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Acoustic Emission From Flexed Concrete Beams Reinforced With Bonded Surface Plates

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Abstract

Acoustic Emission (AE) was studied in stressed structural beams composed of internally reinforced concrete with additional external reinforcement from thin bonded plates. A control beam without a bonded plate was compared to four beams having plates composed of a carbon-fiber composite, glass-fiber composite, aramid-fiber composite, and steel. The dependence of acoustic emission on beam stiffness is described as well as a relation of the number of AE energy peaks to the number of visible cracks in the concrete. The Kaiser Effect was observed in repeated loadings for all tested beams. Attenuation was measured up to a distance of 2.75 m and was not found to be a limitation in acquiring useful data. The change in hit rate and the energy above threshold were closely related to the number of cracks visible at the end of the test. The hit rate consistently decreased as the number of loading cycles increased. The results suggest that an examination of cumulative acoustic emission hits and energy as a function of load can assist in analyzing the cracking behavior, loading history, and stiffness of concrete beams externally reinforced with bonded surface plates.

I. Introduction

Increasing the load bearing capacity of reinforced concrete beams has significant practical applications in structural engineering. Among these are improvements in strength-to-weight ratios and cost efficiencies in new construction, and extending the service life of existing structures. The emergence of high strength adhesives has developed interest in external reinforcement as a complement to the traditional method of using internal steel reinforcing bars. Since the 1960's, studies have examined various techniques such as bonding steel beams to concrete slabs [1] and using fiberglass plates bonded to concrete beams [2]. Recently, Ritchie has tested and compared several thin plate (less than 10mm) materials externally bonded to tensile regions of concrete beams under conditions of four point bending. Increases in stiffness from 17-99% and increases in strength from 40-97% were reported [3]. These beams were simultaneously monitored with acoustic emission equipment and this is the basis of the present study.

II. Experimental Procedure

A. Materials

Acoustic emission monitoring was performed on a series of ten concrete beams reinforced internally with steel bars and externally with an adhesively bonded thin plate. Construction and nominal dimensions of the beams are shown in Figure 1. The concrete was a standard mix with a 19mm maximum aggregate size and 31MPa average compression strength. Internal flexural reinforcement consisted of two #4 (13mm diameter) mild steel bars arranged longitudinally in the tensile side of each beam. Average yield strength of the bars was 414MPa. Internal shear reinforcement was provided by 5mm diameter mild steel deformed bars spaced 10cm apart and mechanically fastened along the length of the #4 bars.

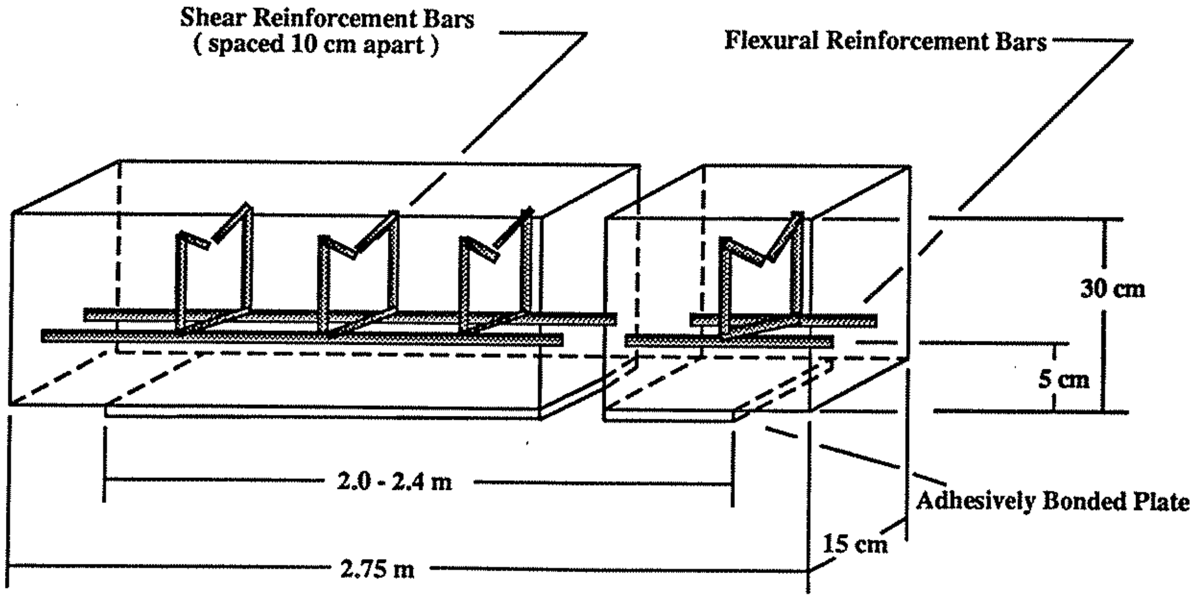


Figure 1. Construction of reinforced concrete beam with adhesively bonded plate.

The thin plates were bonded to the concrete beams with a layer of Lord Fusor 320/322 two art, rubber-toughened epoxy that was approximately 3mm thick. In this preliminary analysis, only five of the beams were selected for comparison from the ten that were monitored. The basis of selection was similar instrument settings and plate thicknesses. The other five were used for establishing instrument settings and sensor placement. A few important properties of the plate materials from the five selected beams are listed in Table 1.

Table 1. Properties of reinforcing plates.

Beam Number	Plate Material	Thickness (mm)	Modulus (Mpa)	Tensile Str. (Mpa)
1	No Plate	---	---	---
2	Glass Fiber Composite	4.8	11,710	161
3	Carbon Fiber Composite	1.3	117,820	1488
4	Steel	2.5	199,810	207
5	Aramid Fiber Composite (Kevlar)	6.4	72,350	1171

The plate in Beam 2 was fabricated from Morrison 0-degree pultruded fiberglass sheet, in Beam 5 from DuPont unidirectional aramid fiber reinforced plastic (Kevlar), in Beam 3 from Hercules 0-deg.(+/-)60-deg. carbon fiber reinforced plastic, and in Beam 4 form ASTM A36 carbon steel.

B. Testing Arrangement

Each test consisted of mounting a beam in a tensile testing machine arranged for four point bending (figure 3). A load was applied to a predetermined level and measurements were taken, then the load was increased to a higher level and measurements were again taken. Upon reaching the maximum desired level the load was decreased to zero. The load-hold-unload cycling was repeated as in Figure 2 until a severe drop in supportable load occurred. Center span deflection of the beam was measured throughout the test.

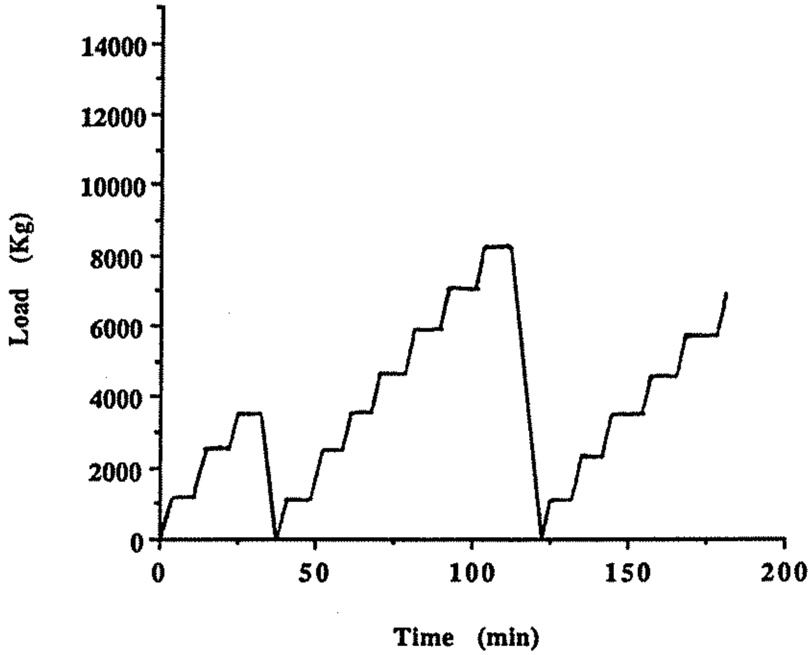


Figure 2. Four point bend test loading pattern.

Four resonant-type piezoelectric transducers with 40 dB integral preamplifiers (Physical Acoustics Corporation R15I) were positioned as in Figure 3. Sensors 1 and 2 were 15 cm on opposite sides of the vertical centerline of a load point in the center of the concrete side face. Sensor 4 was located 30 cm to the right of Sensor 2, near the support. Sensor 3, the only one coupled to the external reinforcing plate, was placed halfway between sensors 2 and 4.

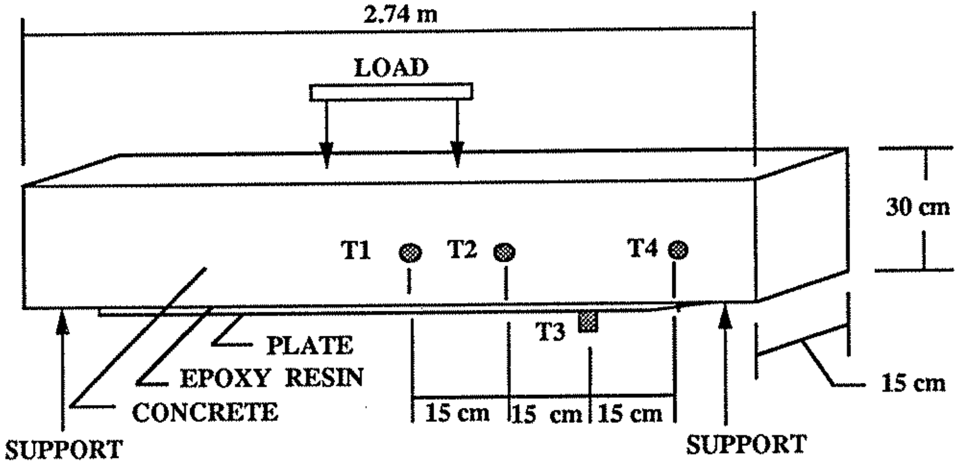


Figure 3. Four point bend test arrangement and transducer positioning.

The four transducers were connected to a Physical Acoustics Corporation Model 3104 Acoustic Emission Analyzer. A parametric input from the load was obtained with a linear voltage differential transformer (LVDT) connected internally to the tensile machine and calibrated to 0.33 mV/Kg. For all tests the load pattern was similar to Figure 2 increasing in steps of 900 Kg. A hold period of 5 to 10 minutes after each load step permitted deflection readings and the marking of visible surface cracks. Upon reaching 3600 Kg the load was decreased to zero. A second cycle immediately followed with similar load steps and holds to a maximum of 7200 Kg before unloading. If needed, additional cycles were performed until the beam ruptured or until there was a severe drop in supportable load. For each of these cycles the maximum load was 3600 Kg higher than the previous one.

The first test monitored was the beam without a plate. The threshold level of the transducer signal was 500 uV, referenced to the sensor. Disk storage became a consideration since the time for an average test was two to four hours and the AE activity was high. The frictional noise at Sensor 4, near the beam support, was excessive. Therefore, insulating pads were added between the beam and supports for subsequent tests. The threshold was increased to 2600 uV, referenced to the sensor, to provide effective noise rejection, reduce the amount of data recorded, and still acquire meaningful acoustic emission signals.

Acoustic emission attenuation in unreinforced concrete has been reported [4] as approximately 100 dB/m although it may be affected by factors such as aggregate size and nonuniformity of mixing. Measurements of attenuation in the reinforced concrete beams of this study were taken from pencil lead breaks at specific distance from the sensor. Figure 5 is a plot of attenuation data from three beams at various gain and threshold settings. The response is logarithmic with the peak amplitude dropping from 100 dB at the sensor to 60 dB at one meter and to approximately 47 dB at two meters.

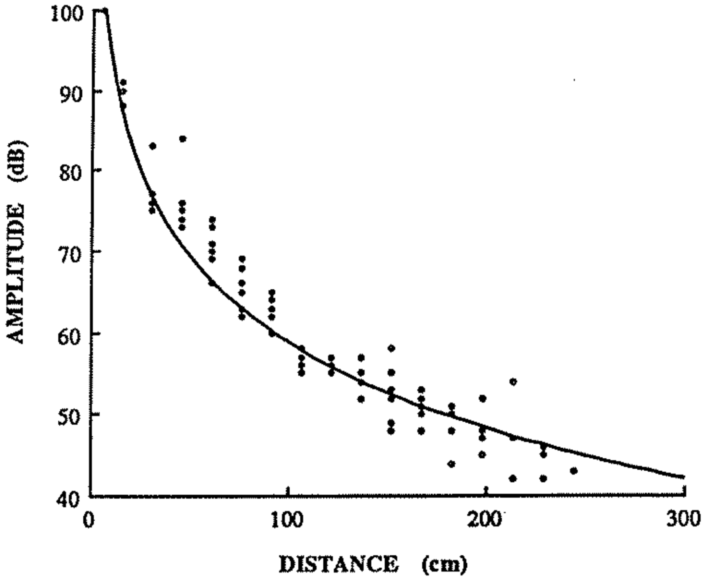


Figure 4. Acoustic emission attenuation in reinforced concrete.

Table 2 lists distances beyond which no AE hits were recorded from pencil breaks at various gain and threshold settings. This information was used to adjust instrument settings for the four-point bend tests.

Table 2. Limits of AE detection at various gains and thresholds.

Gain (dB)	Threshold (Volts)	Distance (cm)
60	0.5	137
60	3.0	71
70	0.5	198
70	3.0	102
80	0.5	234
80	3.0	163

III. Results and Discussion

Table 3 lists increases in stiffness, as reported by Ritchie [3], which resulted from bonding an external plate to the concrete beam. The significance of this data can be appreciated by realizing that bonding a 1.3 mm thick aramid fiber composite plate to a 30 cm thick concrete beam increases the stiffness almost 100%.

Table 3. Percent increase in beam stiffness resulting from plate reinforcement.

Beam No.	Plate Material	% Increase
1	Control Beam (No Plate)	0
2	Glass Fiber Composite	22.1
3	Carbon Fiber Composite	34.8
4	Steel	76.6
5	Aramid Fiber Composite	98.8

Figure 5 plots load versus centerline beam deflection for the five beams being discussed. Figure 6 is similar to Figure 5 except that the cumulative AE hits from all sensors are plotted versus load rather than deflection. Although the plots do not correlate directly, it can be seen that, in general, the cumulative AE hits increase with decreasing stiffness. This is reasonable since lower stiffness results in greater deflection which causes more concrete damage. Results are similar to a previous study by Ohtsu [5] in which the AE count rate was observed to increase for a bonded surface plate.

A second observation, Table 4; is that the percentage of total first arrival AE hits increases at sensor 3 on the plate with increasing stiffness. This does not imply that AE activity is shifting from the concrete to the plate as the stiffness increases. It does, however, demonstrate that the AE activity shifts from the beam center (region detected by sensor 2) to the lower beam-plate area (region detected by sensor 3) as the stiffness increases. The data of Figure 6 can be considered a function of composite modulus since there was no evidence of adhesive debonding and the yield strength of the plate material was not exceeded. It should also be noted that these assumptions are based on one test per beam-plate system and that plate thicknesses and threshold levels varied. Under similar conditions and with additional tests the trends may have been more distinct.

Table 4. Cumulative AE Hits from Sensors on Plate & Beam at 8,000 kg Load.

	Sensor 2 on Beam	Sensor 3 on Plate	Total (2 + 3) Hits	Percent Hits Beam	Percent Hits Plate
Concrete	3500	---	3500	100.0	----
Glass Fiber Composite	6000	500	6500	92.3	7.7
Carbon Fiber Composite	4000	700	4700	85.1	14.9
Steel	1200	600	1800	66.7	33.3
Aramid Fiber Composite	1000	1700	2700	37.0	63.0

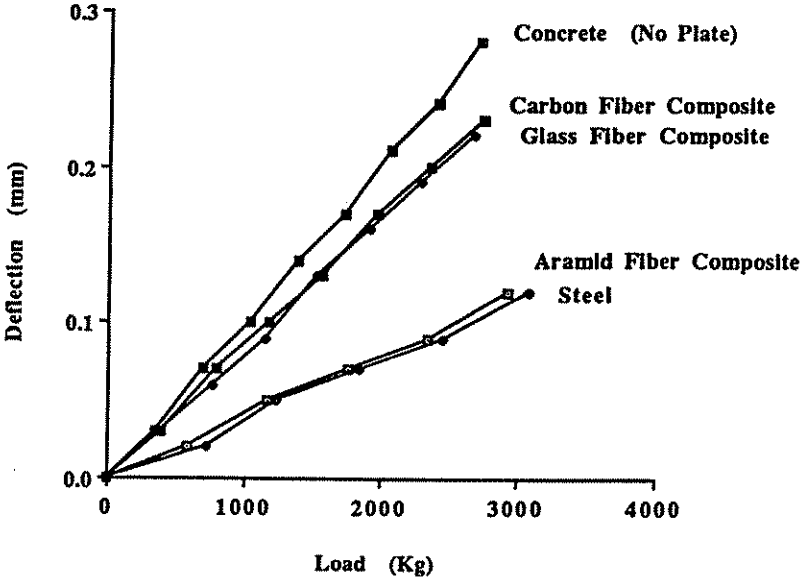


Figure 5. Deflection at centerspan of beam versus load.

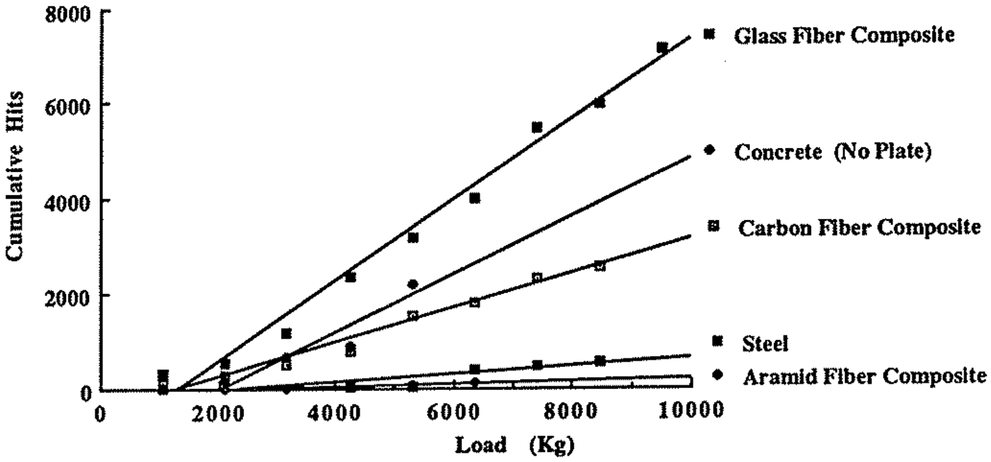


Figure 6. Cumulative acoustic emission from beam versus load.

The Kaiser Effect has been observed in concrete and discussed in the literature [6,7]. It is defined as the absence of detectable acoustic emission until the previous maximum applied stress has been exceeded. Figure 7 shows evidence of this phenomenon for the beam with a carbon fiber composite bonded plate. It was also seen in all of the other beams including the control beam which had no external plate. At higher loads with large visible cracks there was some acoustic emission attributed to reclosure of cracks and aggregate friction during unloading.

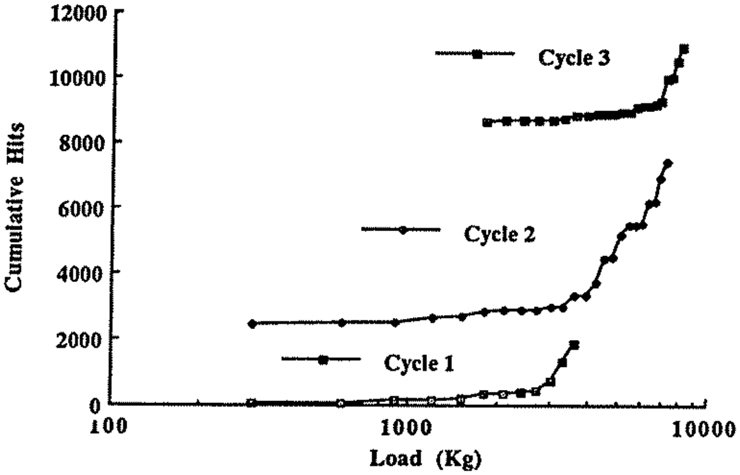


Figure 7. Kaiser Effect in Beam #3.

The data of Figure 7 were normalized by resetting the cumulative hits to zero at the beginning of each load cycle. The results are shown in Figure 8. It can be seen that the hit rate decreases as the number of cycles increase. The interpretation was not that most of the damage occurred during the first cycle. Instead, it is thought that once cracks are present form a previous loading cycle it requires much higher loads to generate an equivalent amount of damage in the beam. As an example, during the first cycle of this test, a load of approximately 3800 Kg generated 2000 AE hits. During the second and third cycles, 2000 hits requires 5100 Kg and 6500 Kg, respectively.

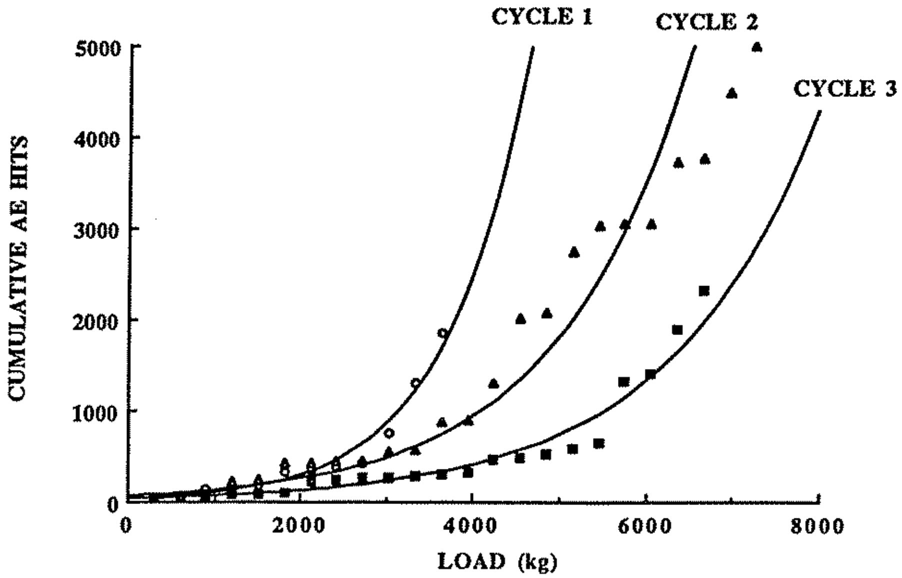


Figure 8. Acoustic emission as function of load and cycle from Beam #3.

Greater detail of cumulative hits versus load behavior for the carbon fiber composite/concrete beam is revealed in Figures 9 (a), (b), and (c) for cycles 1, 2, and 3, respectively. Abrupt changes in AE hit rate or kinks in the line graphs are sequentially numbered beginning at cycle 1. These kinks represent abrupt changes in AE activity. For this beam there were 15 visible cracks at the end of the test and 15 total kinks in the graphs of the three cycles. An assumption that can be made from this plot is that more damage has been caused by the second cycle than the other two cycles.

An important AE parameter in the present study was found to be energy. Defined as the measured area under the rectified signal envelope (MARSE), this parameter, provided by the PAC 3104 system, gave clear indications of major cracking in the beams. The average energy was defined as the sum of the energy magnitudes divided by the total number of hits. Just prior to the formation of a new surface crack an energy peak substantially greater than average was recorded.

Figure 10 illustrates energy versus hits for each of the five beams. An arbitrary threshold of three times the average energy is also shown as a dotted line on each plot. If the energy peaks (dots) above this threshold are counted they closely correspond to the number of visible cracks at the end of the test as listed in Table 5.

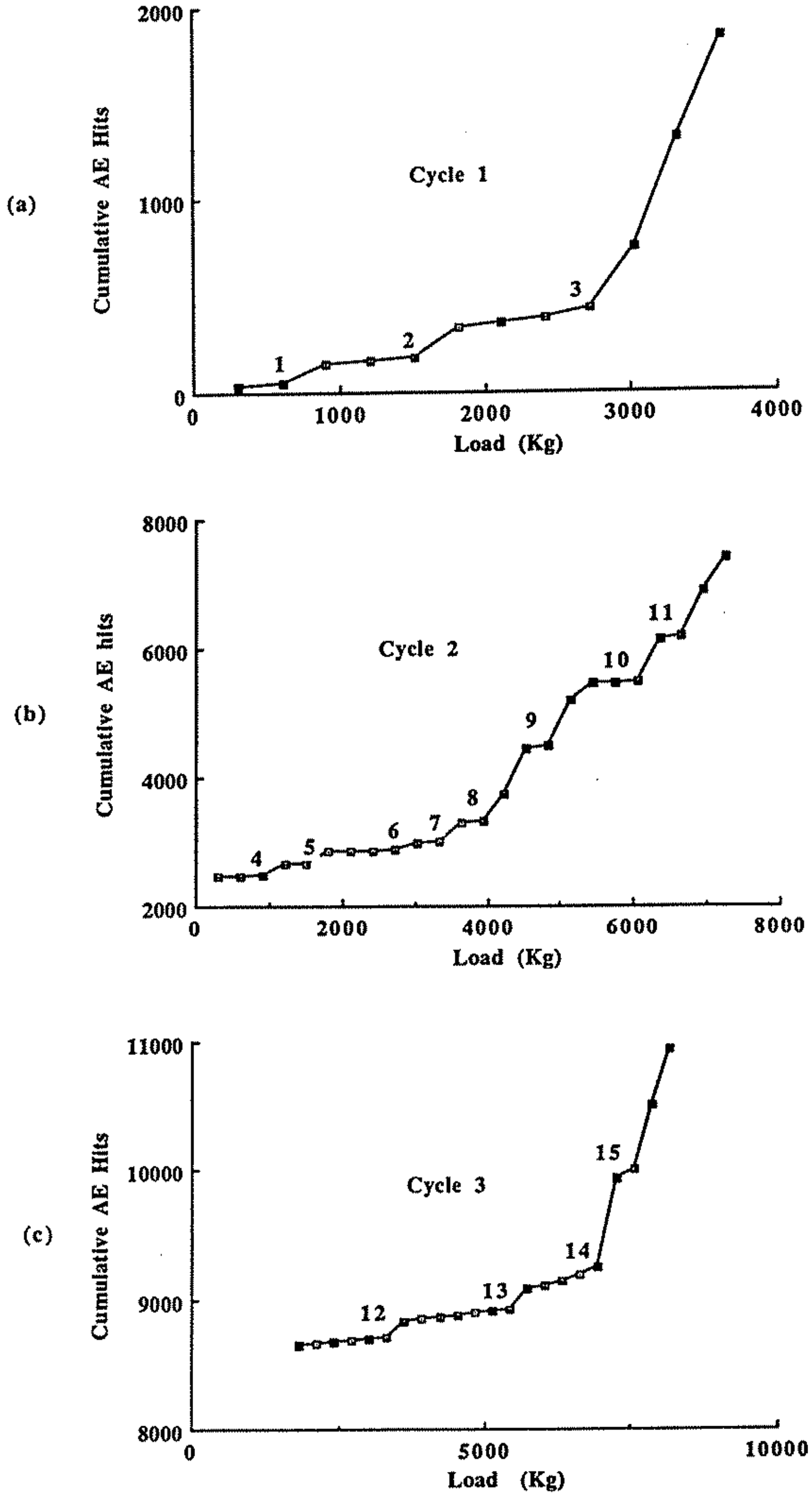
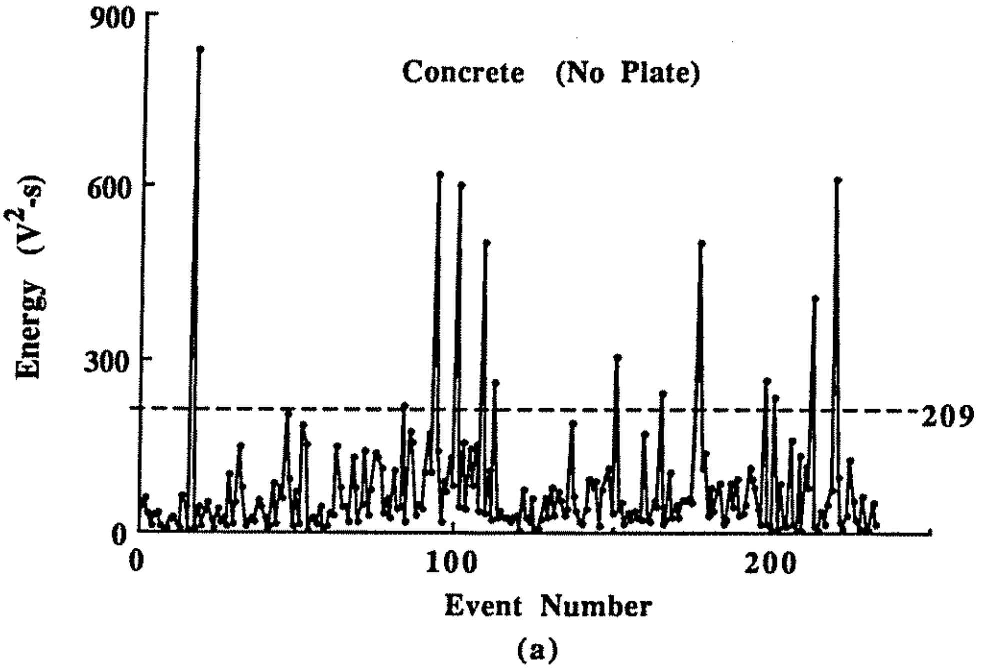


Figure 9. Major cracks identified in Beam #3 by abrupt changes in AE hit rate.



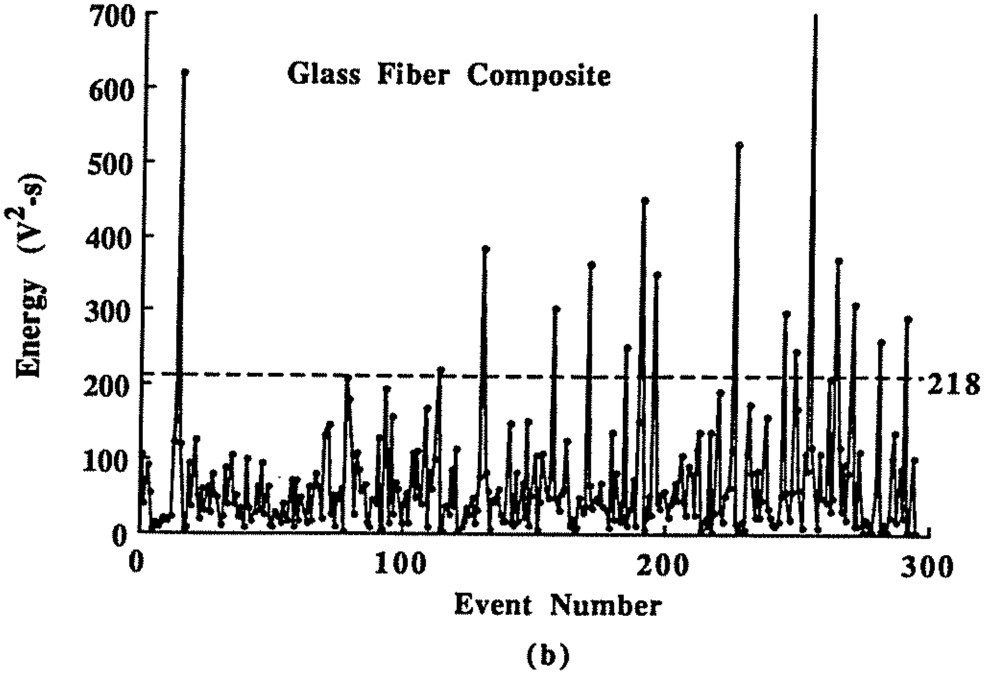
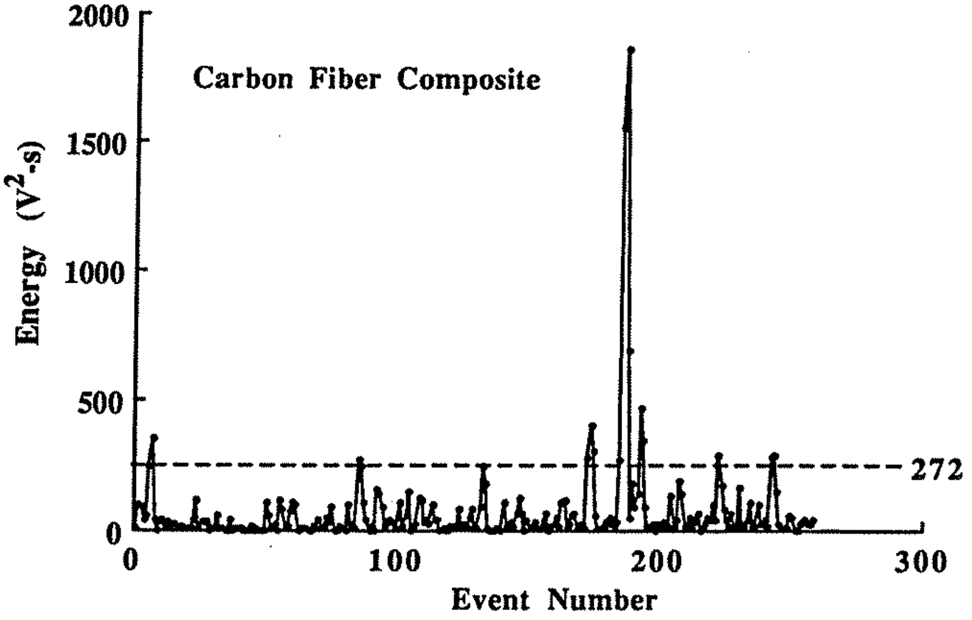
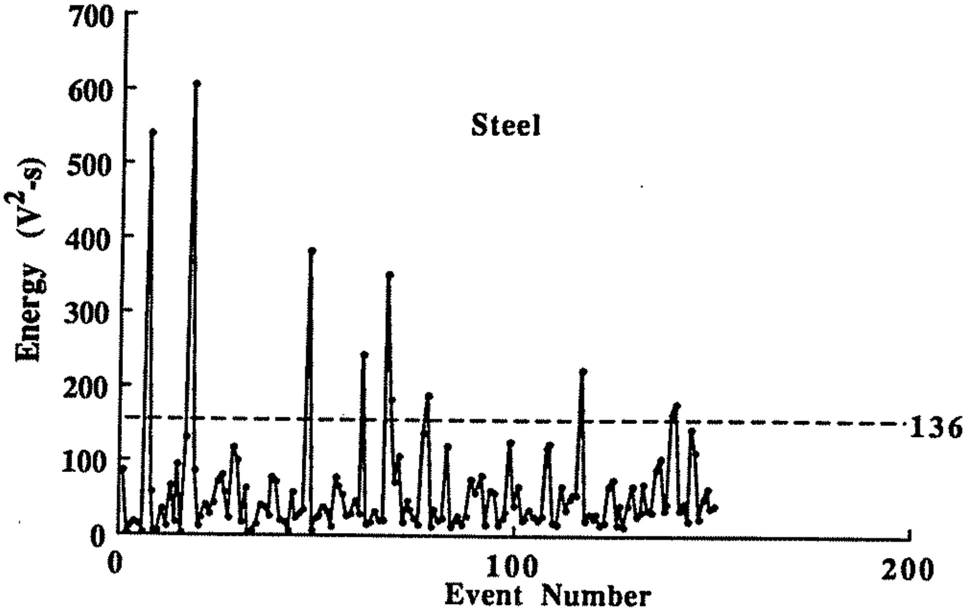


Figure 10. Major cracks identified by AE energy magnitudes in a) Beam #1, b) Beam #2.



(c)



(d)

Figure 10 (Continued). (c) Beam #3, (d) Beam #4.

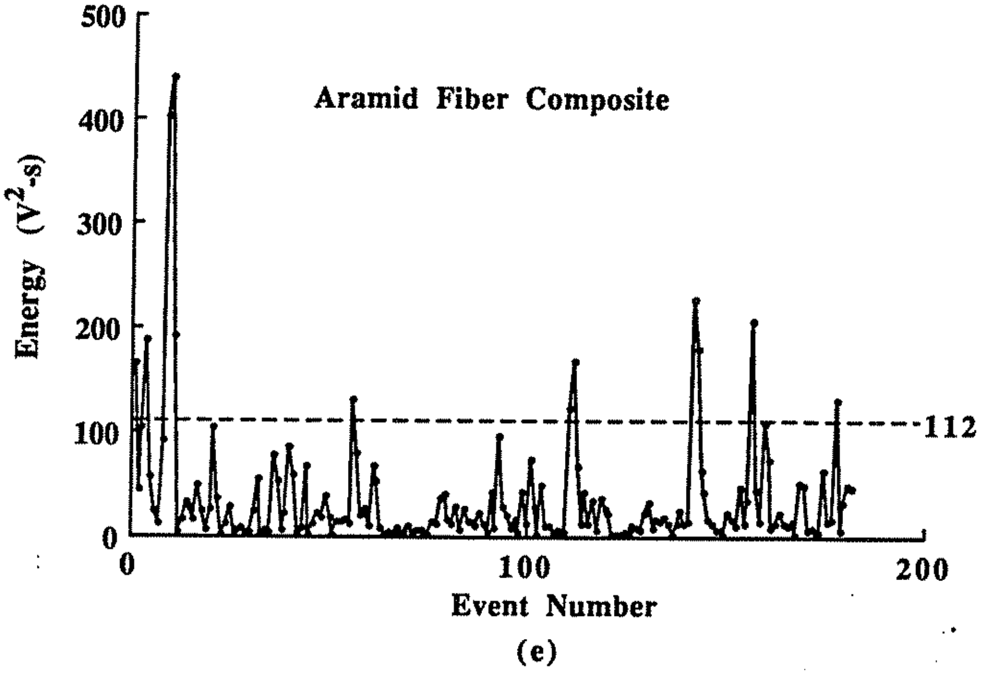


Figure 10 (Continued). (e) Beam #5.

Table 5. Hits above energy threshold as an indication of cracking.

	Number of Cracks	Number of Hits	Average Energy ($Volts^2$-sec)
Concrete/ No Plate	11	14	69.6
Glass Fiber Composite	18	18	72.9
Carbon Fiber Composite	15	16	90.6
Steel	14	12	45.4
Aramid Fiber Composite	13	13	37.4

Other acoustic emission parameters were analyzed for patterns that may have helped to characterize the beams' behavior. In particular energy-related data such as rise time, duration, and average amplitude were plotted and studied. No trends were recognized that could be related to the beams' loading responses.

The methods above demonstrate that with a minimal number of specimens, practical information about the fracture behavior, previous loading history, stiffness, and acoustic attenuation of concrete beams may be derived using acoustic emission analysis.

Conclusions

Acoustic emission is a useful nondestructive technique for monitoring behavior in concrete structural beams externally reinforced with thin bonded plates. The techniques described above demonstrate that with only few specimens, practical information may be acquired. In particular, an examination of cumulative acoustic emission hits and energy as functions of load can assist in analyzing the cracking behavior, previous loading history, and composite stiffness of the beams.

The stiffness of the beam-plate system had a pronounced effect on the AE signals. Systems having less deflection for a given load had lower average energies, less cumulative hits, and a greater percentage of first arrival hits located near, or in, the plates. The Kaiser Effect was observed in all the tests. The number of major cracks visible at the end of the test were closely predicted by counting energy peaks above a predetermined threshold and abrupt changes in hit rate.

Attenuation presented no problem since gain and threshold levels could be adjusted to detect signals from lead pencil breaks at a distance of more than two meters. Distinctions could not be made between the signals generated in the reinforcing plates and those generated in the concrete beams.

Acknowledgements

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