Evaluation of severe damaged reinforced concrete beam repaired with epoxy injection and retrofitted with CFRP using acoustic emission technique

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Abstract. This paper presents the investigation on severe damaged-RC beams repaired with epoxy injection and retrofitted with carbon fibre reinforced polymer (CFRP) on the soffit subjected to monotonic loading concurrent with acoustic emission (AE) monitoring. Ten beams were prepared namely reference beam (S1C) and damaged RC beam repaired with epoxy injection and strengthened with CFRP (S3B). The load, signal strength, average frequency-RA value and crack modes were analysed and discussed. As a result, the S3B produced highest maximum load and AE signal strength compared to S1C. In a nutshell, the AE can be used to identify the integrity of the damaged-RC beam repaired with epoxy injection and retrofitted with CFRP.

1. Introduction
Carbon fibre reinforced polymer (CFRP) and epoxy resin have been utilized in many structural retrofitting and repairing applications. These materials would provide a proper repairing to the structure depends on the type of cracks either the cracks are minor, moderate or severe. In civil engineering construction, most of the repairing has been concentrated on the application of CFRP or epoxy injection standalone which dependent upon to the requirement of the owner. However, the application of both materials CFRP and epoxy injection are able to provide a better repairing to the structure. It is because both materials provided various advantageous for repairing.

The use of CFRP as retrofitting and rehabilitation of RC structure is not a new era in repairing structure. It also has been investigated by many researchers worldwide. For instance, the CFRP has been known as a material which able to increase the load capacity and stiffness of the structures [1]. Jadooe et al. [1] investigated the effect of RC beam strengthened with CFRP after exposure to 600 °C and 700 °C for two hours subjected to loading. They found that the ultimate load and stiffness of the repaired RC beam increased the load capacity and stiffness of the beams compared to beams without strengthening. Yang et al. [2] has been applied CFRP for repairing RC structures such as column and footing, where the CFRP has been utilised as reinforcement to the structure. They found that the repair method using
CFRP was successful in restoring the seismic performance of the column in terms of lateral strength and deformation capacity. The CFRP has been used for repairing of damage steel fibre reinforced concrete (SFRC) beams [3-4]. They found that the CFRP improved the ultimate strength of the SFRC beams up to 97.3 %. It indicates that the CFRP improves the performance of the RC structure and it is enhanced by Abdul-Salam et al. [5] that the CFRP would maintain the integrity of the slab even after failure. The effect of the CFRP on the performance of the high strength reinforced concrete (HSRC) beam has been investigated by Soffian Noor and Noorsuhada [3]. They found that the beam strengthened with CFRP produced higher signal strength compared to reference beam due to the CFRP strengthened the integrity of the HSRC beam. According to ACI 440 [6], the CFRP offers superior performance as well as resistance to corrosion and high stiffness-to-weight ratio. It is also provided extra flexural and shear reinforcement by adhesively bonding to RC structure. However, it is depend on the bonding performance between the concrete and the CFRP.

The use of epoxy resin as a repairing material for reinforced concrete crack has been investigated by Issa and Debs [7]. The epoxy is found able to restore the strength of repaired concrete up to 40.93 %. The epoxy resin is also has been used to repair concrete exposed sea water at different temperatures by El-Hawary et al. [8]. They found that the epoxy deteriorated faster than the concrete when the structure exposed to sea water. Then, they recommended considering the factor of safety in design to enhance the epoxy performance for repairing purpose.

Due to the effectiveness of the epoxy and CFRP for repairing and rehabilitation of concrete structure, Ekenel and Myers [9] investigated the performance of RC beams strengthened with these two materials at environmental condition. They found that the environmental condition would affect the bond performance of the epoxy injection for repaired beam. At the same time, the initial stiffness and maximum strength of RC beam strengthened with CFRP was achieved. From the review indicates that most of the studies are intended to investigate the performance of the structure contacts with these two materials. However, no study has been found on the evaluation of the crack of the damage RC beam retrofitted with epoxy injection and CFRP. Moreover, the use of non-destructive testing (NDT) such as acoustic emission (AE) technique for this purpose is still lack of attention. It seems sensible to investigate a new technique for assessing the damaged RC beam repaired with epoxy injection and retrofitted with CFRP on the soffit.

AE is defined as the class of phenomena whereby elastic waves generated [10]. It is can be used to detect damage occurrence and to diagnose the location of damage in a structure as the damage progresses. It is also has been used for monitoring of cracks that occurred in the reinforced concrete beam under dynamic loading [11]. Hence, in the present study, the AE technique has been used to assess the severely damaged RC beam repaired with epoxy injection and retrofitted with CFRP subjected to monotonic loading to failure. In doing so, the AE signal strength and load with respect to time were analysed, reported and discussed.

2. Experimental Programme

2.1. Preparation of Materials and RC Beams

In the preparation of the ten RC beams size 200 mm x 300 mm x 1500 mm, the concrete grade C40, high yield steel bars and mild yield steel bars were used. Five RC beams were prepared as control beam (S1C) and another five RC beams were prepared for severely-damaged RC beams repaired with epoxy injection and retrofitted with CFRP on the soffit (S3B). The ready-mixed concrete was used with different proportions by weight of water, cement, fine aggregate and coarse aggregate and it was 0.43, 1.00, 1.73, 2.70, respectively. 0.3 % retarder and 0.45 % superplasticiser were added into the fresh concrete mix. The maximum size of coarse aggregate was 20 mm. The compressive strength of the hardened concrete at 7 and 28 days was 50.27 MPa and 56.87 MPa, respectively. The tension and compression parts of the RC beam were designed with high yield steel of 460 N/mm². Diameter of 16 mm (2T16) and 10 mm (2T10) was used for tensile and compression bars, respectively. Meanwhile,
mild yield steel of 250 N/mm$^2$ diameter 10 mm was used for the stirrups with the spacing of 175 mm centre to centre (R8 – 175 mm c/c).

For the preparation of severe damage RC beams, three-point loading was used to produce crack width up to 1 mm with constant load rate of 0.02 kN/s. The crack width was manually observed using crack width gauge as shown in Figure 1a. As stated by Public Work Department of Malaysia (JKR) [12], the crack width of 0.3 mm to 1 mm is classified as severe damage. Meanwhile, according to RILEM [13], the crack width of 0.3 mm to 1 mm is deliberated as moderate crack. Hence, the reference through JKR [12] was referred. In this study, after the required crack width was acquired, the beam was unloaded. The severe damage RC beam was then repaired using epoxy injection and retrofitted using CFRP on the soffit. The low viscosity resin with tensile strength of 25 N/mm$^2$ was used as epoxy resin. It is able to produce bond strength to concrete of greater than 2 N/mm$^2$ after 10 days installation. Hence, it is able to improve the concrete strength of 90 N/mm$^2$ at 7 days. The CFRP supplied by Sika was used to retrofit the soffit of damaged beam. The ultimate strength of the CFRP was 4900 N/mm$^2$ and the elastic modulus was 230000 N/mm$^2$, respectively [3]. Prior to retrofit the damaged-RC beam using CFRP, epoxy injection was first taken place. The packers were mounted at selected location close to the crack on an angle. The epoxy resin was injected to penetrate the crack through the packers using an injection machine. The crack was then sealed with mortar. The surface preparation for lamination of CFRP was carried out. The CFRP was then attached to the concrete surface on the soffit in accordance with American Concrete Institute, ACI [6].

![Figure 1](image1.png)

**Figure 1.** a) Crack width of the pre-damaged beam S3B prior to repair crack with the crack width of 0.5 mm at the beam soffit b) The beam setup in conjunction with AE monitoring.

2.2. Test Set-up and AE Monitoring

Three-point loading with constant load rate of 0.02 kN/s was applied to the beam concurrent with AE monitoring. The three-point loading was performed using Universal Testing Machine (UTM); it was applied monotonically to the beam to failure. The AE was monitored using an AMSYS 6 supplied by Vallen Systeme. The preamplifier with gain of 34 dB was used. Four sensors type VS75-V were fixed onto the beam surface as shown in Figure 1b. The four sensors were designated as CH5, CH6, CH7 and CH8. All four sensors were calibrated using pencil lead fracture to ensure the sensitivity of the sensor to the concrete surface. The threshold level of 40 dB was utilised throughout the AE monitoring. The crack pattern of the beam during testing was imposed onto the graph paper. The AE data such as signal strength and average frequency-RA value were analysed and discussed. The RA value was obtained from the division of rise time (µs) and maximum amplitude (µv). In this study, all five beams for S1C and S3B were analysed and observed in order to examine the AE signal strength, the average frequency – RA value and crack modes. Since all beams presented almost the same pattern of signal strength,
average frequency – RA value and crack mode, only one beam for S1C and S3B was presented in this paper.

3. Results and Discussion

3.1. Maximum Load of the Beams

Figure 2a and Figure 2b show the load versus deflection and load versus time for beam S1C and S3B, respectively. From the graph, it is clearly seen that the severe damaged beam repaired with epoxy injection and retrofitted with CFRP (S3B) represents the highest maximum load compared to control beam S1C with the value of 240.17 kN and 185.20 kN, respectively. The repairing and retrofitting done to the damaged beam increases the strength effectiveness of the beam up to 30%. It indicates that the repairing using epoxy injection and retrofitted with CFRP on the soffit is able to improve the strength of the damaged RC beam. It has been enhanced by Ekenel and Myers [9] that the ultimate strength of the damaged beam retrofitted using CFRP can be achieved with the strength effectiveness of 36.41%. From the Figure 2a, the beam S3B is delayed the time of failure to 6000 s compared to beam S1C with the time of failure is 5500 s. Same goes to deflection, the beam S3B is deflected later than beam S1C with the deflection of 60 mm and 55 mm, respectively. It seems that the repairing and retrofitting using epoxy injection and CFRP are able to delay the time of deflection to the beam.

![Figure 2. a) Load versus time b) Load versus deflection for beams S1C and S3B.](image)

3.2. Crack Modes and AE Characteristic of the Beams

From the observation, seven crack modes were identified. The identification of the crack modes was based on the crack observation and the AE signal strength analysis during the beam subjected to monotonic loading to failure. Crack mode 1 (CM1) is the nucleation of crack, in which the crack is unable to be seen visually. Crack mode 2 (CM2) is the first crack that appeared on the beam’s surface when subjected to load. Crack mode 3 (CM3) is the flexural crack localized, where the crack propagated beyond the neutral axis of the beam. Crack mode 4 (CM4) is the development of the shear crack in the beam. Crack mode 5 (CM5) is the delamination of the CFRP. The delamination of the CFRP was categorized into two as crack mode 5a (CM5a) for starting of the delamination of CFRP and crack mode 5b (CM5b) for the delamination of CFRP at rupture. Crack mode 6 (CM6) is the concrete cover separation or CFRP plate-end debonding failure of concrete either occurred at the bottom or sides of the beams. Meanwhile, crack mode 7 (CM7) is the reinforcement fractured prior to failure of the beam. In this paper, only data obtained at CH6 and CH7 were analysed, reported and discussed.

Figure 3 and Figure 4 show the crack mapped on the beam S1C and S3B when subjected to monotonic load to failure. For beam S1C, five crack modes were identified as CM1, CM2, CM3, CM4 and CM7. Meanwhile, for beam S3B, seven crack modes were identified. Figures 5a and 5b show the relationship between signal strength, load and time for beams S1C and S3B. It is found that CM1
induced higher signal strength for beam S1C compared to S3B with the value of 2760 nVs and 1100 nVs. The signal strength was generated when the beam subjected to 37 kN and 32.42 kN for beam S1C and S3B, respectively. The identification of CM1 was based on the Degala [14] that the high spike of signal strength is represented a possible damage occurrence in the structure. This spike of signal strength gives earlier notification on the occurrence of the first crack in the beam.

As the load increases to 73.81 kN and 59.11 kN for beams S1C and S3B, respectively, the CM2 was identified. These loads were generated spike of signal strength on beam S1C and S3B with the value of 15600 nVs and 11800 nVs, respectively. The CM3 was localised as it is propagated beyond neutral-axis from previous cracks for both beams. The CM3 was occurred when the load reached 96.89 kN and 103.25 kN for beams S1C and S3B, respectively. The cracks produced signal strength of 4580 nVs and 30200 nVs for beams S1C and S3B. It shows that as the crack propagates, the intensity of signal strength also increases [15-16]. The CM4 developed when the load increased to 158.12 kN and 187.30 kN for beams S1C and S3B. This crack generated lower signal strength of 995 nVs for beam S3B and higher signal strength for beam S3B with the value of 3990 nVs.

As the load continuously increased up to 217.47 kN, the CFRP on beam S3B started to delaminate (CM5a). It induced the signal strength of 6320 nVs. The CFRP rupture (CM5b) was taken placed as the load reached to the maximum load of 240.17 kN as shown in Figure 4b. It produced lower signal strength of 1100 nVs collected from the same sensor as previous crack mode. In the context of AE, the signal strength is resulted from the energy released by the material or specimen. Where, the reduction in the energy is indicated the fracture energy is distributed to more hits as the loading continuously applied to the specimen, which resulting to lower energy for each signal [17]. It is also due to lower energy dissipation mechanisms become dominant as well as delamination which emit lower energy that the matrix cracking events in the material [18]. The intensity of signal strength of 42800 nVs was produced as it is associated to the concrete cover separation with the CFRP at particular location still contact to the concrete surface. This high signal strength was also associated to the formation of new cracks and crack propagation from the existing cracks. It was occurred when the load reached 200.52 kN. The
reinforcement was fractured (CM7) for beam S3B when the load reached 172.34 kN and produced the signal strength of 2610 nVs. However, the first steel bar on the tension part was visually fractured (CM7) when the load reached 146.68 kN for beam S1C, which produced extremely high sound with the highest signal strength of 40200 nVs. Similar finding has been shared by Budano et al. [19] where the higher AE energy is closely related to brittle fracture, which is accompanied by an audible noise. Meanwhile, the lower AE energy is closely related to the stable ductile crack propagation. This has been supported by Nayak et al. [20] when the author explains that the flexural failure occurred due to complete yielding of the longitudinal reinforcement in the RC structure.

![Figure 5. Load and signal strength versus time for beam a) S1C b) S3B.](image)

3.3. Average Frequency- RA Value

The progression of cracks from tensile to shear can be identified using Average frequency-RA value. Data obtained from CH6 was analysed for both beams S1C and S3B as shown in Figures 6 and 7. From the Average frequency-RA value, the diagonal line indicates the transition line between two cracks, tensile and shear cracks which occurred in the beams [11, 21-22] when subjected to monotonic load. In this paper, only average frequency-RA value for CM1, CM2 and CM7 would be presented.

![Figure 6. Average frequency-Ra Value and its illustrated crack modes for beam S1C experiences a) CM1, b) CM2 and c) CM7.](image)

It is found that, as no crack appeared on the beam surface, the plots were concentrated in the tensile crack zone. Despite the crack unable to be seen visually, the average-frequency can be used to predict the occurrence of the crack in the beam. Early damage state which corresponds to the tensile crack mode
exhibits higher average frequency and lower RA value [23]. As the CM2 appeared on the beam surface for both beams, the average frequency-RA value shows that the beam has experienced shear crack. Although no shear crack is visually observed, this relationship can be used to predict the forthcoming crack in the beam. Aggelis et al. [23] emphasised that the shift of RA value to the shear crack is due to the accumulation of damage in the structure. More plots can be seen in the shear crack region and at the same time more cracks appeared on the beam surface as the CM7 occurred in the both beams.

![Image: Illustration of crack modes]

**Figure 7.** Average frequency-Ra Value and its illustrated crack modes for beam S3B experiences a) CM1, b) CM2 and c) CM7.

4. Conclusion

In the present study, acoustic emission signal strength of severe damaged RC beams repaired with epoxy injection and retrofitted with CFRP on the soffit subjected to monotonic loading are investigated. It is found that five crack modes were identified on beam S1C and seven crack modes were identified on beam S3B. The occurrence of the new crack produced high signal strength on both beams. In term of strength, the S3B produced higher maximum load compared to S1C due to presence of the epoxy injection in the crack and the retrofitting of the CFRP on the soffit of the beam. From the average frequency-RA value, the crack progressions from tensile crack to shear crack were made and well-matched to the illustrated crack pattern for both beams.

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