DAMAGE DIAGNOSIS TECHNIQUE FOR BRICK STRUCTURES USING ACOUSTIC EMISSION

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Abstract

Acoustic emission (AE) is known as a non-destructive test under external load/variation of stress distribution within materials; AE waves are difficult to generate without those stress variation. Railway bridges are the structures where the external load variation can be easily applied due to over-passing railway traffic. In this study, in order to apply AE technique to the damage evaluation in railway brick structures, fundamental experiments using brick specimens sampled from an actual old brick foundation of a bridge are carried out. This is performed to find the applicability of AE technique to brick materials. Next, in order to know the deterioration process and to establish a damage evaluation table, brick specimens made in laboratory are subjected to cyclic loads, and AE activities with crack growth are examined. Finally, in-situ AE monitoring is performed on an “elevated arch railway bridge” where obvious penetration-cracks are observed. For in-situ monitoring, AE activities directly generated from the observed cracks are distinguished from those induced by the railway traffic.

Key words: brick, calm ratio, damage diagnosis/degree, load ratio, railway structures

1. Introduction

In Japan, many masonry structures using bricks have been constructed over 60 years ago. During service, they have sustained damage from several earthquakes and long-term weathering. In order to confirm the safety for service, it is essential to investigate the deterioration and degree of damage of the structures. Also the investigation result is important in performing appropriate rehabilitation/reinforcement for the deteriorated structures. Thus far, such techniques as visual observations and crack displacement have been used in the investigation of elevated bridges made of bricks. As for the lower portions of the elevated bridges, however, since they are normally utilized as commercial buildings, the same techniques are difficult to apply. Again, it is required to establish another technique to diagnose the integrity of brick structures even where conventional techniques are difficult to apply. Several NDT techniques, radar, ultrasonics, electric exploration and acoustic emission (AE), had been performed in brick structures as preparation. However, the results except from the AE technique were useless. Thus, this study only focuses on the AE technique.

When the AE technique is applied to railway brick structures, it has the following unresolved points:

1) How the external loadings or variation of internal stress are applied to induce AE activity?
2) Is AE signal from cracking in bricks really obtainable?
3) How do the types of crack affect AE activity?
4) AE activity might decrease with repetition of loads; i.e., Kaiser effect may exist.
5) Detected AE activity might include AE signals, which is not related to crack behavior directly but related to the dynamic behavior due to railway traffic loads.

In this paper, answers to these points are explained with the following procedure. First, fundamental experiments using brick specimens that are sampled from an actual old brick foundation of bridge are carried out (answer point 2). Second, in order to evaluate the deterioration process and to establish the damage evaluation method, brick specimens made in laboratory are subjected to cyclic loads, and AE activities with crack growth are examined (for points 3 and 4). Finally, in situ AE monitoring is performed in an “elevated arch railway bridge” where obvious penetration cracks are observed (for points 1 and 5).

2. Experiments

2.1 Fracture tests using sampled specimens [1]

There exists a brick bridge of over 80 years old. Four beam specimens were sampled from the substructure of the bridge. Figure 1 shows the configuration of the specimen with the arrangement of AE sensors. The tests are performed with 4 different specimens and 3 different conditions of axial force as shown in Table 1. The axial stress of 1.0 MPa in No. 1 specimen is the maximum load when the train passes on the arch, in which the span is 7.8 m; the axial force of No. 2 is 50% of the assumed maximum load. Monotonic bending load was applied to the specimen with AE monitoring. 12 AE sensors of 60-kHz resonance were placed on the surface with wax couplant (see Fig. 1). The signals detected were pre-amplified 40 dB and processed by a DSP-based MISTRAS AE system (Physical Acoustics Corp.) with the 40-dB threshold (ref. 0 dB = 1 µV at sensor). Both AE parameters and waveforms are recorded; the latter with 1-MHz sampling and 1-kword length. In this experiment, the AE activity corresponding to the fracture stages classified by using the load-displacement relation is studied, considering with/without axial force. The monotonic load was applied in a step-wise manner with 5 kN increment.

<table>
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<th>No.</th>
<th>b (mm)</th>
<th>h (mm)</th>
<th>L (mm)</th>
<th>a (mm)</th>
<th>Axial force (MPa)</th>
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<td>600</td>
<td>600</td>
<td>1,500</td>
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</tbody>
</table>

2.2 Cyclic tests using laboratory-made specimens

In general, AE activity generated due to crack nucleation and formation is referred to as “primary AE activity,” whereas AE activity due to the friction of pre-existing crack interfaces is referred to as “secondary AE activity.” In this cyclic test, in order to study the secondary AE activity, the cracks are first introduced into the newly made specimens with loading. The specimen has a length of 1776 mm, a width of 360 mm and a depth of 330 mm as shown in Fig. 2. 12 AE sensors are placed on the surface. The condition of AE monitoring system is the same as in the previous test. Lateral force (i.e., axial stress) of 0.33 MPa was first applied to the specimen, then the vertical load was applied until a penetration crack was observed. Changing the shear span,
bending and shear loads were applied (see Fig. 2). After introducing the penetration crack, the specimen was subjected to cyclic loads. We applied five repetitions of cyclic load at 10, 50 and 75% of the load, at which the penetration crack was observed. After cycling, monotonically increasing load was applied until the specimen broke and dropped from the stand.

2.3 In-situ AE monitoring at an elevated arch railway bridge

In order to generate AE activity, it is essential to apply the external load or to give the variation of stress distribution within materials. For railway structures, both can be possible by the train passage. The monitored structure is a double-tracked brick arch elevated bridge constructed in 1910. The bricks used for the foundation are laid by means of English bond. A penetration crack was already visible in the direction of railway (see Fig. 3), and out-of-plane displacement of approximately 0.2 mm was measured with each train passage. Thus, the AE activity from the bridge is expected due to the crack movement. A set of AE sensors with 15-kHz resonance were placed on the bridge bottom as shown in Fig. 3. Subsequently, these were exchanged with 60-kHz sensors. To monitor the acceleration due to the train passage, accelerometers were also set up. The AE system used and the monitoring condition are the same as in the previous tests.

3. Results and Discussion

3.1 Fracture tests using sampled specimens

A typical behavior of displacement and AE activity are shown in Fig. 4. This is the result of specimen No. 1, where axial force was applied. In the chart, the vertical displacement at the
Fig. 3. A penetration crack and an arrangement of AE sensors in an arch bridge.

Fig. 4. Displacement and average frequency in specimen No. 1 with axial force. The arrows show the times when a crack was first observed and then reached the yield point.

loading point and AE average frequency obtained by AE (ring-down) counts and duration are given as a function of elapsed time. The average frequency is the average of the latest 100 AE hits; i.e., using a method of moving average [2]. As seen in Fig. 4, the axial force was imposed during the initial 430 s. With subsequent loading, the average frequency increased, accompanied by the repetition of rise and fall until a crack was observed. The manner of the repetition corresponded well with the stepwise increase of the load step of 5 kN. The average frequency ranges from 20 to 60 kHz in the cracking process (i.e., 430 - 1775 s). The repetition was also found after the yield point at 1775 s. However, the average frequency became smaller to around 20 kHz. Thus, the progress of fracture in brick structures can be classified into the following three processes: 1) Micro-cracking due to tensile/shear stresses accompanied by the AE activity of high average frequency; 2) Formation of macro-cracks by connecting the micro-cracks, and local generation of macro-scale shear fracture due to yielding, accompanied by the AE activity of low average frequency; 3) The friction between pre-existing fracture planes, accompanied by the AE activity of low average frequency.
3.2 Cyclic tests using laboratory-made specimens

Figure 5 shows the applied load and AE hit rate per 10 s against elapsed time in the shear cyclic test. In this figure, the AE activity increases with the first applied monotonic load, and there is no active AE occurrence during cyclic load at 25% of the nominal cracking load. The no AE activity during the cyclic load at 25% was caused by the following: 1) Shear stress due to bending was too small. 2) Kaiser effect was observed. During cyclic load at 50%, however, AE activity with loading can be observed in every repetition. AE hits are actively generated during 75% cyclic load both in loading and unloading. These suggest that Kaiser effect started to break down from 50% of the cracking load, and continuous AE activity was obtained not only in loading but also in unloading to and from 75% of the maximum load.

Figure 6 shows the average frequency and the load applied against elapsed time. After the penetration of cracks, the average frequency increases from 20 to 30 kHz without the final buckling process. This range of the average frequency is almost the same as in the bending specimen, and agrees well with the result in the sampled specimen after yielding (see Fig. 4). Figure 7 shows results of 3D source locations projected to the front surface of the specimens with observed cracks. The sources are classified with scale of the peak amplitude. In both bending and shear specimens, cracks are generated not only in direction of the axial load (i.e., vertical), but also parallel to the axial force. This implies that even when the bending loads are applied, cracks
Fig. 7. 3D source locations projected to the front surface. AE sources are classified with the peak amplitude.

Fig. 8. Damage degree map. (S: damage is given by shear load. B: damage is given by bending load)

are sometimes generated horizontally along the interfaces among bricks; the shear type of cracks also occurred even in the bending test. Thus, the reason why the same average frequency was obtained in both types of specimens is that the same shear fracture had occurred in both bending and shear specimens. In addition, the location of cracks observed is identical to the AE sources with large peak amplitude. This leads to a conclusion that macro-scale cracks could be estimated from AE activity with large peak amplitude.
Fig. 9. Typical frequency spectra of detected AE waves with 15-kHz (left) and 60-kHz (right) resonant AE sensors.

Fig. 10. 2D AE sources classified with the average frequency (left: with 15-kHz, right: with 60-kHz resonant AE sensors).

From all of the results, a damage map of brick structure is constructed as shown in Fig. 8. The map is based on the NDIS 2421 [3], “Load” stands for ratio of load at the onset of AE activity to previous load, and “Calm” stands for ratio of cumulative AE activity under unloading to that of previous maximum loading cycle. With an increase of the degree of damage, the plots distributed toward the upper left side of the map, irrespective of the types of loading conditions. Thus, it is found that evaluation of integrity in brick structures is possible using the damage degree map based on the AE activity.

3.3 In-situ AE monitoring at an elevated arch railway bridge

With each train passage, AE signals could be detected in AE sensors of both 15-kHz and 60-kHz resonance. Figure 9 shows the typical frequency spectra of detected AE waveforms with 15-kHz (left) and 60-kHz (right) sensors. In each chart, a comparison is made between Ch-4 and Ch-5, which are the AE sensors close to the observed crack and far from the observed crack, respectively. Both sensors have the common frequency component of 10 kHz, irrespective of the location from the crack. In the 60-kHz sensor data, however, the frequency component from 25 to 35 kHz is only found at Ch-5 being close to the crack. This implies that AE signals having the
frequency component ranging from 25 to 35 kHz are generated from the existing crack. Here, the 2D source locations obtained are classified with average frequency as shown in Fig. 10. The AE signals for the first arrival are used in the classification. In the arrangement of 15-kHz resonant AE sensors, AE sources disperse over the monitoring area, whereas for 60-kHz resonant AE sensors, AE sources higher than 25 kHz are distributed around the center of the monitoring area. The AE sources distributed in the center area appear to be the AE events generated from the existing cracks, although this area is not completely identical to the location of the crack observed. This is because; 1) the heterogeneous velocity-distribution existed in the vicinity of the large cracks, and 2) the actual cracks distributed in 3D space, normally with curved crack surfaces. Thus, it seems reasonable that the distribution of AE sources, higher than 25 kHz, may not be completely identical to the position of the surface-breaking crack. It becomes clear that by using AE sensor of 60-kHz resonance and focusing on AE signals around 30 kHz, the secondary AE activity due to the friction between the pre-existing crack interfaces can successfully be detected.

4. Conclusions

In this study, the AE technique was applied for the damage evaluation in brick structures. It can be concluded that:

1. AE signals could be obtained during the cracking process of bricks, and there exists the secondary AE activity generated due to the friction of pre-existing crack faces;
2. Deterioration/cracking process could be evaluated using AE parameters;
3. Using the proposed damage map based on AE activity, the degree of damage of brick structures could be reasonably evaluated;
4. With the sensor of 60-kHz resonance and using the high pass filtering over 25 kHz, AE activity directly related to the crack behavior could be distinguished from those related to the dynamic behavior due to railway traffic loads;
5. Railway traffic could induce AE activity generated from pre-existing crack faces, and the damaged area could be estimated as a distribution where higher frequency AE sources over 25 kHz were generated; and
6. From all of the findings, the AE monitoring range is limited to 1.5 m using AE sensor of 60-kHz resonance, and the threshold of 40 dB. For the future work, additional ideas to expand the monitoring areas would be needed.

References