Monitoring Real-time Fracture within Reinforced Concrete under the Load Test Using Acoustic Emission Recording Technique

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ABSTRACT

Pre-stressed reinforced concrete (PRC) containment with post-tension system design is mostly used for nuclear power plant with pressurized water reactor system (PWR) to prevent concrete fracture due to the inside peak pressure. The post-tension system results in a distributive pressured state within the concrete of the entire containment wall; however, some parts of this system like the anchor trumplates and bearing plates may cause noticeable concentration load in the concrete. Fracture damage may occur there. Since most concrete non-destructive testing techniques (NDT) may be limited to inspect that area, to evaluate the integrity can be difficult.

Reinforced concrete (RC) is known as a composite material. Stress waves or ultrasonic waves emitted by defect formation or material failure within RC can be complicated in characters, but can be useful in tracing the fracture during the loading process. It is noted that the post-tension system has to be checked during the scheduled in-servers-inspection (ISI); loosing and reloading the sampled tendons are part of the ISI process. Therefore, the emitted acoustic during the ISI for tendon may be useful to evaluate the concrete integrality under the anchorage. This research provides an initial study and experiment combining RC load test and Acoustic Emission (AE) technique to evaluate the above assumption. The AE technique using a self-developed instrument (for RC) is applied to record/monitor the emitted ultrasonic wave in RC slab specimens during load test. The obtained hit-count history profiles (vs. time or load) revealed many significant characteristics or phenomenon, such as the Kaiser effect (or the crack incubation) and the crack-control mechanism of re-bars, etc.

INTRODUCTION

Pre-stressed reinforced concrete (PRC) containment with post-tension system design is mostly used for nuclear power plant with PWR system to prevent concrete fracture due to the inside peak pressure — the consequences of postulated breaks of high-energy reactor coolant pressure boundary piping (the LOCA). The post-tension system (or the tendon system) results in a distributive pressured state within the concrete of the entire containment wall; however, some parts of this system like the anchor trumplates and bearing plates may cause noticeable concentration load in the concrete. Plastic or fracture situation may occur under the anchorage. Since most concrete NDT techniques may be limited to inspect the zone near the embedded part of anchorage and the re-bars mat under the trumplate, to evaluate the possible fracture can be difficult.

The post-tension system usually has to be checked during a routine ISI; loosing, measuring and re-tensioning the sampled tendons are part of the program. Since the defect formation and material failure in concrete may cause stress waves (or ultrasonic waves) emitting, the fracture under the anchorage plate may be identified when the loading on the sampled tendon is changed. Based on this assumption, an inspection procedure combining Acoustic Emission (AE) technique and traditional load test was considered in this research. However, since an in-site inspection to a real anchorage has not been available, this paper is addressed in a preliminary experiment and study including specimen testing and data analysis.

Acoustic Emission testing was a known technique to monitor the fracture behavior of material for more than three decades. Not like the stress wave in Ultrasonic testing (UT) or Impact Echo examination, the emission wave/pulse is not created by the transducer but energy release due to fracture or plastic yielding of material itself. This “passive” method has been used commonly in fatigue test under laboratory environment; also been applied in field monitoring for the steam pipes and pressure vessels of nuclear power plant. Current researches led the application to composite materials, such as reinforced concrete (RC) or fiber-reinforced polymer (FRP).

Reinforced concrete is known as a composite material containing aggregates, cement paste and re-bars. Therefore, the acoustic waves emitted by defect formation or material failure can be more complicated, as well as their propagation through the concrete medium. Plain concrete (PC) without re-bars is a brittle composite. Stress concentration may occur near the pore or pre-crack within the cement gels (weak portion) when the structure is on loading. Previous experiments [1,2] for PC showed that significant increasing of emission signals typically occurred after the loading stress was higher than 80% of ultimate stress (f_c’). In other word, changing load on PC with good integrity cannot create acoustic emission, but on the contrary for the PC with initial cracks. Moreover, few previous works [1, 3] hinted at that the Kaiser effect could be indicated for RC structure. The tensile cracking, splitting or rebar de-bounding (the “events”) within the RC structure/specimen under loading are all irreversible processes, and their appearances distribute more "scattered" along the loading stage. Therefore, AE measurement can be appropriate to figure out the previous maximum load and to evaluate the integrity of RC structure.

EXPERIMENTAL PROGRAM

In this research, AE technique using a NI-based instrument was to record and monitor the emitted ultrasonic wave in RC-slab specimens during load tests. The tests were applied on three different 2m×2m reinforced concrete slabs with a concentrated force near the center. After loading, loosing, reloading and breaking processes applied on these slabs, the result AE record, count hit rate histories, signal types and the load test reading can be obtained and used to describe the fracture development and real-time situation in the slabs.

AE Instrumentation

In this research, a self-developed AE system using a data acquisition (DAQ) components and a real-time program (LabView7-) was assembled for inspection. This system is able to continually record (4 digital channel / 800 kHz /16bits) emissions over the entire load test (up to 4 hours). The obtained binary data can be displayed and counted for later analysis.

Because of the high ultrasonic decay rate in concrete, emission wave can be damped or distorted during its propagation to the sensor. To get a better signal reading, more sensors (with higher / wider band) and DAQ facilities are required. However, reasonable sensor distribution and frequency band have to be considered for practical usage and cost. It is known that the initial fracture of re-bar cause higher frequency emission than the breakage of gravel or concrete for its high strength. But the frequency may be too high for the wave spreading in concrete. Concrete fracture usually occurs at its weakness; most cracks extend along the sand-cement mortar surrounding the gravels. Moreover, de-bound and rub between re-bar and nearby gravel also creates emission with lower frequency. In this research, the sensor with 40db Integral Preamp function and 500 kHz spectral response range (150 kHz Max.) was used. Emissions with frequencies in 10k to140 kHz were mainly concerned.

Design of reinforced concrete slab

Mixture Design

Two compressive strengths of 27.4 MPa (4000psi) and 41.2 MPa (6000 psi) were designed for those slabs made with normal aggregate concrete, as referred to normal strength concrete (NC) and high strength concrete (HC) in the mix designs in Table 1. They were fabricated and wet-cured for 28 days in a pre-cast factory until one day before testing.

Table 1 Mixture of concrete

Mix I.D.	NC	HC
W/C	0.42	0.35
Cement, kg/m^3	425	316
Water, kg/m^3	180	155
Aggregate, kg/m^3	976	1030
Sand, kg/m^3	734	748
Slag, kg/m^3	-	136
Super-plasticizer, kg/m^3	-	4.0

Specimen Preparation

In this research, concentrated load tests on simply-supported square RC slabs were investigated. Both Mixtures, NC and HC, were adopted to built the slabs. The slab dimension is 2m×2m (1.75m in span) with two thicknesses of 100mm and 125mm. The slabs reinforcement design places the re-bars at a 95 mm spacing in orthogonal directions in one layer, as shown in Fig. 1. The 10 mm bar was selected and a clear cover to the outer bars was 20 mm. Three slabs were selected and tested in this research. Each slab was identified according to its design, which could be described by the symbols, such as NC stands for normal concrete, H and M stand for high strength and medium strength, S stands for one layer reinforcement.

For example, a high strength lightweight concrete slab with one-layer reinforcement and 100 mm thick, can be represented by HNC-S95-T100.

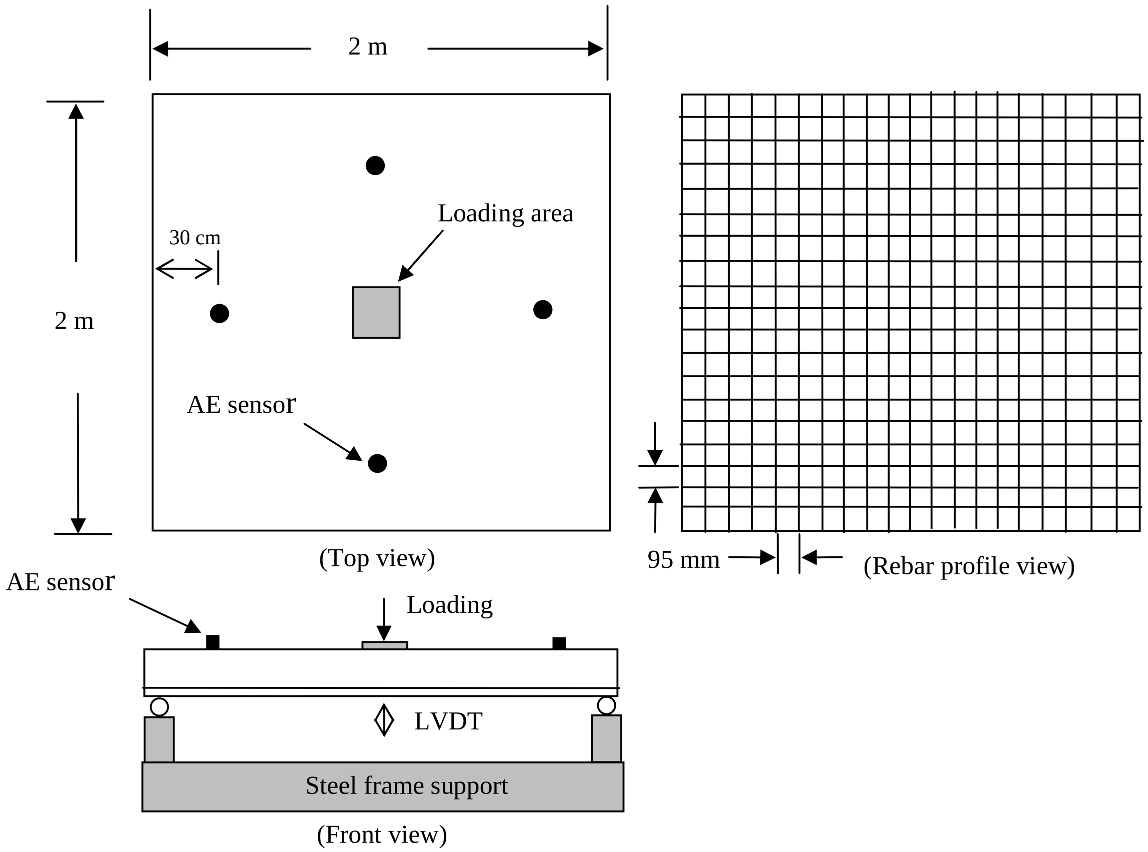

Fig. 1 A schematic profile of load test of RC slab and AE sensor locations

Concentrated Load Test

Load test was conducted in a configuration as shown in Fig. 1 that the slab is placed on a steel frame as a reaction support that contains four steel rollers located along the center line of the top girders of the frame. An actuator of a closed-loop servo-hydraulic testing system (MTS) is then located on the center of the slab as a concentrated load. A rubber pat of 250mm × 250mm × 25mm was placed between the actuator and the concrete slab to transfer the force smoothly. In addition, a reference bar is attached below the slab and across the middle of two top girders in order to measure vertical deflection while the slab was being loaded. A LVDT are amounted at middle of the reference bar. Strain gages were also attached on the top surface of the concrete slab to monitoring the stress while the load was being applied.

Additionally, four AE sensors which can simultaneously monitor and acquire the data as load test being conducted were placed on four locations at a distance of 300 mm from the middle of the edges**.** The reason to place the sensors on the top (instead of bottom) of the slab is because of that the load test will induce cracks on the bottom face that can interrupt the wave transfer in concrete.

CASE DISCUSSIONS OF AE MONITORING ON CONCRETE SLABS

This paper presents three AE monitoring cases using different RC slabs design. Slab *HNC-S95-T125* ($2 \times 2 \times 0.125\text{m}$) in Case A was made of high-strength concrete with normal aggregates (*HNC*) and reinforced with a single layer of re-bar mat (in space of 95mm, *S95*). We should note that the thickness of the first slab (0.125m) is different from the others. In Case B, Slab *HNC-S95-T100* ($2 \times 2 \times 0.1\text{m}$) was used. The Case C Slab, *MNC-S95-T100* ($2 \times 2 \times 0.1\text{m}$), was built with the same design as Case B, but was made of medium-strength concrete.

Case A: (2m $\times$ 2m $\times$ 0.125m slab with high strength concrete and spacing at 95mm)

In this case, the load test lasted 1659 seconds with an ultimate record about 205kN. The maximum deformation of the slab was 53mm; deformation due to re-bar yielding (22 to 53mm) occurred when the load was increased from 190kN to 205kN. The histories of loading and deformation record are shown in Figs. 2 and 3. It can be observed that an unload-reload event occurred when the loading is near 190kN (1186.6sec.). The load was quickly released to 70kN and then re-loaded to the ultimate value.

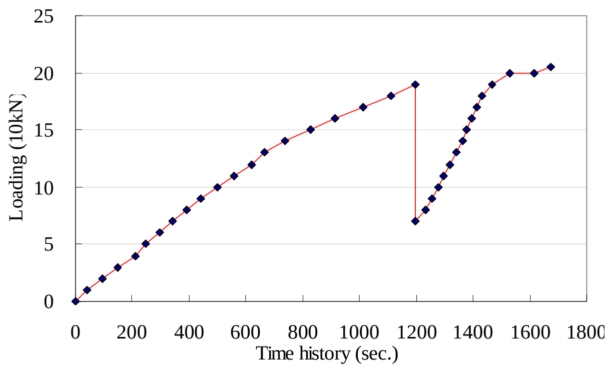

Fig.2 Loading history in Slab *HNC-S95-T125*

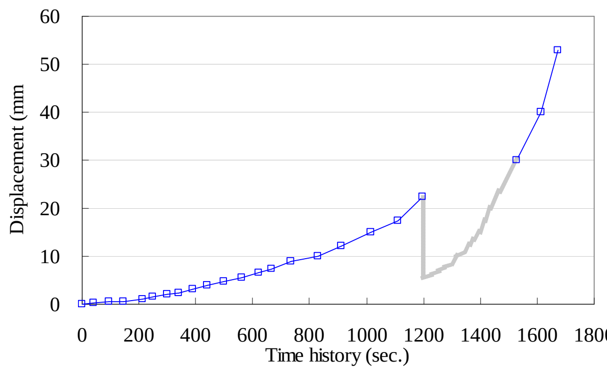

Fig.3 Displacement history in Slab *HNC-S95-T125*

In this case, the AE record included all the load test period. The first obvious AE signals occurred when the loading reached 30kN; then noticeably increasing of emission signals occurred after the loading was higher than 40kN. When the unloading occurred (190kN), a group of emission signals were shown and followed by the crack-incubation stage (during reloading). In this stage, rare signals had been detected until the load was back to 120kN. But the major increasing of AE signals began after the load was over 175kN. The emission silence during the reloading can be referred to the Kaiser effect.

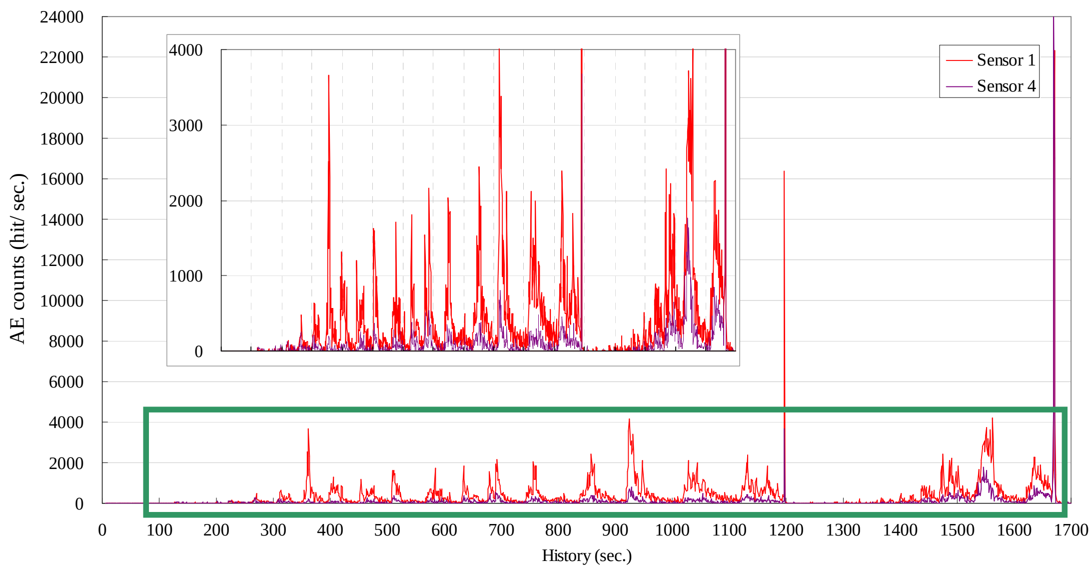

Fig.4 History of AE hit rate (per second) over the load test in Slab *HNC-S95-T125*

The AE real-time record can be counted and shown by diagrams. Fig.4 shows the history of AE hit rate over the load test; Fig.5 presents the AE hit rate per 10kN load during the load test. The lines plotted in both figures are for the different sensors. In Fig.4, the final rupture cause extremely high emission hit counts. The Kaiser effect appeared within the 1186 to 1400 sec. period, as well as the 70 to 175kN range. It can be observed that the lasted curves of the hits/second rate perform in an "intermittent" distribution (Fig.4). This phenomenon could be related to the crack-control mechanism by the re-bar mat. In RC slab element, the embedded re-bar mat restrains the crack during the loading. After the crack initiation, its extension will be hold back by the re-bar. The re-bars are then elongated and the extensional stresses in slab will be re-distributed. If the load is increased, the re-bars get longer and the cracks open. The subsequent fractures or new cracks will occur with AE. The "intermittent distribution" presents the regularity of the fracture process within the slab.

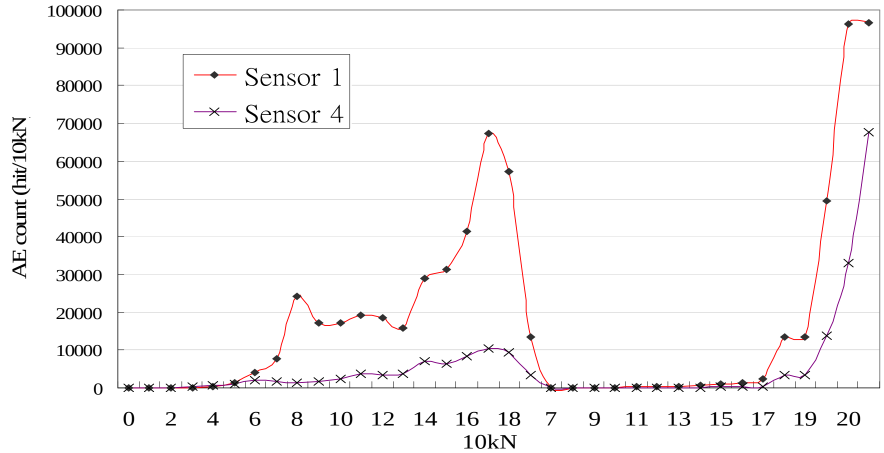

Fig.5 AE hit rate per 10kN load Slab *HNC-S95-T125*

Case B: (2m × 2m × 0.10m slab with high strength concrete and spacing at 95mm)

The test lasted 742 seconds with an ultimate load about 173kN and a maximum deformation near 61 mm. Deformation due to re-bar yielding (44 to 61 mm) occurred when the load was up to 170kN. The histories of loading and deformation are shown in Fig.6 and 7. In the AE inspection, noticeably increasing of emission signals occurred after the loading higher than 20kN. Fig.8 shows the history of AE hit rate (per second) over the load test; Fig.9 presents AE hit rate per every 10kN load in the load history. Fig.8 shows that the final rupture does not cause the AE signal counts like that in case A. But the "intermittent" performance of the hits/second rate curves reveals that the crack-control mechanism was regular and functional during the loading. Since crack extension in slab was well controlled, no big rupture appeared to cause a sudden failure in the slab. Referring to Fig.8, we found that the AE hit rate became irregular after 625 sec. The final collapse might begin at that time due to the yielding in re-bars. At the same time, the loading was 170kN and was close to the ultimate. We also note that the material property of this slab seems to be more elastic than the slab in case A.

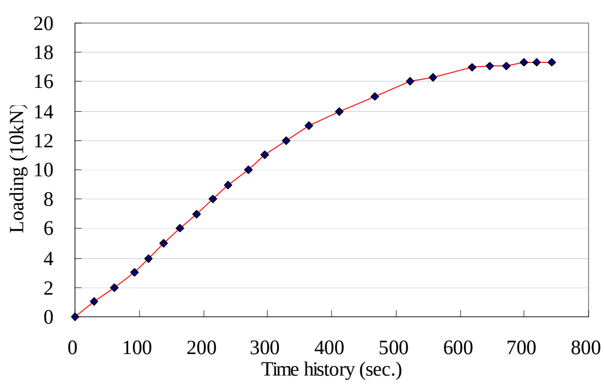

Fig.6 Loading history in Slab *HNC-S95-T100*

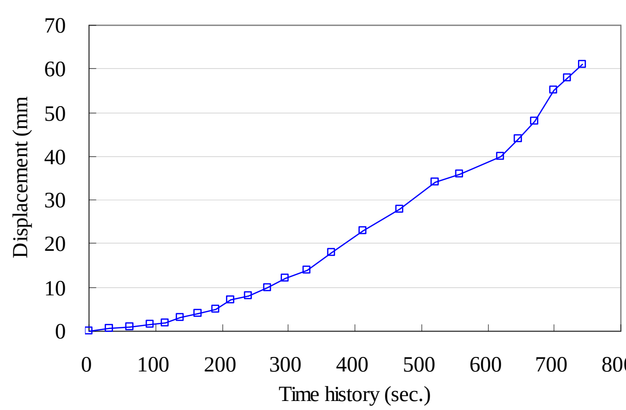

Fig.7 Displacement history in Slab *HNC-S95-T100*

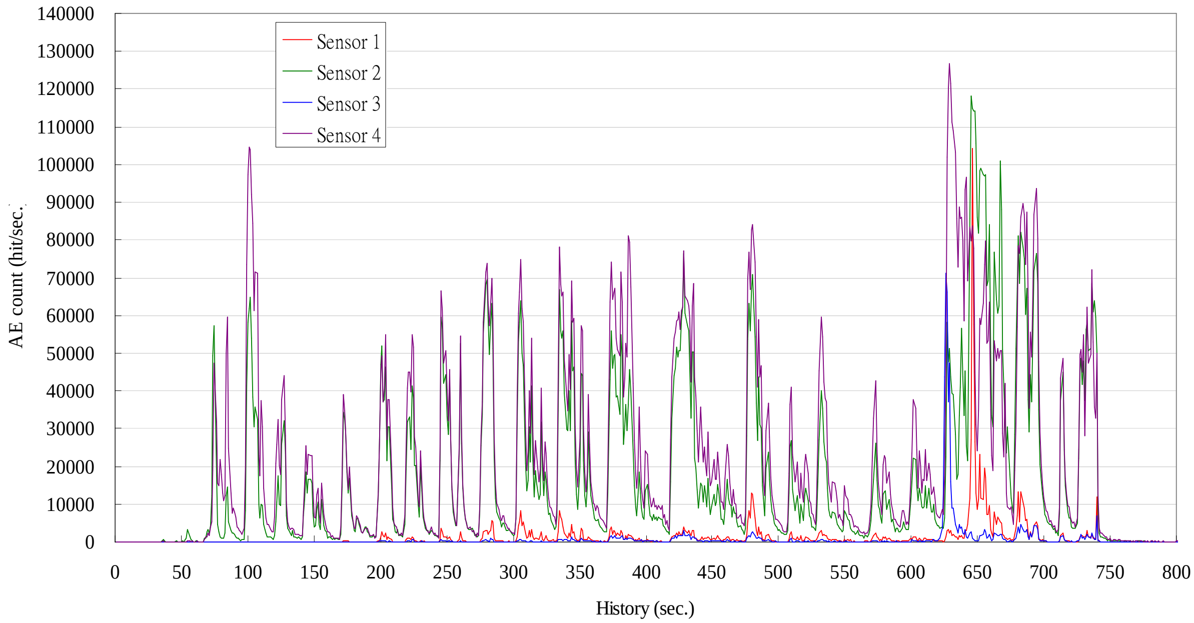

Fig.8 History of AE hit rate (per second) over the load test in Slab *HNC-S95-T100*

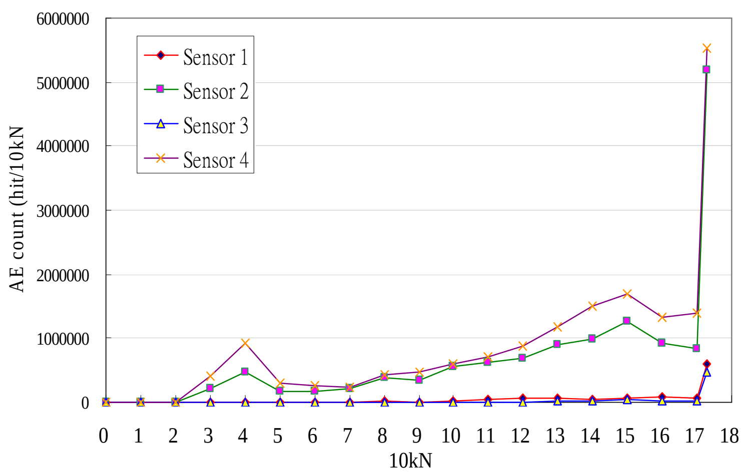

Fig.9 AE hit rate per 10kN load in Slab *HNC-S95-T100*

Case C : (2 m× 2 m× 0.10m slab with medium strength concrete and spacing at 95mm)

In this case, the load test lasted 539 seconds with an ultimate record about 140kN. The maximum deformation was 34mm. The histories of loading and deformation are shown in Fig.10 and 11. In this test, deformation due to re-bar yielding was uncertain. Noticeably increasing of AE signals occurred after the loading was higher than 30kN.

Fig.12 shows the history of AE hit rate (per second) over the load test; Fig.13 is for the AE hit rate per every 10kN load in the load history. Due to manually slowdown of loading at 275 to 325 sec., AE signals almost disappear. In Fig.12, final rupture causes extremely high emission hit counts like the case A; no "intermittent" appeared. We also note that some high emission reading was obtained by the sensor 4 during 125~175second. It seems that a major crack or damage happened earlier (20kN to 50kN).

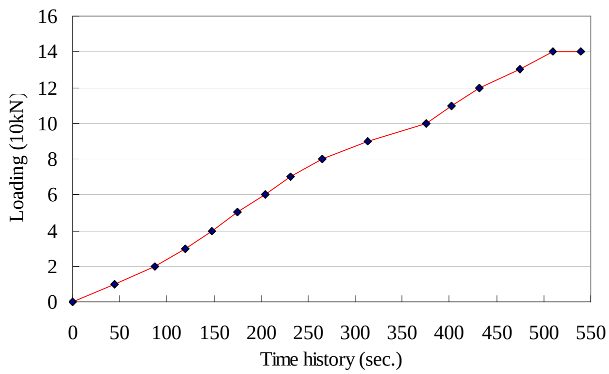

Fig.10 Loading history in Slab *MNC-S95-T100*

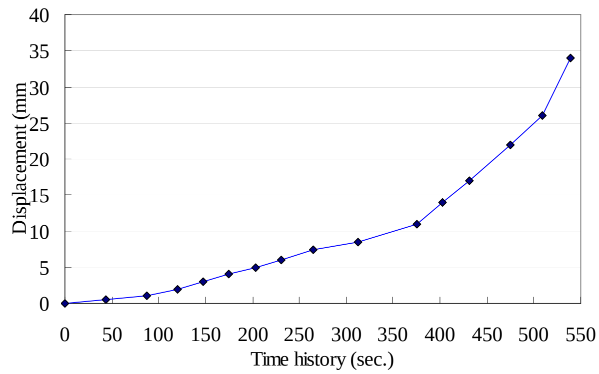

Fig.11 Displacement history in Slab *MNC-S95-T100*

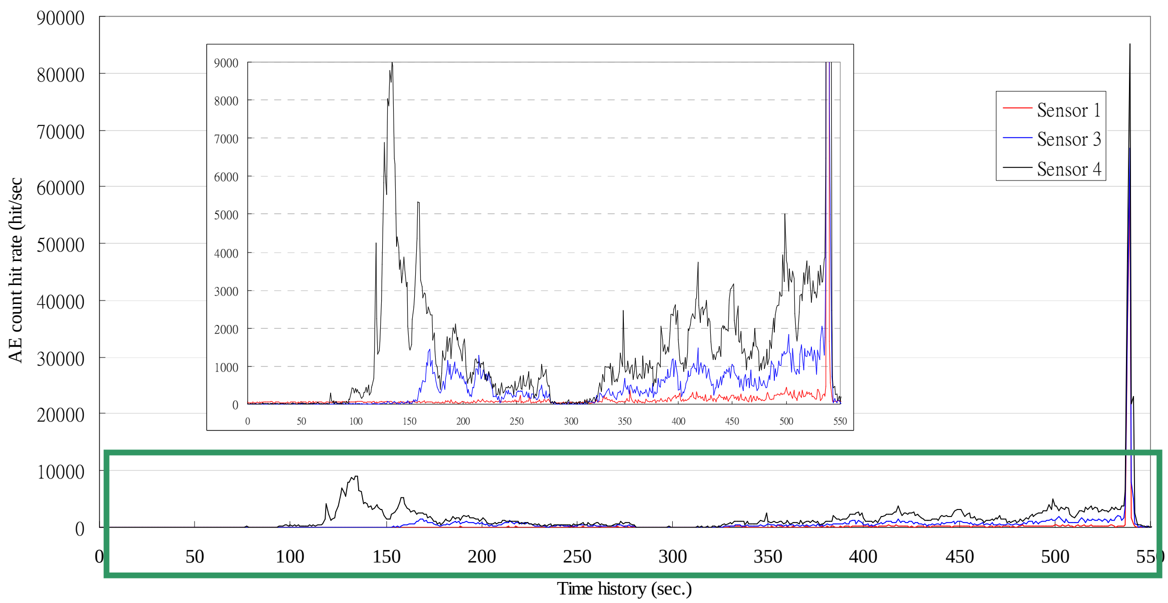

Fig.12 History of AE hit rate (per second) over the load test in Slab *MNC-S95-T100*

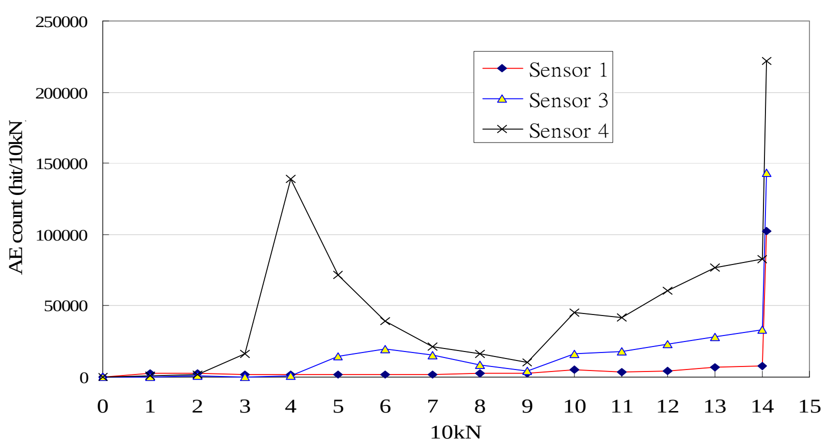

Fig.13 AE hit rate per 10kN load in Slab *MNC-S95-T100*

CONCLUSIONS

The acoustic emission signals obtained from the load tests of RC slabs revealed many significant characteristics. It was detected the difference in fracture processes for the high strength concrete slabs and the normal one. Because of better homogeneous in high strength concrete, the aggregates might be split apart during the loading process (not only the sand-cement mortar). Signal hit rate record with a clear serial intermittent can be obtained due to the functional crack-control mechanism. We also note that the hit rate record became irregular for the normal slab. The material inconsistency may disturb the crack-control mechanism, as well as the stress re-distribution. In addition, Kaiser's effect was apparently found in this experiment and the previous loading could be evaluated.

In this research, results form AE inspection present excellent details to describe the fracture behavior in load test. Using this combinational technique to checking the integrity of the concrete under the tendon system can be possible. However, more experiments and AE databases to the different structure elements will be required for further application and confirmation. Mockup test to the tendon system can be considered as a future work.

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