Dynamic Monitoring of Fatigue Crack Process of Orthotropic Steel Bridge Structure with Acoustic Emission

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Abstract This paper introduces how to use acoustic emission (AE) technology to monitor dynamic process of crack growth of a segment model of a full size orthotropic steel bridge structure during a 30 day fatigue test. The dimension of the test model is 12.54x2.99x0.6 (LxWxH) meter. Multiple AE sensors were located on different places of the structure. Crack initiation, location and development process were dynamically monitored and recorded. This paper discusses how AE technology is used in the fatigue test of large structure, how is burst crack signal captured, how is crack location identified, what are the behavior of crack developments and how is the result of visual inspection in comparison with the AE technology. The results of the fatigue test monitored with AE have shown that AE is a very valuable technology for monitoring dynamic process of crack development. It can be used not only for various tension, compression and fatigue tests in labs, but also for structure health monitoring in the fields.

Keywords Fatigue Crack, Fracture, Damage, Acoustic Emission, Dynamic Monitoring

1. Introduction

Although orthotropic steel bridge structure is getting more and more widely used, fatigue cracks on the welds and the structure material are still concerns due to the complexity the orthotropic structure and stress concentration in the welds under repeated loadings of the structure[1-2]. It is not uncommon that cracks were found in an orthotropic steel structure that is younger than its design or predicated life age. The actual fracture behavior of orthotropic steel structure were not fully studied and experimentally tested yet.

In fatigue tests of structures or materials, strain or stress measurement is usually a very common way for fatigue crack detection. But, not only the strain measurement cannot tell the development process of the crack growth, but also for a big or complex structure, e.g. a full size orthotropic steel deck, it is hard to predict where the cracks are going to occur and where are the optimum positions that strain gauges should be installed. Each strain gauge can only measure the stress where the strain gauge sticks to and its vicinity, it is not possible to show crack stresses which are certain distance away from the strain gauge.

On the other hand, it is quite common that cracks were visually inspected in fatigue tests. However, disadvantages of visual inspection are also obvious. First of all, a fatigue test process might need to be stopped in order to have a reliable visual inspection. Secondly, crack initiation is not possible to be visualized due to its microscopic size. Thirdly, if a structure size is big or cracks are located in blocked or inaccessible areas of the structure, the cracks are not able to be picked up by visual inspection. Actually, it is relatively feasible to visually check crack development during fatigue test of small samples, but it is very difficult to know overall crack growing process from a fatigue test of a big structure, e.g. how many active cracks exist in one time? when is each crack initiated? where are cracks located? what are the behaviors of crack growth? This is particular true for a big steel bridge structure test that lasts for days and months.

Although, in some instances, NDT technology, e.g. dye penetration, ultrasonic, eddy current and radiology methods is also used to inspect fatigue cracks, they are actually not real time monitoring technologies, the fatigue testing process has to be stopped in order to perform the NDT tests. Not only it interrupts the fatigue testing process, but also it takes a lot extra time to prepare the NDT test. If the tested part is not a small object, but a very big object like the full size orthotropic steel deck, it would be impossible to inspect the complete structure or to inspect all potential crack areas within a limited time.

In the recent years, acoustic emission (AE) technology is getting more and more widely used in not only fatigue tests in the laboratories, but also active crack detection of bridge structures[3-7]. There are quite a few unique advantages in using AE for crack detection and structure health monitoring, such as

- Real time on-line structure health monitoring
- Very sensitive to crack development or active crack growth
- Global area monitoring with sensors away from exact crack locations
- Location of one or more crack sources
- Suitable for long term Ethernet or wireless remote monitoring

With these advantages, it is possible to answer the questions regarding crack initiation and development of full size steel structures during a fatigue test or actual structure health monitoring. Wang et al[2] has used AE to test a full size orthotropic steel bridge deck, but it only monitored very short time when a crack has already been found before AE applied, there was no crack development process studied.

In this paper, a fatigue test process of a full size orthotropic steel bridge deck with dimension 12.54x2.99x0.6 (LxWxH) meters is studied. Initially, the objective of this test is pretty straight forward, i.e. to find out all fatigue cracks with visual inspection and their corresponding fatigue cycles when the test is done. However, it was soon realized that this is not a simple task as the structure is too big and it would be not possible to identify real initial crack with its location and actual fatigue cycles with visual inspection. Therefore, AE technology is introduced in the test, it tries to identify in what fatigue cycle that a crack is initiated? How earlier that a crack can be detected by AE than by visual inspection? Can AE locate the crack sources? What is the behavior of crack growth during the fatigue process? Where are the tangible crack locations in the orthotropic steel bridge deck etc.. Experimental results have shown that AE is a very effective tool for monitoring the dynamic process of fatigue crack growth of larger structures.

2. Cracking monitoring with acoustic emission

AE is a phenomenon of rapid energy release of stress concentration in the material. Cracking is associated with stress relief and therefore generation of burst AE signal. AE does not depend on the length and width of the existing crack, but on if the crack is actively opening or growing, no AE exists if there is no active cracking. As such, AE can be effectively used for monitoring crack growth processes.

The frequency range of crack induced AE is usually in between 20 – 1000 KHz which is above the frequency range of auditable sound range. The detectable fracture related AE signal level varies considerably in accordance with materials and cracking status. In a very quiet lab environment, AE induced by material crystal dislocation can be detected with a signal level in 20 dB. On the other hand, AE can also be detected in macro fracture or sudden break of a structure with a signal level in 120 dB with the same AE system without gain adjustment. Figure 1 depicts an active cracking process with AE monitoring. When a crack is growing microscopically or macroscopically, burst type AE is generated at the crack tip with acoustic wave energy travels along the structure with a velocity that is inherent with particular type of material. AE sensors installed in surrounding areas would pick up the acoustic wave energy in a time order depending on the distance between the crack source to the sensors. AE system does the data acquisition and signal processing with filtering, AE feature extraction, crack identification and source location to determine if a crack is in active growing and where is the crack located.

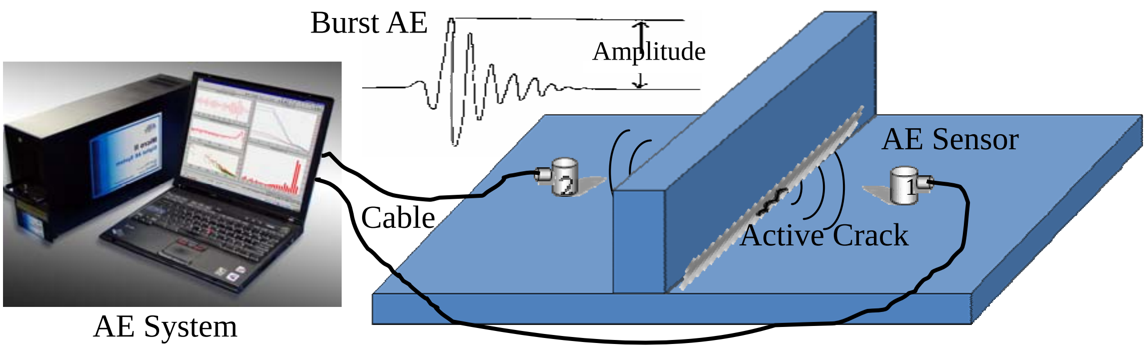


Figure 1. Illustration of active crack monitoring with AE

3. Setup of fatigue test of orthotropic steel bridge deck and AE monitoring

A fatigue test and AE monitoring were conducted on a segment model f a full size orthotropic steel bridge deck. A sketch drawing of the tested model is shown in Figure 2. The dimension of the deck model is 12.54x2.99x0.6 (LxWxH) meter, it consists of 5 U ribs and 4 webs. The deck was alternatively loaded with two actuators at 1 Hz fatigue cycle. The locations of the two actuators are indicated in Figure 2. The intersection areas of the U ribs and the first two webs were monitored with AE. Figure 3 shows photos of the orthotropic steel bridge deck and AE sensors installed. 150 KHz integral preamplifier AE sensors R15I made by Physical Acoustics Corporation were installed on the U ribs in front of the first two webs.

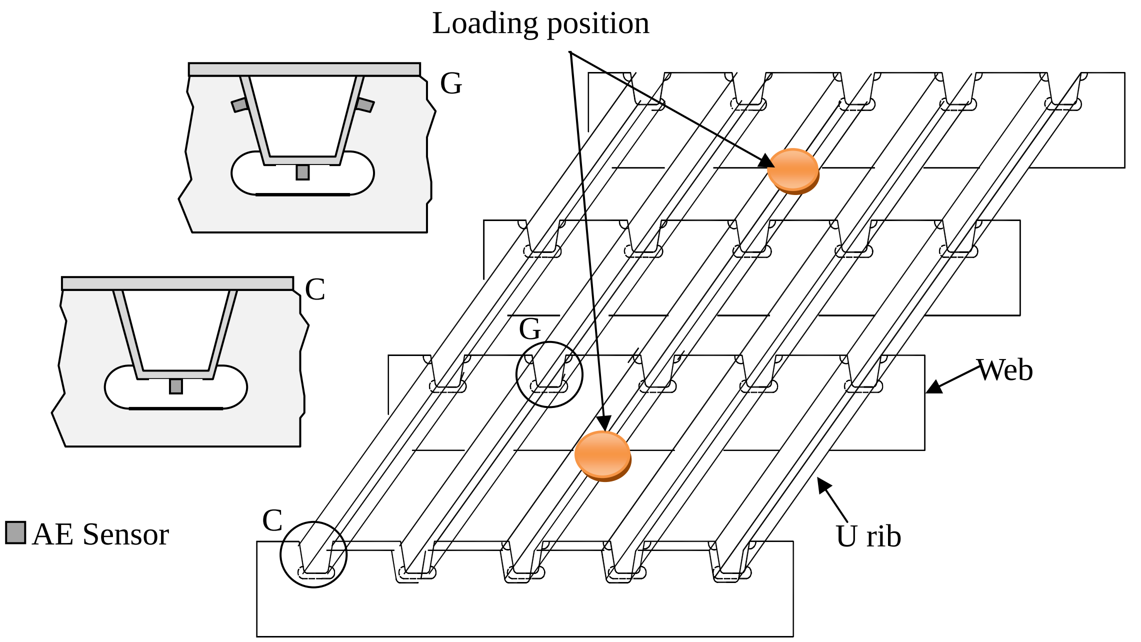
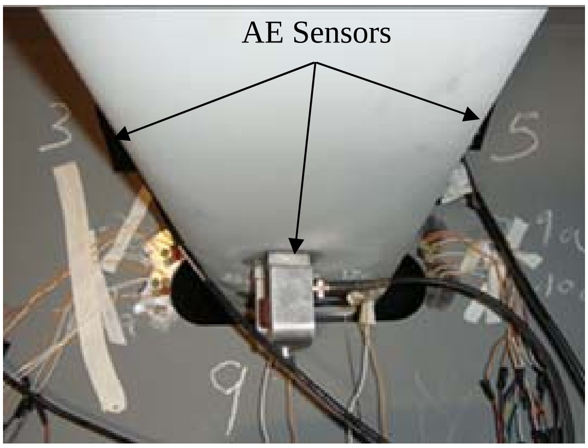


Figure 2. Drawing of the orthotropic steel bridge deck and actuator locations



(a) Photo of an orthotropic steel bridge deck (b) Area monitored with 3 AE sensors

Figure 3. Fatigue test and AE monitoring photos

Figure 1 also shows illustrations of sensor installations with one AE sensor and three AE sensors. In the latter case, one sensor is installed at the bottom of the U rib, two more sensors were installed at the left and right side of the U rib respectively to perform crack source location. A 16 channel smart AE monitoring system MicroII made by Physical Acoustics Corporation was used for continuous monitoring of the fatigue test process. The fatigue test lasted for 30 days, the AE sensors were not installed until 7 days or 504 thousands load cycles of the fatigue test.

4. Behavior of acoustic emission in fatigue crack development

During the 30 day fatigue test, visual inspections on the deck were conducted from time to time in each day in order to find out if there is crack initiation or crack growing. Specifically, the visual inspection is focused on

a). areas that AE has indicated crack activity so that to find out if the observed crack matches with the AE indication;
b). if there is a crack in somewhere that AE hasn't picked it up before it is visualized.

In the end of the 30 day fatigue test, the orthotropic steel bridge deck was thoroughly inspected and cracks were found in 12 locations. Among them, 10 of the locations are at the intersections of the U ribs and the lateral webs where AE sensors were installed. 2 of the locations are not in the web area, but in the middle of two webs with crack direction along with the rib length. At all 10 locations where the AE sensors were installed nearby, crack initiations were found by AE well before the visual inspection. However, since there was no AE sensors installed in middle of the webs, the 2 cracks located in the midway of the U ribs were not found by AE because the AE sensors were too far from the crack positions so that the AE signal was greatly attenuated before it reaches to the AE sensor.

In order to illustrate how AE behaviors during crack initiation and development, the AE data in the two of the seven crack locations where AE sensors were installed were analyzed here. The two crack positions are labeled as C and G as shown in Figure 2.

4.1 Case study 1: AE activities at position C

Take the position C as the first example, the elapsed time and the fatigue cycles along with AE monitoring and visual inspection results at location C are shown in Table 1. As is seen in the table, crack initiation was observed about 142.3 fatigue hours or 513 thousand fatigues cycles by the AE. The crack was not visually found until 182.6 fatigue hours or 657.5 thousand fatigue cycles when a 20 mm crack was observed. So, in this example, the AE was able to report the crack initiation in about 40 hours before visual inspection.

On the other hand, the crack initiation and development process can be clearly identified from a time history graph of AE hit activity as shown in Figure 4(a). In this figure, the vertical axis is the AE hit rate per second, the horizontal axis is the fatigue testing time from 139.9 to 160.2 elapsed fatigue hours. Crack was initiated in about 513 thousand fatigue cycles or 142.3 hours after the fatigue test started, then the AE activity keeps relatively quite which implies that the crack was rest for a while after initiation. In about 6 hours later or 535 thousand overall fatigue cycles, significant crack activity or crack growth that was lasting for about 4 hours was observed. The AE amplitude in this period is shown in Figure 4(b), each dot in the figure represents the amplitude of each AE hit. Trending of the AE amplitudes around 40 dB is clearly seen in the figure, this indicates continuous crack growth in this period though occasionally the amplitude drops below 35 dB. By further zooming the instant signal around 12:00 am of August 3rd in Figure 4(b), the AE amplitudes in less than one minute span are shown in Figure 4(c). The amplitudes are scattered in fairly regular interval which coincides to the fatigue cycle, i.e. one per second. In other words, there is one AE hit or one crack event in every fatigue cycle in this period.

Table 1. Remarks of crack monitoring alone with elapsed fatigue time & cycles at location C

Date	**Time of the Day**	**Elapsed Time (Hours)**	**Fatigue Cycles (Thousands)**	**Remarks**
2/Aug	14:07	139.9	504	AE monitoring started.
	16:32	142.3	513	AE activity that indicates crack initiation was observed in the first time.
	20:17	146.1	526	AE activity lasting for about 10 minutes was observed.
	22:42	148.5	535	Significant AE activity that indicates continuous fatigue crack development in about 4 hours was observed in the AE.
3/Aug	08:30	158.3	570	**Visual inspection didn't find crack.**
	14:24	164.2	592	**Visual inspection didn't find crack.**
	16:05	165.9	598	Stepwise AE activity that indicates crack growing and resting was observed.
4/Aug	05:50	179.6	647	Long lasted AE activities were observed.
	08:50	182.6	658	**Visual inspection found crack with 20mm long, in 40 hours later than that AE reported crack initiation.**

Besides the continuous cracking activity observed, a stepwise cracking activity was also observed in location C. Figure 5 shows the AE amplitude in about 598 thousand fatigue cycles or 165.9 elapsed fatigue hours. Not only the amplitude shows an increasing trend, but also the amplitude drops down to a lower level and then it increases again. This phenomenon implies crack growing and stress relief during the fatigue process. When micro cracking is build up, the AE amplitude is increased until the stress concentration is big enough to generate macro cracking which results in stress relief and therefore decrease of the AE amplitude. Then the micro cracking would rebuild up again so that stepwise AE amplitude is observed. Obviously, the micro cracking or stress concentration build up didn't show regular trend, occasionally, sometimes it builds up quickly, sometimes it takes a long resting time before micro cracking is rebuild up again.

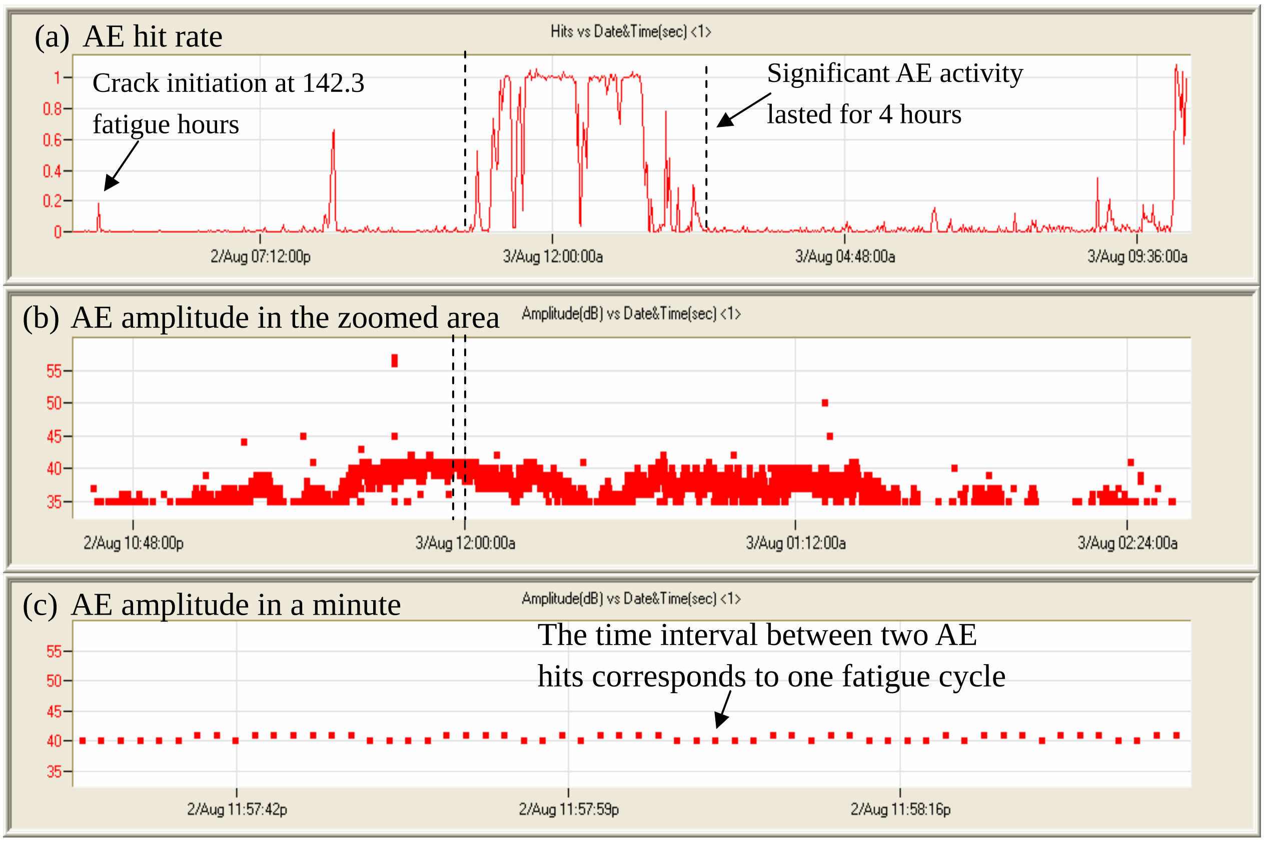


Figure 4. AE hit rate and amplitude at location C from 139.9 elapsed fatigue hours

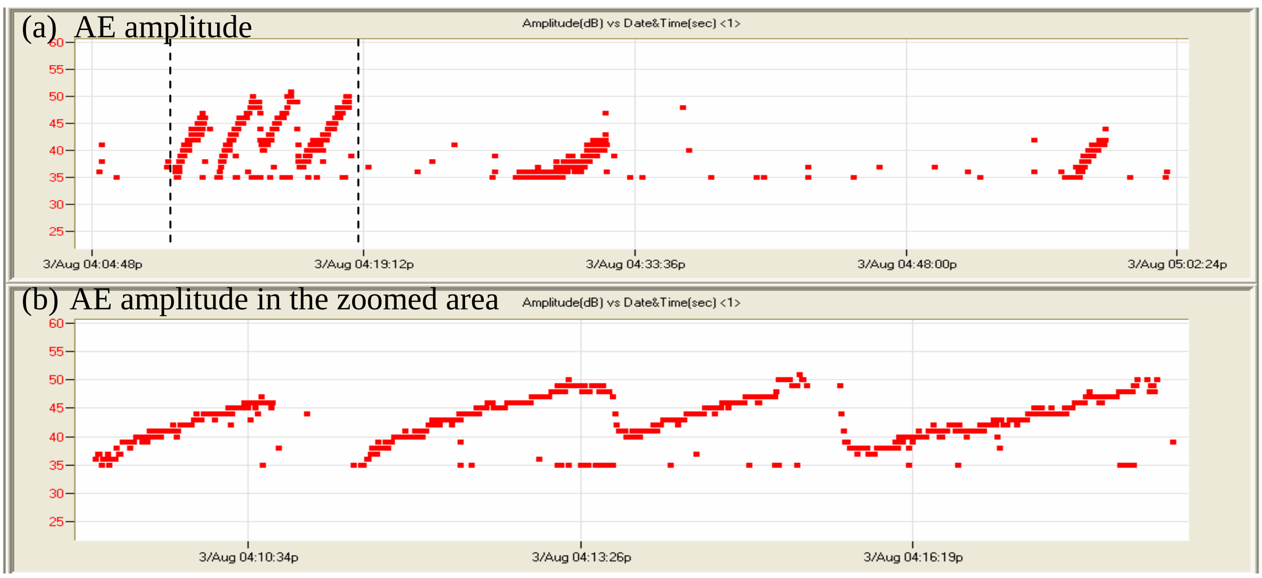


Figure 5. AE hit amplitude versus testing time that shows stepwise crack growth.

4.2 Case study 2: AE activities at position G

The second example is for the crack monitoring of position G of Figure 2. The elapsed time and the fatigue cycles along with AE monitoring and visual inspection results at this position are shown in Table 2. Figure 6 shows the AE hit rate from 139.9 to 237.8 elapsed fatigue hours. AE activity or crack initiation started from 148.4 elapsed fatigue hours or 534 thousand fatigue cycles, then continuous AE activities lasting for over 12 hours were observed, there is also long resting period that no or very rare AE activity was observed after the crack initiation. Since three sensors, numbered as 1, 8 and 2, were installed in position G, crack locations are able to be picked up with the linear location algorithm applied to the AE hits detected by the three sensors. Figure 7(a) shows a distribution of the located crack events along with the linear coordinate of the sensors, it shows two clustered location groups around the sensor 8, one is in between sensors 1 and 8 and another one is in between sensors 8 and 2. These two clustered location groups indicate that two cracks exist in these two areas. However, as is seen in Table 2, visual inspection couldn't find cracks in the following 21 days which it challenged the findings of the acoustic emission.

Table 2. Remarks of crack monitoring alone with elapsed fatigue time & cycles at location G

Date	Time of the Day	Elapsed Time (Hours)	Fatigue Cycles (Thousands)	Remarks
2/Aug	16:07	139.9	504	AE monitoring started.
	22:35	148.4	534	AE activity that indicates crack initiation was observed in the first time.
3/Aug	9:30	159.3	574	Visual inspection didn't find crack.
	13:47	163.6	589	Visual inspection didn't find crack.
4/Aug	8:50	182.6	658	Visual inspection didn't find crack. AE activity was relatively quiet in this period.
5/Aug	8:45	206.5	744	Visual inspection didn't find crack. Significant AE activities with locations were observed in next few days which indicate long lasted continuous fatigue crack development.
	13:07	210.9	760	Visual inspection didn't find crack.
6 – 23 /Aug				AE kept indicating crack activities, but no crack was found with visual inspection at this location in this period.
24/Aug	9:00	662.8	2880	After applying higher load and faster fatigue frequency up to 2 Hz, visual inspection eventually found two cracks in 220mm and 15 mm long respectively.

With continued fatigue cycles, although AE kept indicating crack activities, no crack was found at this monitoring area for over 21 days after the crack initiation was detected with AE.

Before finishing the 30 day fatigue test, accelerated fatigue test parameters, e.g. higher load and faster fatigue test frequency up to 2 Hz, were applied to the structure to speed up the damage process. Then two cracks were eventually visualized in about 22 days after AE detected crack initiation. A photo of the crack location after the overall 30 day fatigue test is shown in Figure 7(b), one crack in 220mm long is located at the web in between sensors 1 and 8, another crack in 15mm long is located along with the weld of the rib in between sensors 8 and 2, these two cracks are located at the same positions that AE technology has reported in about 22 days ago. This illustrates that either the microscopic initial crack was too small to be visualized or the crack was not in the surface of the visible area in early stage of fatigue crack growth. However, AE not only detected the crack initiation and growing process, but also it located crack positions in so many days before visual inspection found the cracks. The visual inspection results eventually proved the effectiveness of the AE technology for dynamic monitoring of fatigue crack process of large structures.

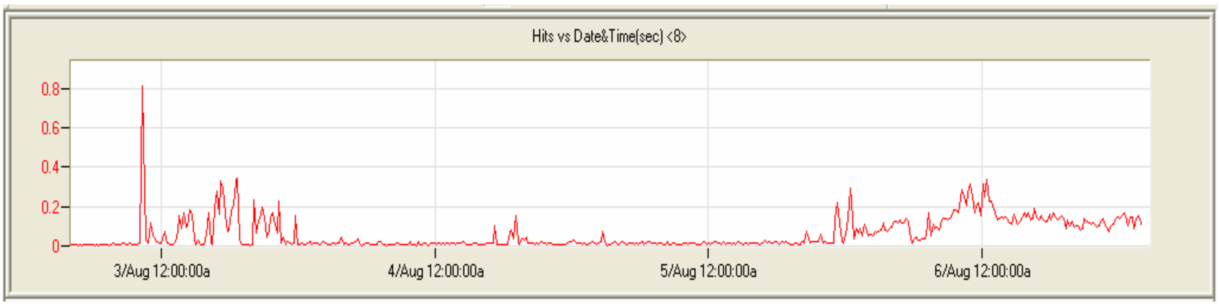


Figure 6. AE hit rate at position G from 144.4 elapsed fatigue hours

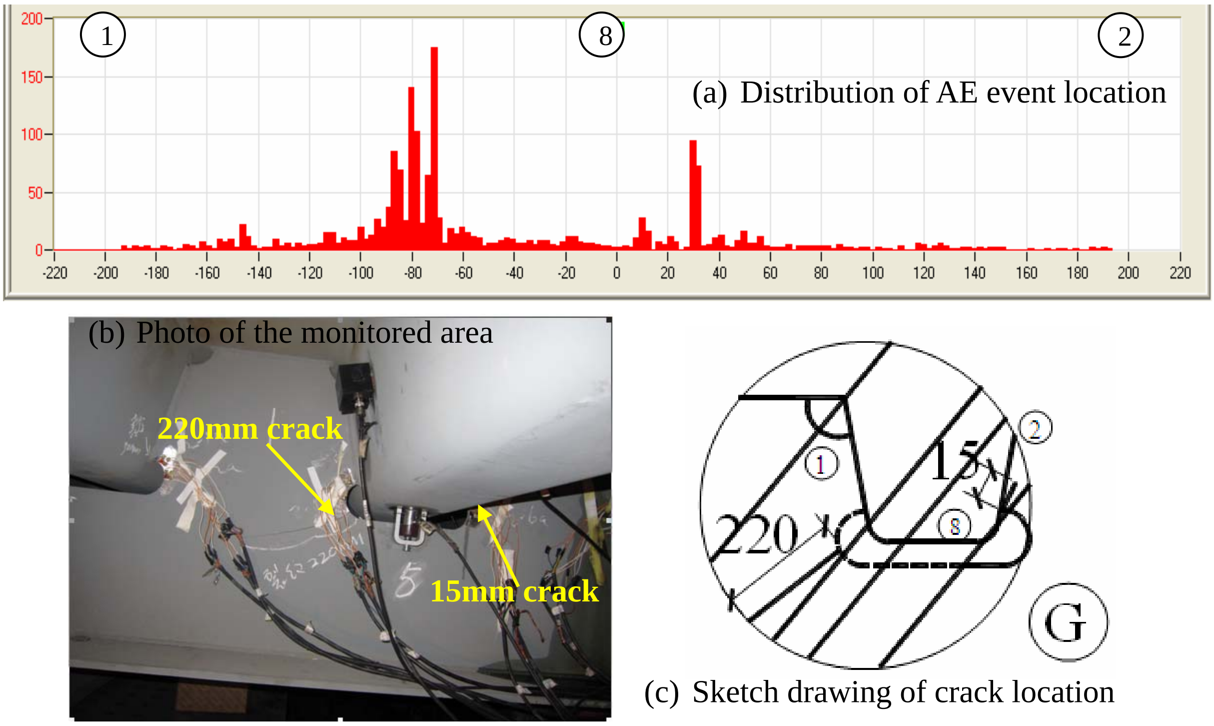


Figure 7. AE crack event location and indications of the cracks found

5. Conclusions

This paper has applied acoustic emission technology for monitoring the dynamic process of fatigue crack initiation and growing of a full size orthotropic steel bridge deck. Experimental results have proven:

1). AE is an effective technology for structure health monitoring, specially AE can monitor the whole dynamic development process from crack initiation and growth to structure fracture. Not only AE can tell when a crack is initiated, but also it can tell where the crack is located and how it develops.

2). AE has much higher sensitivity for active crack identification than any other NDT technologies. It can detect microscopic crack activity and is able to report crack initiation in hours or days in advance of visual inspection and other technologies. This actually draws another inference, i.e. a fatigue test may not be able to find correct material life cycle without using AE for crack detection.

3). In the experiment, it was found that the cracks of the tested deck are not necessarily found in welds, but also it existed in other weak locations of the structure material.

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