The slip between the concrete deck and steel girder was measured at the location of shear connectors. To this end, two dial gages and one linear potentiometer were installed per shear connector group. In addition, linear interpolation was used to estimate the slip for intermediate shear connectors. To validate the proposed AE monitoring approach, the transferred shear force was estimated for each pair of shear connectors. For such estimation, the girder's axial strain was measured at four vertical sections per shear connector group and used to calculate axial force (see Figure 3(d)). Then, the difference between the axial forces at two sections located before and after a shear connector pair was attributed to shear transferred by the pair.

To record AE, eight sensors were installed on the south span of the specimen. Specifically, four R15α sensors (Mistras group) were installed every 0.914 m (36″) in each group of shear connectors. To attach the sensors to the top flange of the girder, magnetic holders were used. Before attaching the magnets, ultrasonic couplant was applied on each sensor. AE signals were a 40 dB amplified (Mistras 2/4/6 preamplifier) and then recorded by an eight-channel AE system (Micro Express, Mistras). Due to the noisy test environment, the threshold of the system was set at 70 dB. To localize AE sources, linear localization functionality of the AEWin software (Mistras) was used, and the wave velocity was experimentally determined to be 4800 m/s. Finally, b-value analysis and k-mean clustering were performed during post-processing in MATLAB.

Figure 4 visualizes the loading process of the specimen[26]. In particular, four point loads were applied in three sequences to simulate the maximum positive and negative moment by a moving truck, and the loading process was repeated 20 times. This loading protocol simulates 20 passes of heavy trucks from north to south. Each point load was 645 kN (145 kips). The capacity of hydraulic rams used for point load A and D was 2220 kN (500 kips), while the capacity of those used for at B and C was 1780 kN (400 kips). To measure the applied loads a canister load cell was placed between each hydraulic ram. The capacity of load cells used under load A and D was 2220 kN (500 kips), and the capacity of those used for at B and C was 890 kN (200 kips). Prior to the AE testing, the specimen was subjected to 1.7 million cycles of fatigue testing to represent an aged bridge. In addition, it was shaken down under 627 kN (141 kips) point loads applied with the same load protocol shown in Figure 4. Shake down here means the load was applied several times until the maximum deflection under load does not change from one cycle to the next. After the 20 cycles of applying 645 kN (145 kips) the girder sagged and experienced residual displacements of 39.9 mm (1.57″) and 37.8 mm (1.49″) under loads A and D, respectively.

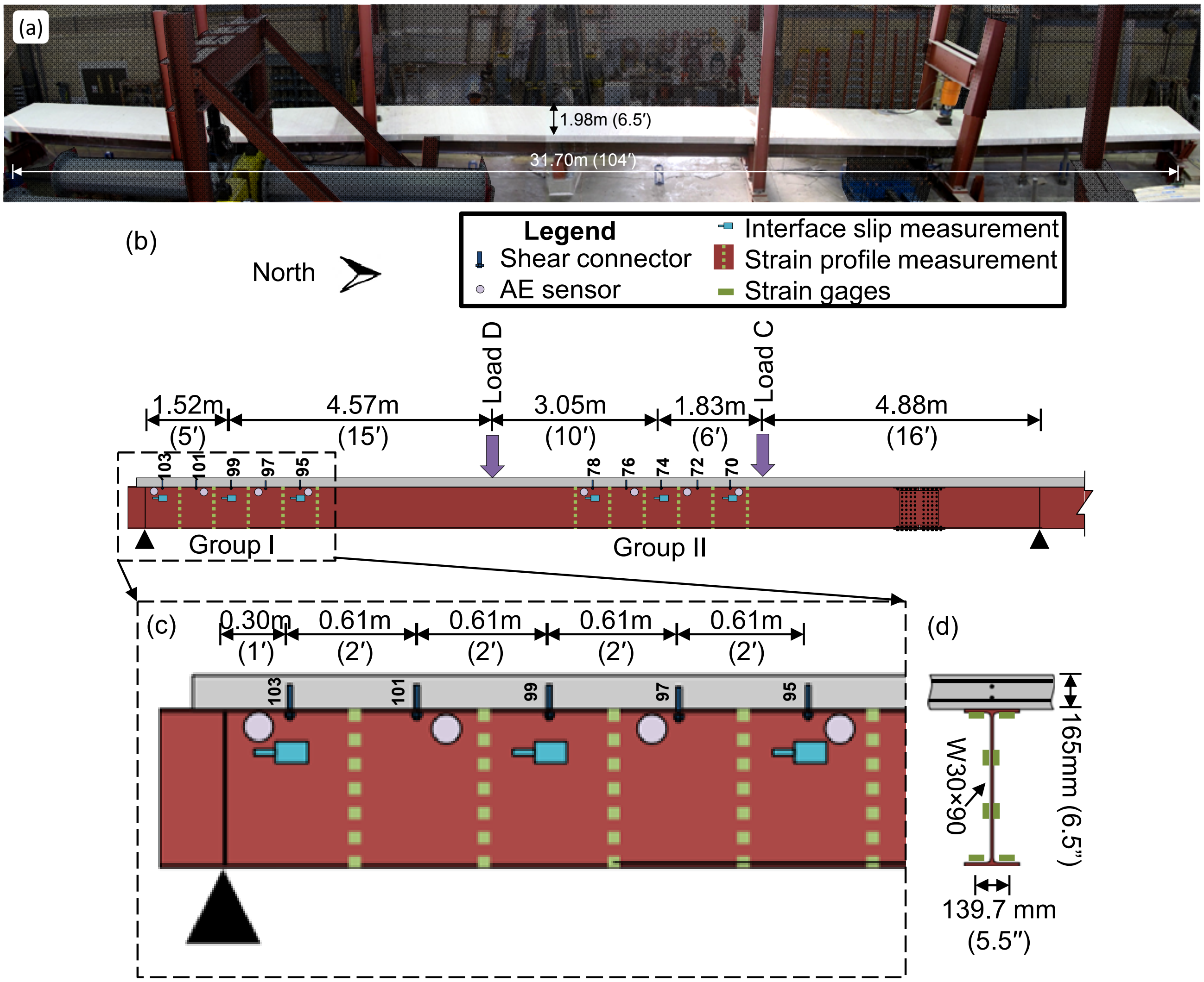

Figure 3. Experimental setup: (a) test specimen, (b) schematic view of the instrumented specimen, (c) magnified view of the instrumentation, and (d) cross-section of the specimen.

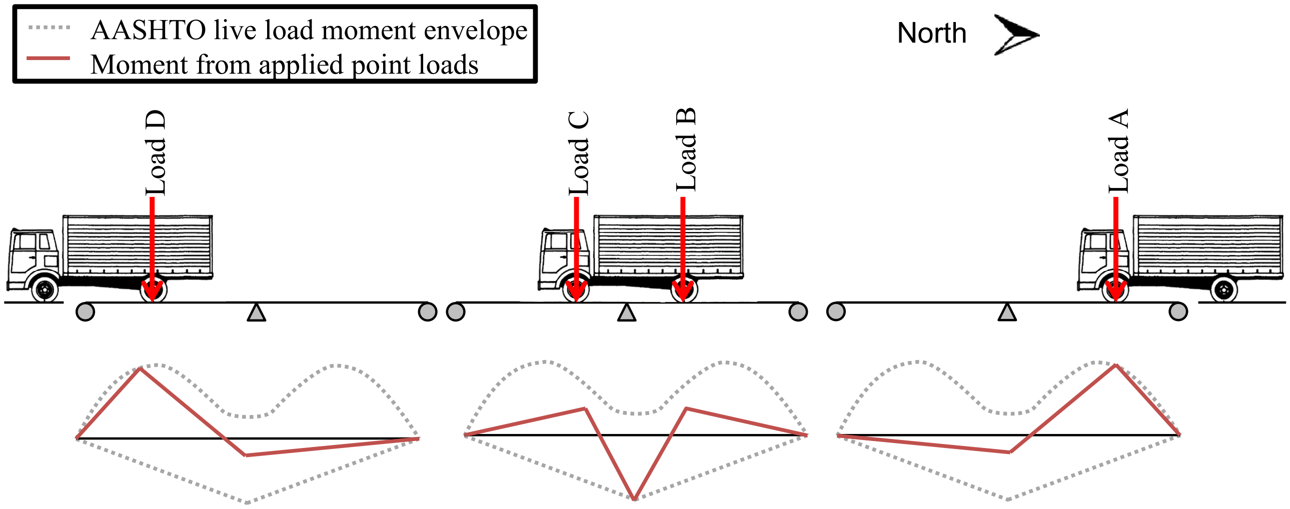

Figure 4. The location of point loads and their loading sequence simulate highest moments applied by moving trucks from north to south.

5. RESULTS

This section presents the results of the proposed AE monitoring approach. Figure 5 shows the histogram of AE events' location. All 20 load cycles were compiled together, and the width of each histogram bin is 0.86 mm (0.034″). Overall, 95,848 AE waveforms (hits) were recorded and 7,984 AE events were localized. The figure shows that most events occurred near shear connectors. Since the threshold was 70 dB, this indicates that most loud noises were related to shear connectors.

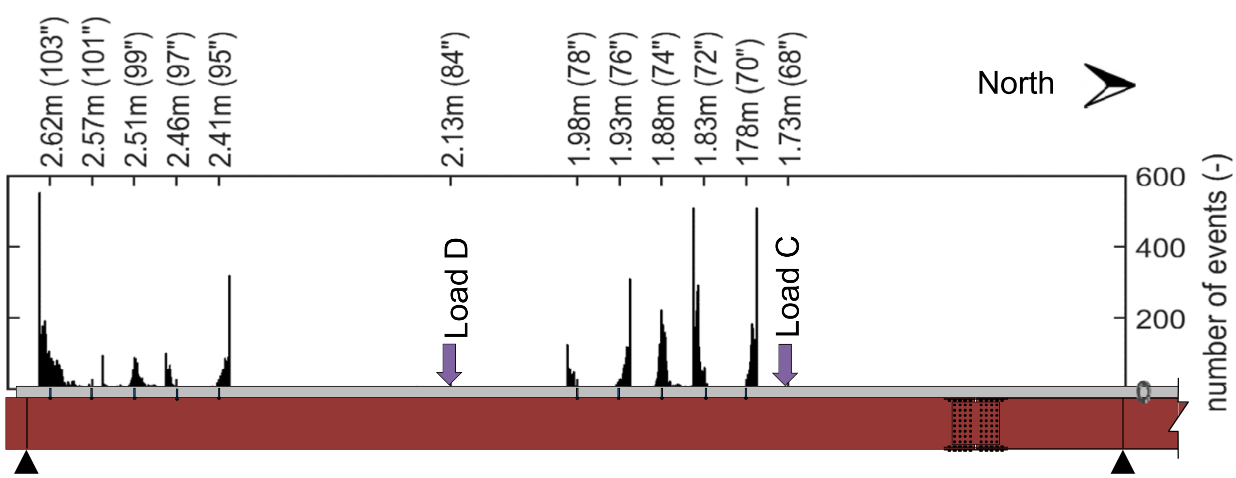

Figure 5. Histogram for the location of AE events; most events occurred near shear connectors.

Figure 6 shows the process of calculating b-value for at a given slip. As the figure shows, all 20 load cycles were compiled together, and the direction that experienced a larger slip (and load) was selected as the positive direction. Although the bridge was sagged and had residual deformation prior to testing, the unloaded stage of the specimen was conveniently considered as zero slip. For each shear connector pair, AE events were synchronized with slip measurements. Note that the proposed AE monitoring approach does not use estimated load values obtained from strain gages. At any given slip during unloading, AE events with slip values ranging from 0.25 mm (0.001″) less than the given

value and 0.5 mm (0.002″) more than the given value were selected (see Figure 6(a)). Then, a 10-bin histogram was used to count the frequency of AE events, n, with different amplitudes (see Figure 6(b)). Finally, a line was fitted to the logarithm of n. The slope of the fitted line is 20 times the b-value.

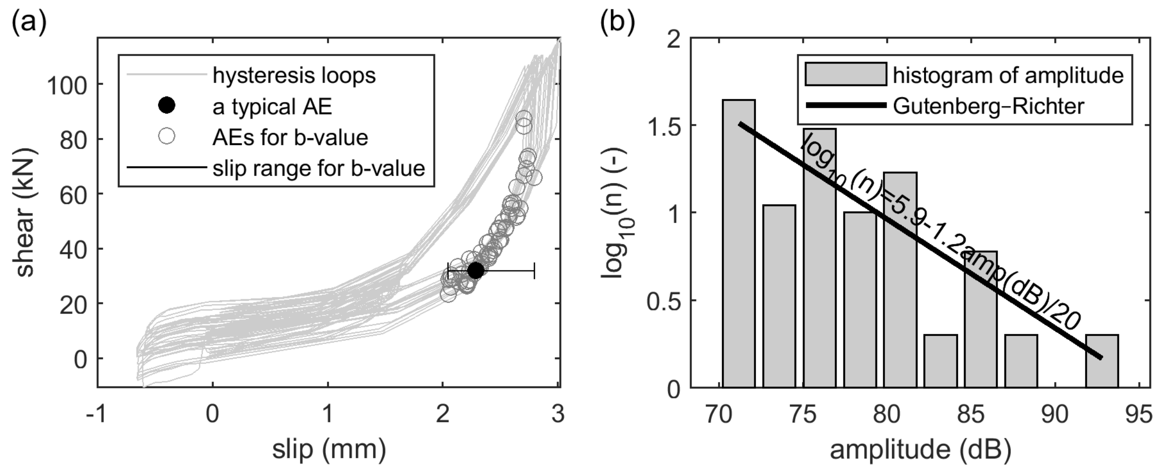

Figure 6. Calculation of b-value for shear connector pair 103: (a) selected AEs for b-value analysis at slip=2.25 mm; (b) Gutenberg-Rishter relationship for the selected AE, b-value is 1.2.

Figure 7 shows k-mean clustering results and the corresponding decision boundaries for shear connector pair 103. First, k-mean clustering, with $K = 2$, was applied to the b-values of all AE events localized near the shear connector pair. This clustering was performed regardless of the slip values. The cluster with smaller b-values was labeled as "cluster 1", and the cluster with larger b-values was labeled as "cluster 2" (see Figure 7(a)). As the figure shows, the decision boundary was the average of the largest b-value in cluster 1 and the smallest b-value in cluster 2. Then, the corresponding slip values of AE events in each cluster were plotted in Figure 7(b). The slip at which the source mechanism of AE event changes was determined as the average of the smallest slip in cluster 1 and the largest slip in cluster 2.

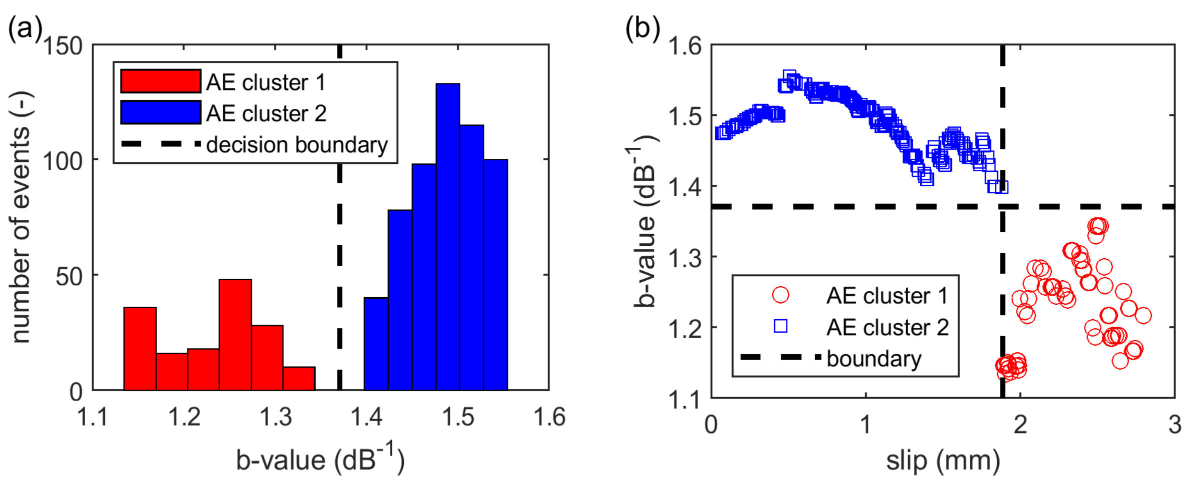

Figure 7. Decision boundary used to cluster AE events of connector pair 103: (a) histogram of b-values, (b) b-value at any slip.

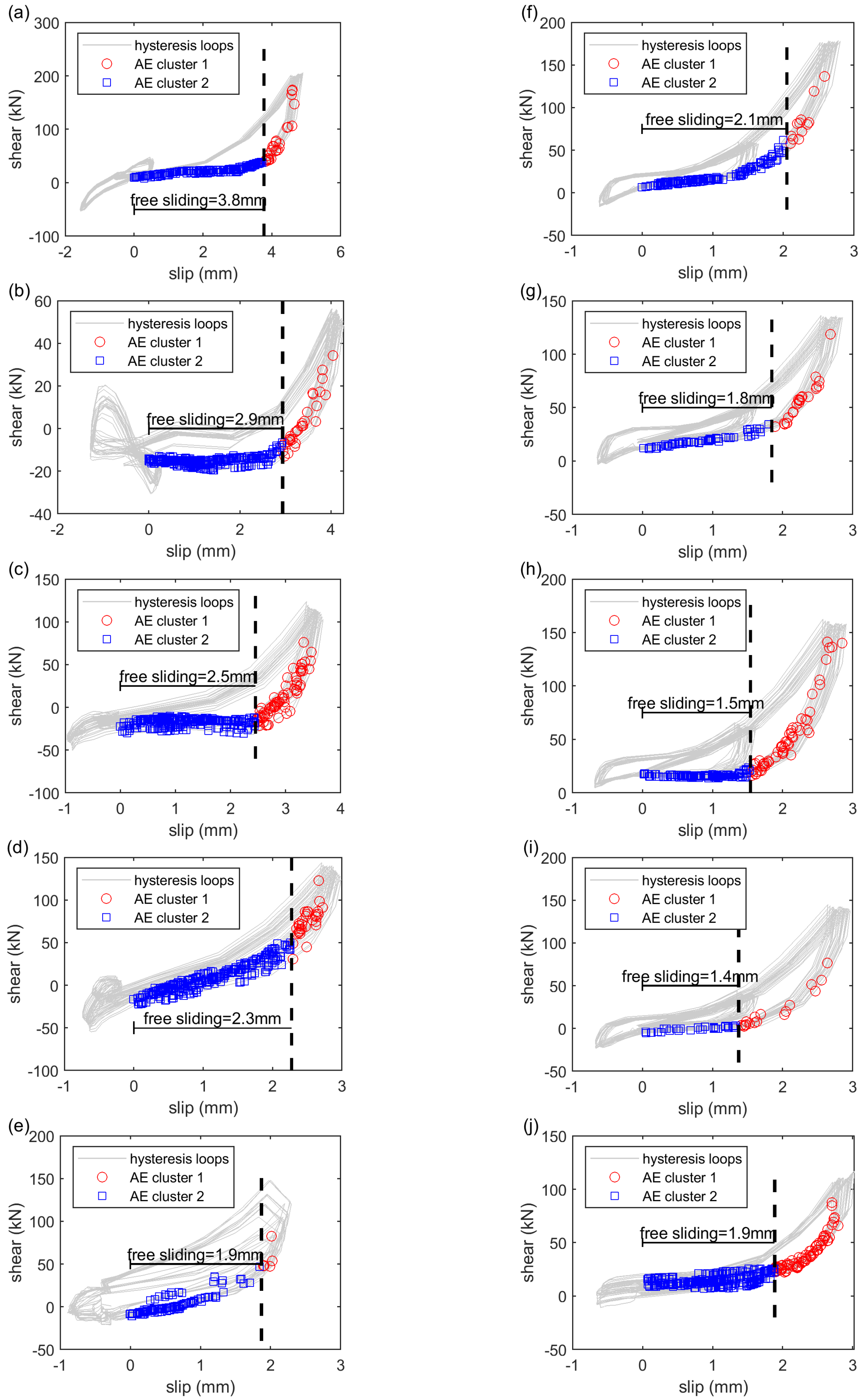

Figure 8. Comparison between mechanical behavior and acoustic emission data: alphabetical labels indicate shear connecotrs 70, 72, …, 78, and 95, 97, …, 103, respctively.

Figure 8 compares the estimated free-sliding (i.e. the width of the low stiffness region) of each shear connector pair with their hysteresis loops. Since estimated load values obtained from stain gages were not used in the proposed monitoring approach, this comparison serves as performance verification. As the figure shows, the estimated free-sliding for all 10 pairs of shear connectors corresponds with the slip at which their stiffness changes. This observation confirms the applicability of the proposed AE monitoring approach for estimating fatigue in post-installed shear connectors.

1. CONCLUSIONS

Post-installed shear connectors in bridges may gradually lose their effectiveness. As such shear connectors wear off, the displacement at which they engage in shear transfer increases. To estimate the remaining life of shear connectors, this study proposed a novel acoustic emission (AE) monitoring approach that estimates the displacement at which a shear connector engages in shear transfer. The approach was validated on a full-scale steel girder subject to large cyclic loads. The girder had a concrete deck that extended over two spans and was strengthened with post-installed shear connectors.

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