Influence of UHPC laminate application type on fracture behavior of reinforced concrete beams strengthened in flexure

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ABSTRACT: Ultra High Performance Concrete (UHPC) is a cement-based composite which attracts the researchers' interest due to its superior mechanical and durability properties. It has high strength and energy absorption capacity under bending loads. Because of these properties, UHPC has also been involved in strengthening procedures.

Acoustic emission (AE) is one of developed nondestructive testing methods giving integrated information about active fractures. It is also proper to utilize AE for identifying failure mechanisms of UHPC. In this study, influence of application type of UHPC laminate on fracture behavior of reinforced concrete (RC) beams under flexure was investigated. For this purpose, three RC beams were produced and two of them were strengthened with UHPC laminates. While UHPC laminate of one of strengthened beams was attached with epoxy, the other was anchored. The beams were tested under four-point-bending and simultaneously monitored with AE. Both mechanical and AE results show that fracture behaviors change with application type.

Keywords: ultra high performance concrete (UHPC) laminate, acoustic emission, flexural strengthening.

1 INTRODUCTION

Various methods can be found in the literature used to strengthen deficient structural reinforced concrete (RC) members. Utilization of Ultra High Performance Concrete (UHPC) is also one of developing strengthening methods and it is fiber-included, ductile, durable and high-strength cement-based composite. While structural members can be produced with UHPC, UHPC laminates can also be used for strengthening of existing members. Numerous studies on mechanical properties of UHPC-strengthened RC members have been conducted and remarkable points have been obtained: Crack widths become smaller (Martinola et al., 2010), ductility and rigidity of the member increases (Wuest, 2006; Hussein et al., 2012; Iskhakov et al., 2013), and flexural and shear load capacities (Ferrari et al., 2013, Lima et al., 2014) are enhanced. Such studies focused on only visible damages of UHPC-strengthened members. To identify invisible damages, Acoustic Emission (AE) is an effective tool. Accordingly, this study aims to investigate influences of UHPC laminate application type on AE behavior of strengthened RC beams under flexure.

1.1 Acoustic Emission (AE) Technique

Acoustic Emission (AE) can be defined as a micro-seismic event in which elastic waves in a stressed material propagate and are detected by appropriate receivers. When damage occurs due to the release of stored strain energy, elastic waves are generated and propagate through the material. These waves are detected by AE sensors placed on the surface, transformed into the electrical signal and amplified. Some signal parameters such as amplitude, average frequency, energy, duration, rise time and count are evaluated to obtain information about AE activities. Besides, in order to consider only meaningful signals apart from the noises, a “threshold” is set. Obtained AE signals can be processed by different methods to have information about crack locations, their origination times and types.

2 MATERIALS & METHOD

Cylinder compressive strength of concrete used for production of the test specimens was 20 MPa and mix design of this concrete is given in Table 1. Longitudinal bars and stirrups used within the specimens were S420 steel. UHPC mix design of laminates is also presented in Table 1. UHPC laminate was attached to Test Specimen-2 with Sikadur 31 epoxy which is a solvent-free and two-component adhesive.

Table 1. Mix designs of conventional concrete and UHPC

Conventional concrete		UHPC	
Material	Dosage (kg/m^3)	Material	Dosage (kg/m^3)
Cement (CEM-I 42.5R)	315	Cement (CEM-I 42.5R)	200
		Water	1000
Water	222	Silica fume	250
		0.5-1 mm quartz	531
Fine aggregate	863	0-0.4 mm quartz	227
		Micro steel fiber (13 mm)	215.1
Coarse aggregate	978	Plasticizer	25

Three beam specimens were designed as flexurally-deficient and two of them were strengthened with UHPC laminates with different application types. Geometrical and reinforcement details of the beams are given in Figure 1.

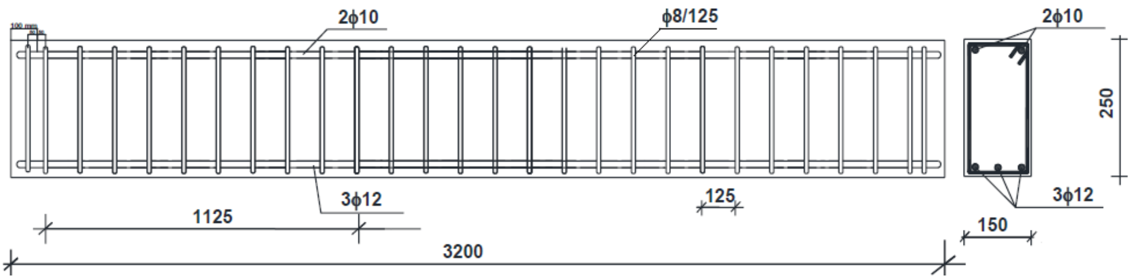


Figure 1. Flexural-deficient beam: Test Specimen-1.

During strengthening, the surface of Test Specimen-2 was roughened. After application of 2 mm-thickness epoxy to the surface, UHPC laminate was placed and was compressed with clamps. Finally, the specimen was kept in the laboratory conditions for 14 days for setting of the UHPC. In order to anchor the UHPC laminate to Test Specimen-3, UHPC laminate and RC beam were drilled. Subsequently, the holes of RC beam were filled with mortar and steel bars were placed within them. After setting of the anchorages, UHPC laminate was placed and 50 x 50 x 5 mm steel plates and bolts were used to prevent failure due to higher stress concentrations (Figure 2).

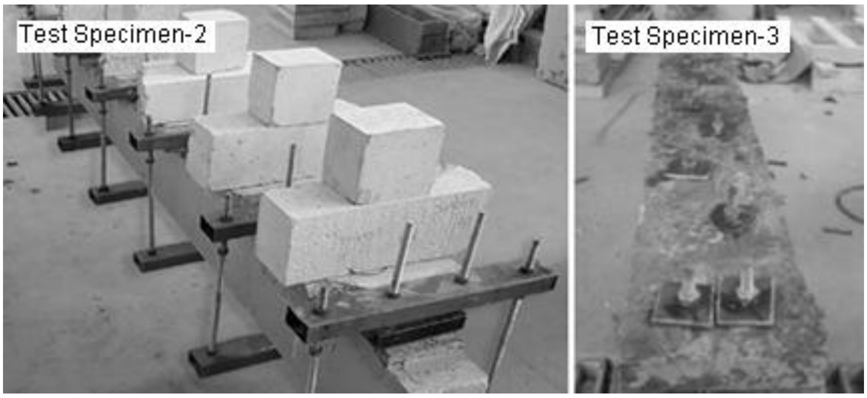
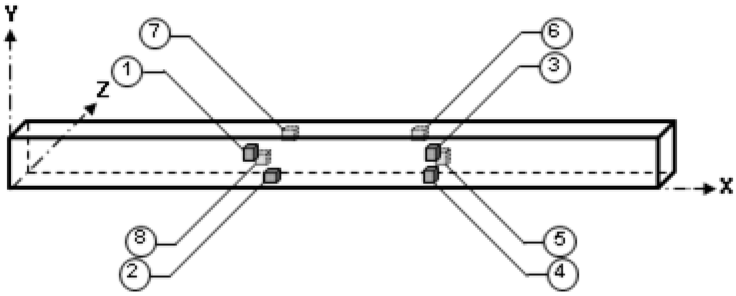


Figure 2. UHPC-strengthening of the test specimens: a) Test Specimen-2, b) Test Specimen-3.

2.1 Test setup

The specimens were tested under monotonic four-point-bending loading. Mechanical findings were compared with AE data which were obtained from an eight-channel DiSP AE system by Mistras Group. The AE system consisted of eight sensors, eight pre-amplifiers with 40 dB gain, a recorder and a monitor. Threshold was set as 42 dB to eliminate noise. Locations of sensors placed on the specimens are given in Figure 3.



Sensor	X	Y	Z
1	1.15	0.2	0
2	1.25	0.05	0
3	2.05	0.2	0
4	1.95	0.05	0
5	2.05	0.05	0.15
6	1.95	0.2	0.15
7	1.25	0.2	0.15
8	1.15	0.05	0.15

Figure 3. AE sensor coordinates

3 RESULTS

3.1 Mechanical results

Load vs. deflection curves of the specimens are presented in Figure 4. First flexural crack in Test Specimen-1 was observed at 10.50 kN load level at mid-span of the beam. As the load increased and multiple cracks originated, rigidity of the beam decreased. The maximum load capacity of the specimen was 42.99 kN when the deflection was measured as 14.48 mm.

Longitudinal bar yielded at 15.61 mm deflection level and Test Specimen-1 failed in flexure at 75.53 mm deflection level.

First flexural crack in Test Specimen-2 was observed at 23.05 kN load level. After the load increased and multiple cracks originated, debonding activities of fibers in UHPC laminate concentrated and crackles were heard at 37.35 kN load level. When the load reached up to 39.50 kN, a major crack in UHPC laminate became visible. Although the specimen showed same downward trend as Test Specimen-1 at 42.42 kN load level, then it continued to carry the higher loads with the effect of UHPC laminate. When the load was 51.00 kN, UHPC laminate fractured, the beam resisted maximum 52.34 kN load level and longitudinal bar yielded. Finally, it failed at 65.25 mm deflection level.

First flexural crack in Test Specimen-3 was observed at 14.32 kN load level. After the load increased and multiple cracks originated, debonding activities of fibers in UHPC laminate concentrated and crackles were heard at 29.10 kN load level. When the load reached up to 30.12 kN, two major cracks in UHPC laminate became visible. As the load reached up to 32.50 kN level, two major flexural cracks originated on RC beam propagated through the compression region. When the load was 44.84 kN, UHPC laminate fractured into three parts. Longitudinal bar yielded at 45.08 kN load level (~97% of ultimate load capacity) and the specimen failed at 54.35 mm deflection level. Failure views of all specimens are given in Figure 5.

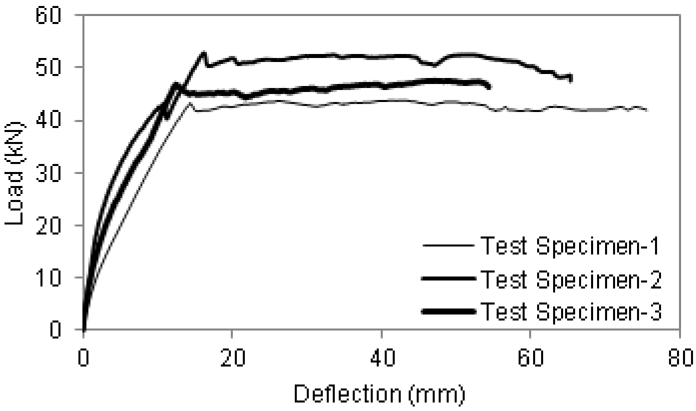


Figure 4. Load vs. deflection curves of the test specimens.

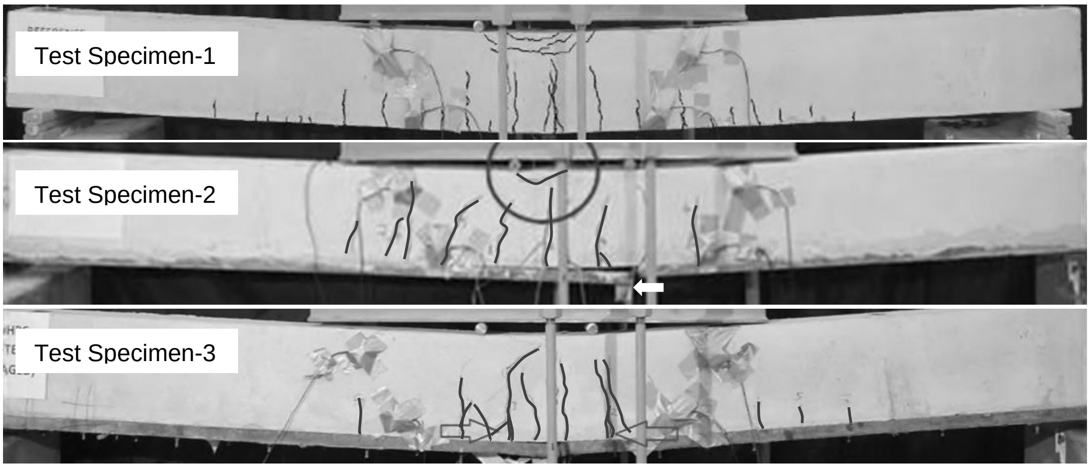


Figure 5. Failure states of the specimens.

3.2 AE results

As seen from Figure 6, total 2796 AE hits were recorded from eight sensors for Test Specimen-1. When the first flexural crack was seen at 115th sec (10.52 kN), AE hits and energies started to accumulate. Also, average frequencies of these hits were in higher values. This state proves tensile-type activities (JCMS-III B5706, 2003). Then, energy and average frequency values were lower and after origination of second flexural crack at 549th sec (14.48 mm) moving average of average frequency distribution showed increasing trend. Maximum energy value per one hit and total energy of this specimen were 1142 aJ and 26195 aJ, respectively.

Due to presence of extra fiber activities, 225586 AE hits were recorded from eight AE sensors for Test Specimen-2 (Figure 7). Even at 2 kN load level (115th sec) more AE activities originated and significant AE parameter values were obtained at 202nd sec when the first flexural crack was seen compared with the reference specimen. The maximum AE energies formed at the moment of fracture of UHPC laminate. After this, any differences were not seen in Test Specimen-2. In addition, sudden increases in moving average of average frequency distribution indicate multiple tensile-type activities. At 75.53 mm deflection level, average frequency trend started to decrease. Maximum energy value per one hit and total energy of this specimen were 65535 aJ and 7119413 aJ, respectively.

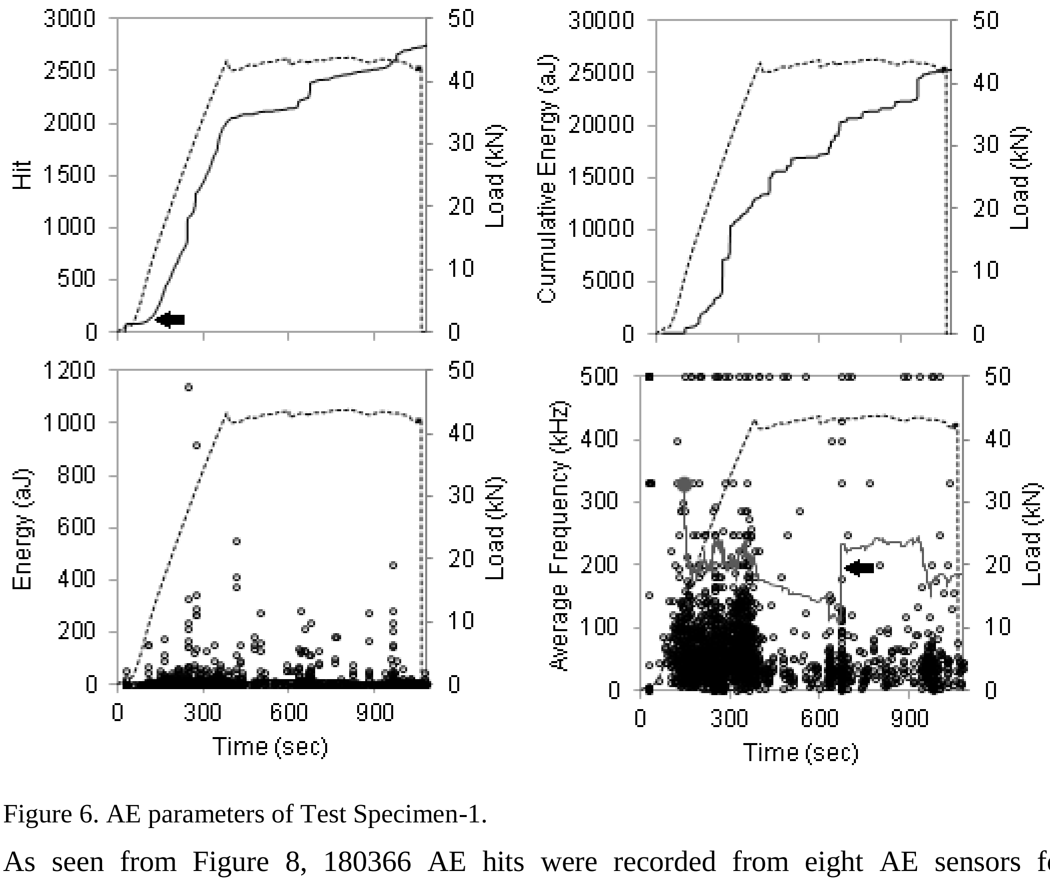


Figure 6. AE parameters of Test Specimen-1.

As seen from Figure 8, 180366 AE hits were recorded from eight AE sensors for Test Specimen-3. In contrast to Test Specimen-2, AE activities of this specimen started to originate with first flexural cracking events. In addition, much more and more frequent AE formations were observed until the laminate fractured. While moving average of average frequency distribution was nearly constant at this region, a big increasing trend started at 637th sec (23.77 mm). This state proves that while stress concentrations in anchorages caused more AE activities, they decreased tensile-type effectiveness of the cracks. Maximum energy value per one hit and total energy of this specimen were 4566 aJ and 9672866 aJ, respectively.

To compare amount of AE activities and their energies, Figure 9 was composed. As seen, maximum hits were recorded in Test Specimen-2 and maximum cumulative energy was obtained in Test Specimen-3. However, energy per one hit of Test Specimen-3 was the highest. Thus, anchoring procedure decreased energies of the damages.

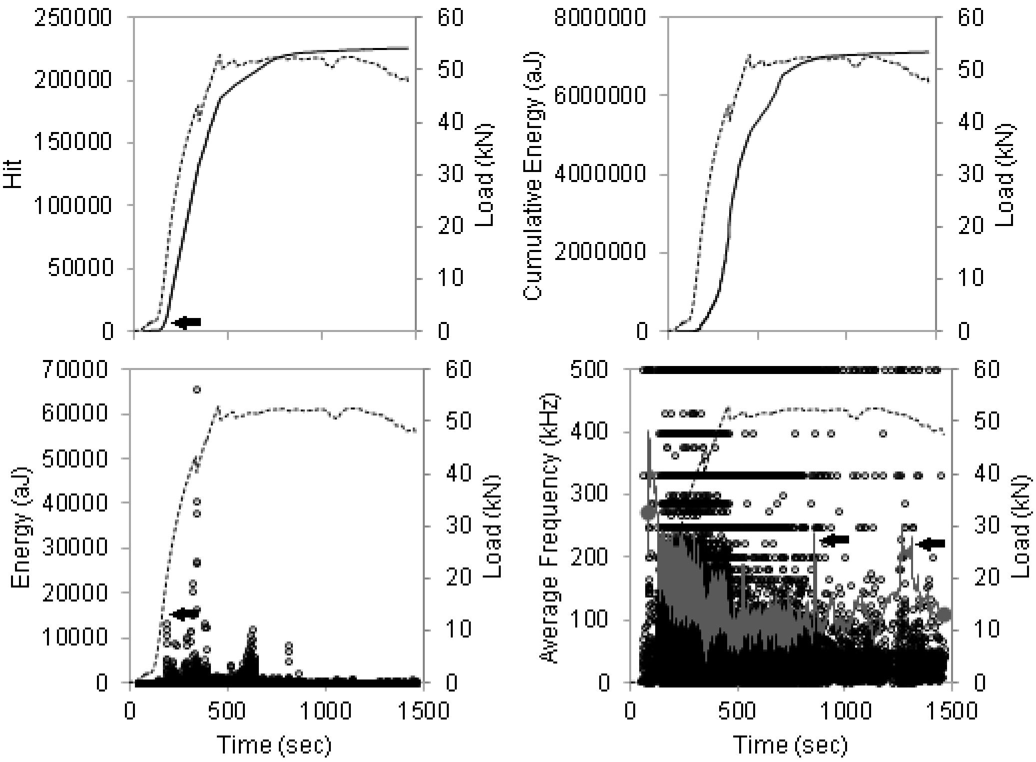


Figure 7. AE parameters of Test Specimen-2.

RA value vs. average frequency distributions of the specimens were also obtained according to (JCMS-III B5706, 2003). As seen from Figure 10, activities having higher average frequencies originated in low load levels for all specimens. As the load increased, concentration ranges and maximum values of RA value distributions changed. Although RA values of Test Specimen-2 and Test Specimen-3 are lower than those of Test Specimen-1, higher RA values in low load levels were observed in these specimens due to effectiveness of shear-type fiber activities. In addition, the lowest RA values were obtained during the test of Test Specimen-3. This state indicates higher tensile effectiveness due to higher amount of tensile stresses concentrated in anchorages.

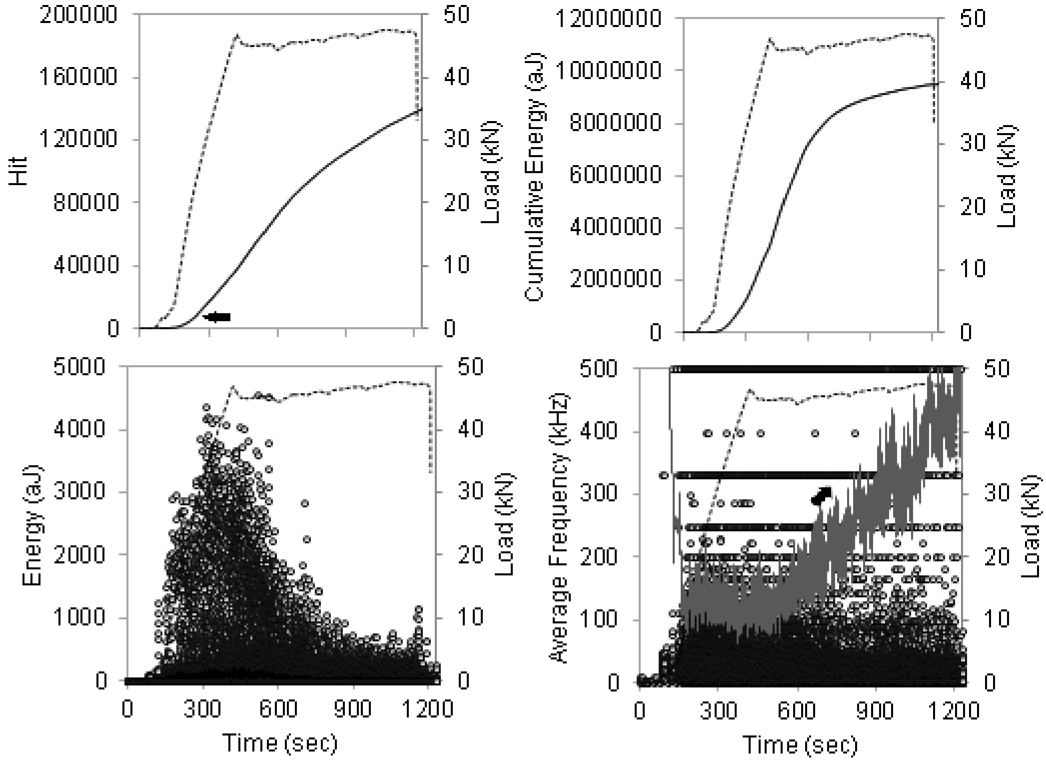


Figure 8. AE parameters of Test Specimen-3.

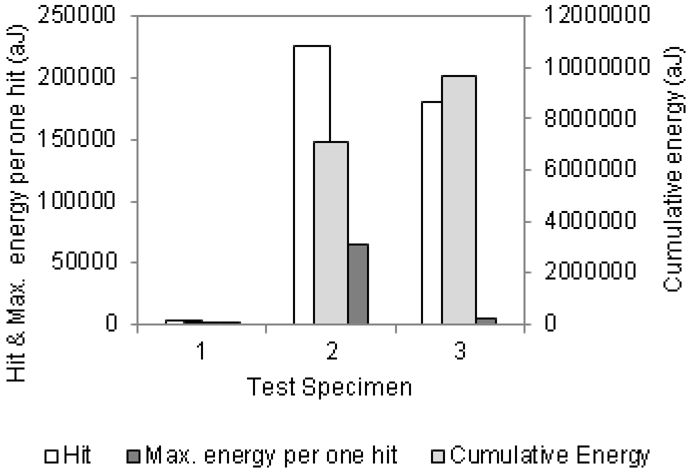


Figure 9. Comparison of AE activities of the test specimens.

4 CONCLUSIONS

This study investigated effect of application type of UHPC laminate on fracture behavior of reinforced concrete (RC) beams under flexure. Accordingly, two RC beams were strengthened with UHPC laminate using epoxy and anchorages. Their mechanical and AE behaviors under flexure were compared with a reference flexure-deficient RC beam and following conclusions were obtained: Presence of UHPC laminate retarded origination of the first crack. Ultimate load capacity increased after strengthening. However, displacement capability decreased.

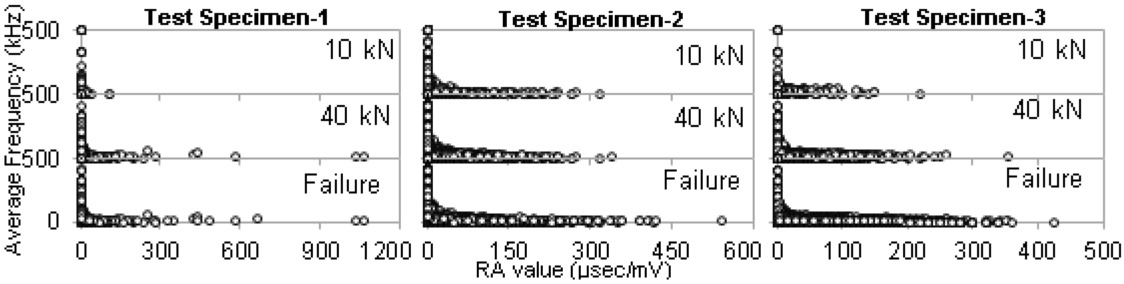


Figure 10. RA value vs. average frequency relations of the test specimens.

Presence of steel fibers in UHPC laminates increased amounts of AE activities. Time-based origination of AE hit and energy softened due to steel fiber activities. Thus, formation of sudden damages was prevented. Correspondingly, anchoring UHPC laminate is an appropriate application technique to decrease energies of the damages.

As the load increased, concentration ranges and maximum values of RA value distributions changed. Although RA values of strengthened specimens were lower than those of reference specimen, higher RA values in low load levels were observed in these specimens due to effectiveness of shear-type fiber activities. In addition, the lowest RA values and upward trend of average frequency variation were obtained in the anchored specimen due to higher tensile stress concentrations in anchorages.

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