Monitoring masonry arch bridge response to traffic loading using acoustic emission techniques

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ABSTRACT: Condition assessment and monitoring of the ageing European masonry arch bridge stock generally relies on visual observation and there is practically no information available on the bridge's actual response to its traffic loading. The efficacy of acoustic emission monitoring technique has been investigated on a series of masonry arch bridge tests in laboratory and in field conditions. The technique has shown to be able to identify damaged regions, potential areas of damage, record ongoing crack propagation prior to crack opening, warn of residual damage and identify the fatigue limit of masonry arches for the first time. It can help adjust the weight of traffic to prevent residual damage and avoid sudden failure or collapse. Due to the quick and easy installation process, the technique has shown great potentials as a routine condition assessment and monitoring tool for masonry arch bridges in the field.

1 INTRODUCTION

The majority of masonry bridges are now over 100 years old and still carry heavily increased road and rail traffic. Most bridges have suffered some form of deterioration during their life time. Condition and life cycle assessment are some of the main considerations for bridge owners to ensure safe use of their bridge stock. Condition assessment of masonry bridges generally relies on visual observation and give little insight into the structure's condition and response to traffic loading.

Acoustic emission (AE) has the ability to record fracture activity within the structure before it becomes visible on the surface. It also has the advantage of being able to record long-term real-time data which makes it suitable for use under traffic loading. Acoustic emission is increasingly widely used for monitoring concrete and metallic bridges, however, its application for masonry bridges is currently very limited. The reason for this is that while acoustic emission is well suited for quasi-homogeneous materials (e.g. concrete and metallic structures) with good acoustic transmission, its use on heterogeneous materials such as masonry is much more problematic. The paper attempts to introduce how acoustic emission technique may be applied to masonry arch bridges despite of the complications caused by their material composition and uncertainties.

2 ACOUSTIC EMISSION

Deterioration of masonry arch bridges is generally indicated by outward signs of some form of localised defect that may effect the overall load bearing capacity of the structure. Although internal deterioration may well precede any visual sign of damage, detecting internal crack propagation is significantly more problematic.

Any crack formation (fracture) is caused by the fracture energy of the local material being exceeded and is accompanied by some degree of energy release. Acoustic emission techniques have the ability to record the released fracture energy during crack development by measuring the energy that is transmitted by the generated transient elastic wave. The present paper attempts to show how acoustic emission techniques might be used to give practical information on internal fracture development of masonry and how that may be related to the bridge's ability to carry any given loading and its fatigue load capacity.

For Acoustic Emission (AE) monitoring a Physical Acoustics DiSP system was used with four channel PCI DSP4 boards and filter set to 20-200kHz. Preamplifiers were IL40D with 20-100kHz frequency. The sensors were Physical Acoustics R6D resonant piezoelectric sensors with a response range of 40-100kHz. The sensors were selected based on advice and past experience as a good compromise of detection / distance and avoiding noise from the loading rig. The filter bandwidth was broader than the preamplifier and sensors to ensure that signals were not distorted. AE WIN software was used to process data and in addition to the AE hit recordings load and deflection were also measured every time emission was received. Up to eight AE sensors were attached to the brick surface using a thin layer of hot-melt glue. This technique had been tested to provide good coupling for transmitting AE signals.

3 EXPERIMENTAL PROCEDURE

3.1 Arch dimensions

A series of 3m span two-ring and 5m span three-ring brick arches have been tested at the University of Salford as part of EPSRC and EU Sustainable Bridges projects to assess their endurance limit, fatigue load capacity and modes of failure. The arch dimensions are listed in Table 1. In addition to the standard test methods acoustic emission technique was also applied during the tests to gain deeper understanding of the fracture process of masonry during quasi-static and long-term fatigue loading.

Table 1 : Arch dimensions.

Span (mm)	3000	5000
Rise (mm)	750	1250
Ring thickness (mm)	215	330
Arch width (mm)	445	675
Number of rings	2	3
span : rise ratio	4:1	4:1
Dead load	2 x 10kN	2 x 22.5kN

3.2 Material properties

Two types of bricks were used: strong class A engineering bricks and weak Britley Olde English bricks. Material properties for the bricks, mortar and triplets are shown in Table 2. Although the class A engineering brick was significantly stronger than the Britley Olde English brick, their masonry strength was not greatly different. This is due to the fact that the higher porosity of the weaker bricks enabled a better bond between the brick and the mortar. Masonry strength is primarily dependent on the brick surface texture rather than the brick strength as described by Lange (1993).

Table 2 : Compressive strength for brick, mortar and masonry.

	Compression N/mm2	Density kN/m3
Brick (Strong)	154	23.7
Brick (Weak)	18.9	16.2
Mortar	1.86	15.5
Masonry triplet (Strong)	18.2	21.8
Masonry triplet (Weak)	11.7	16.9

3.3 Loading

All arches were loaded by two point loads at the ¼ and ¾ points by hydraulic jacks to represent the vertical dead load of the fill on the arch. Some arches were tested under quasi-static and others under long-term cyclic loading. Live load was applied at the ¼ point for quasi-static tests and alternatively at the ¼ and ¾ points for cyclic tests using hydraulic jacks. Cyclic loading was applied at 2Hz frequency to represent the flow of traffic at approximately 25-30miles/hour speed over the bridge for at least 1,000,000 cycles at each load level, starting from less than 50% of the static failure load. If no damage occurred after 1,000,000 cycles, the live load was increased by 2kN and the process was repeated until failure occurred.

4 MASONRY ARCH FAILURE PROCESSES

Since 60% of the European masonry bridges are over 100 years old, the rate of deterioration and potential life expectancy is of increasing interest to the bridge owners. Currently there are no assessment methods available to estimate how long the masonry bridges will be able to carry any given traffic loading. Generally a safe limit of ca. 50% of the static load capacity is assumed, due to the lack of experimental test data. Although this may give a reasonable estimate, it is not certain that fatigue limit is indeed above 50% of the static loading. Laboratory test results carried out at the University of Salford on long-term fatigue loading of large-scale masonry arches have indicated that fatigue capacity may in some cases be around 40-50% of the static capacity. While under the fatigue limit theoretically infinite number of loading cycles can be applied to the structure, rapid deterioration occurs as soon as the fatigue limit is exceeded. Since most masonry arch bridges carry traffic well above their design loads, a small amount of load increase may easily exceed the fatigue limit of the bridge and significantly reduce its life expectancy.

4.1 Failure process during static loading tests

In order to demonstrate the efficacy of acoustic emission techniques for masonry bridges, an arch under quasi-static loading will first be considered. A 5m span three-ring arch loaded at the ¼ span is shown in Figure 1 together with its failure pattern and location of eight AE sensors. Crack propagation was visually observed at 20 and 25kN loading and at 30kN when the arch failed by ring separation. The AE amplitude readings during the loading history are shown in Figure 2 for all the eight AE sensors. Out of the eight sensors four (AE1, AE2, AE3 and AE4) show clear AE activity (increased amplitude and spatial intensity) in the vicinity of their locations from an early stage of the loading history, while no significant emission was recorded by the other sensors in other regions. Live load was applied at the ¼ span which was responsible for the increased AE activity and damage around sensors AE1 to AE4. Empirical observations from the AE readings can already give instant indication of crack development in certain regions and of potential damage locations.

Although significant acoustic emission activity was recorded from the start of live load application by some of the sensors, crack opening was visually observed only at 20, 25 and 30kN loading stages. Increased AE emission prior to crack opening suggests that accumulated crack development precedes any visual sign of crack opening. The ability to record crack propagation prior to crack opening and to identify potential damage locations indicates great potentials for AE techniques to be used for condition assessment of masonry arch bridges.

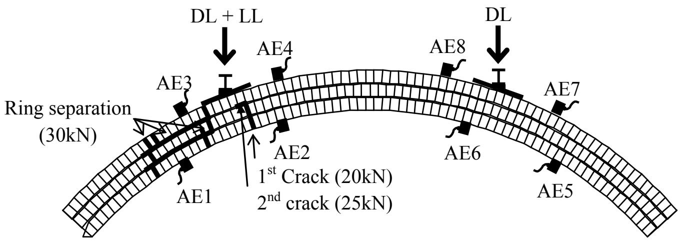

Figure 1 : Ring separation failure and AE sensor locations (5m arch)

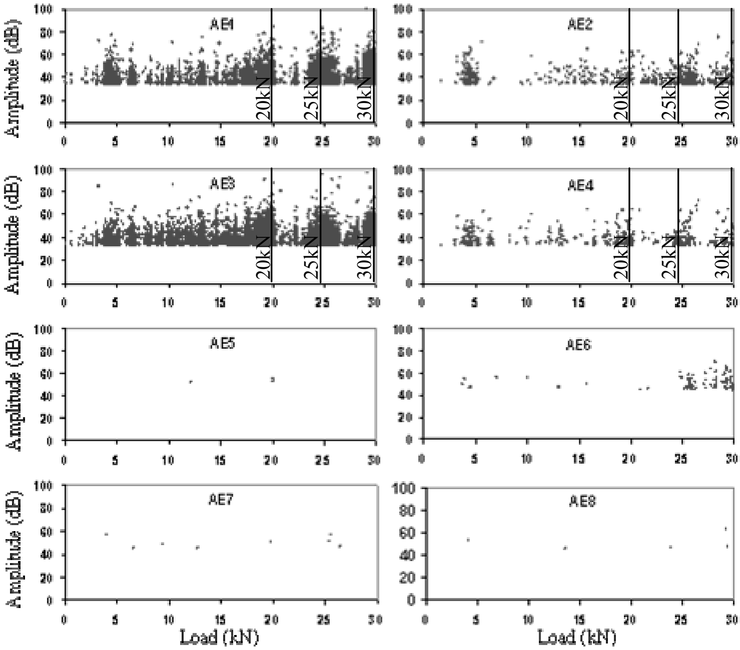

Figure 2 : Static loading – Amplitude vs. Load

AE recordings also allow deeper insight into the development of failure mechanism with the help of recording the released absolute energy throughout the loading history. Figure 3 shows the accumulated absolute energy plotted against load for the same arch. The different energy characteristics during the energy history are labelled [a], [b] and [c] for which some examples are marked. Gradually increasing absolute energy [a] is associated with crack development and is caused by opening of a large number of small internal cracks. Once the stress limit is reached within the joint, a crack opens which is recorded as a steep vertical increase [b] in the absolute energy plot. As a crack opens, the strain energy is released and stress redistribution takes place. This process is associated with a plateau [c] in the absolute energy graphs. At this stage, despite a load increase, the increase in absolute energy is limited. As the stress re-distribution takes place, the local stress levels reduce below that at which cracking occurs and no significant crack development takes place immediately after crack opening. Only when the load increases to a level where cracking can continue, does the absolute energy level begin to increase again.

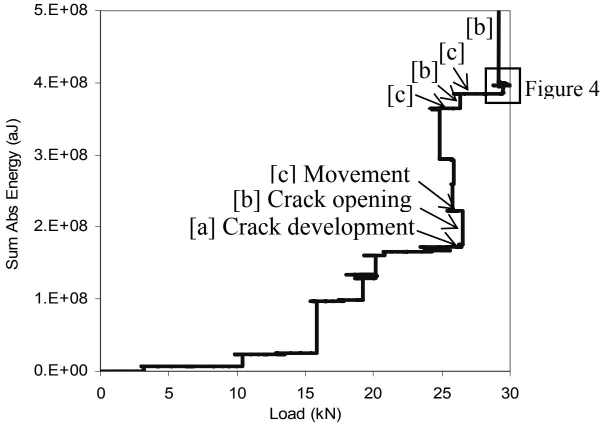

Figure 3 : Static loading – Sum Abs Energy vs. Time

To enable closer inspection of the final ring separation process, a small section of Figure 3 immediately prior to ring separation is considered in greater detail in Figure 4a. Similarly to Figure 3, the magnified section also shows a sequence of crack development [a], crack opening [b] and movement [c] processes as a function of the released absolute energy. Figure 4b shows the relevant loads for the same (magnified) section with the same vertical axis. After each period of crack development, crack opening occurred rapidly and was followed by reduction of the load as the structure released itself and moved away from the loading constrains. Crack development and crack opening only continued when the load was reapplied and reached or exceeded the previous level.

It is also interesting to note, that final ring separation occurred at a lower load level than the maximum load applied to the structure. Once 30kN was reached, a series of small internal cracks developed as a chain-like reaction under reduced loads which caused the shear stresses in the remaining bonded area increase to a level where the shear strength of the bond is exceeded and sudden ring separation occurred. Crack opening in masonry is therefore associated with a long history of initial crack development events, which if detected, can warn of potential damage. Damage to the structure can be subsequently avoided by prompt removal of the critical loads. Because of the difficulties associated with the detection of microscopic internal crack development, AE has been identified as a unique tool for providing information on the structure's actual response to any specific loading condition and on internal fracture development processes.

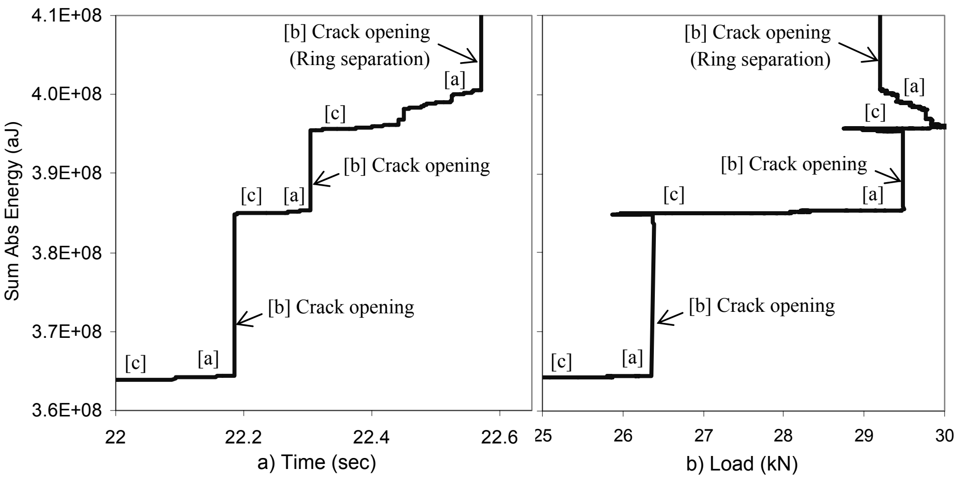

Figure 4 : Static loading – Sum Abs Energy vs. Time and Load

4.2 *Failure process during cyclic loading tests*

In order to gain information on the fatigue damage process of masonry, a series of arches have been tested under long-term fatigue loading. Figure 5 shows AE recordings for a 5m span three-ring brickwork arch. The arch was loaded for 10^6 cycles at each load level from a relatively low load. The load was increased by 2kN after every 10^6 cycles and the arch failed suddenly by ring separation under 18kN. Figure 5 shows the average released absolute energy per cycle at the beginning and end of each load setting. While no sign of damage propagation was visually observed before ring separation occurred, the average absolute energy clearly increased above 14kN. Increased absolute energy suggests that the fatigue limit of the arch was around 14kN, above which residual damage occurred to the structure and led to ring separation failure at 18kN.

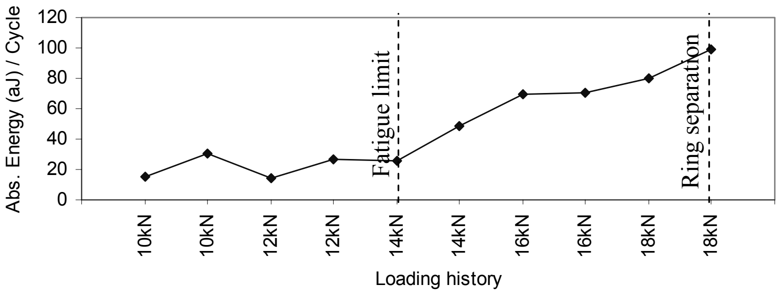

Figure 5 : Cyclic loading – Abs. Energy per cycle vs. Loading history (5m span undamaged arch)

So far only newly built arches without any major damage have been discussed. The European bridge stock however largely consists of bridges which have been in use of over 100 years and most certainly have suffered some form of damage, e.g. incidental overloads, weathering or mortar wash-out. Any monitoring technique is only useful in the field, if they can be applied for structures with significant damage and still inform of any loss of structural integrity.

Figure 6 shows the released absolute energy per cycle during the loading history of a badly damaged arch. The 5m span three-ring brickwork arch had suffered ring separation and was strengthened with FRP and radial pinning. Long-term fatigue loading was subsequently applied to the arch similarly to the previous example. Despite of high noise levels during the entire loading history, Figure 8 shows relatively constant energy release up to 32kN, above which significant energy increase is clearly visible. Fatigue limit for the arch is likely to be around 32kN, above which residual damage led to ring separation failure at 36kN.

Acoustic emission technique can therefore be used to help identify the fatigue limits of masonry arches under traffic loading for the first time. Limiting the traffic loading (axle weight) below the fatigue limit can help avoid residual damage and extend the life expectancy of bridges in both good and poor condition.

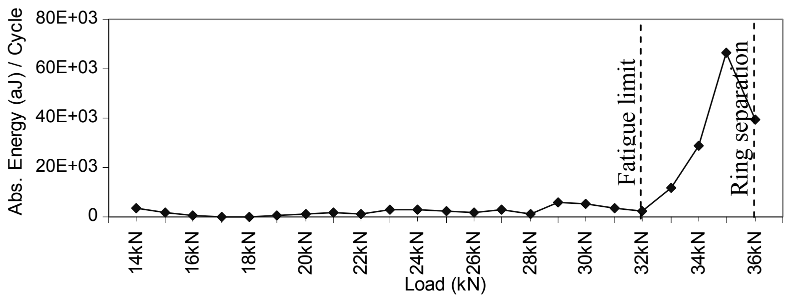

Figure 6 : Cyclic loading - Abs Energy per cycle vs. Loading history (5m span damaged arch).

5 FIELD TESTING

For field use the acoustic emission technique offers the possibility for either short-term routine condition assessment under current traffic loading or long-term monitoring for progressive damage development. Short-term condition assessment should identify damaged regions in the arch barrel and the arch's response to traffic loading. Long term monitoring should indicate the rate of deterioration of the masonry and can be carried out either by built-in permanent sensors or by a sequence of short-term readings over time.

To demonstrate the efficacy of the acoustic emission technique for field use, a small brick arch bridge was selected. For the bridge dimensions see Table 3. The bridge elevations are constructed in stone masonry. The bridge carries two railway tracks over a narrow country lane.

The condition of the brickwork was relatively sound, however three longitudinal cracks were clearly visible under the railway tracks and half way between them. Normal railway traffic includes light passenger trains almost every 30 minutes during normal times of operation and less frequent freight trains, loaded and unloaded. Maximum permitted axle weights are 24,2–25,4 tonnes and maximum line speeds are 130 km/h.

Table 3 : Bridge dimensions.

Span	3600 mm
Rise	1800 mm
Soffit height	3900 mm
Arch width	8600 mm
Span : rise ratio	2:1
Shape	Semi-circular

Six acoustic emission sensors were attached to the arch intrados using hot melt glue directly under each set of railway tracks (see Figure 8 for AE sensor locations). Acoustic emission monitoring took place under regular traffic loading. Figure 7 shows an AE recording under a heavy freight train with ten wagons (approximate 22 tonnes/axle). The largest emission was recorded by sensors AE3, AE4 and AE5 directly under the middle third of the arch.

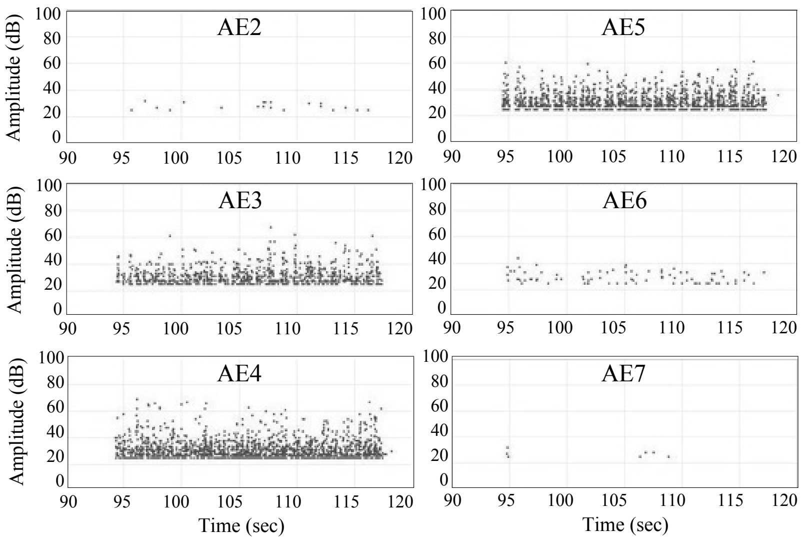

Figure 7 : Traffic loading - Amplitude vs. Time.

By identifying the accumulated absolute energy associated with all AE events according to their locations along the arch, regions with the largest impact can be identified (see Figure 8). Although the train is approaching from the right hand side of the picture, the opposite side of the arch experiences the greatest emission near the crown (around AE4). This is caused by the top left part of the arch being pushed towards the left, against the backfill. On the right hand side, the arch barrel is being moved away from the backfill, hence the smaller emission. Sensors AE2 and AE7 experience very small noise levels and it can be assumed that the traffic loading is only actively 'felt' in the middle third of the arch (by sensors AE3–AE5). This is the area where the arch is showing the greatest amount of damage caused by heavy weight traffic. For the present bridge a train impact depth is less than 1.3 m from the bottom of the string course. This information can be highly useful if the arch section is being considered which is most affected by the traffic and is expected to suffer the greatest deterioration and possible damage.

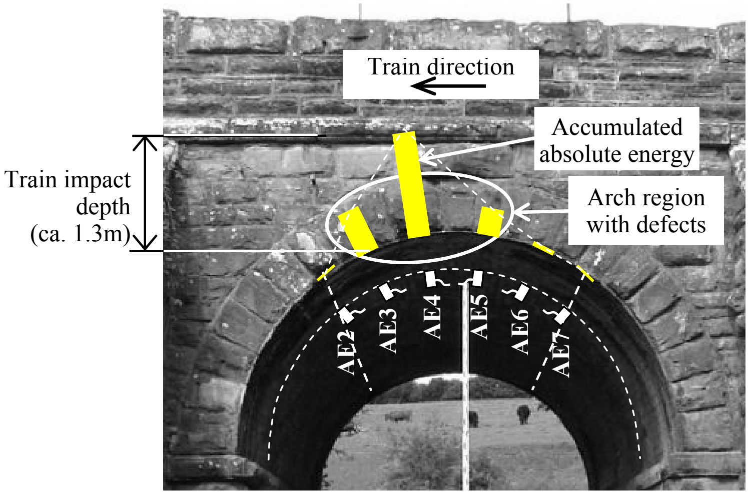

Figure 8 : AE sensor locations, Total absolute energy and damage locations.

6 CONCLUSIONS

The efficacy of acoustic emission monitoring technique was investigated for masonry arch bridges. A series of large-scale laboratory tests and field investigations were carried out. The AE technique has been shown to be able to

- identify damaged regions and potential areas of damage within the structure
- detect damage propagation before it can be seen or measured with other monitoring techniques
- help identify internal crack propagation processes
- warn of ongoing damage occurring to the arch
- help identify the fatigue limit of masonry arches.

By identifying ongoing fracture development and the fatigue limit for the bridge, bridge managers can take action to adjust traffic loads to ensure longer life expectancy of their bridges. AE recordings can also detect crack propagation with potentially sufficient time available to remove critical loads and avoid failure or collapse.

Due to the quick and easy installation process, the technique has shown great potentials as a routine condition assessment and monitoring tool for masonry arch bridges in the field.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of EPSRC, EU Sustainable Bridges project, Network Rail, Cardiff University and the University of Salford in particular Philip Latham.

REFERENCES

BAZANT, Z. PLANAS, J. 1997. *Fracture and size effects in concrete and other quasi-brittle materials.* USA: CRC Press.

LANGE, D.A. JENNINGS, H.M. and SHAH, S.P. 1993. Relationship between fracture surface roughness and fracture behaviour of cement paste and mortar. *Journal of American Ceramic Society* 79, (3), p. 589-597.

MELBOURNE, C. TOMOR, A.K. 2006. Application of Acoustic Emission for Masonry Arches, *Strain - International Journal for Strain Measurement*, 42, p. 165-172.

MELBOURNE, C. TOMOR, A.K. WANG, J. 2004. Cyclic Load Capacity and Endurance Limit of Multi-ring Masonry Arches, *Proc. Arch04 Conference*, Barcelona, Spain, p. 375-384.