Civil Engineering and Architecture 9(5A): 121-127, 2021 http://www.hrpub.org
DOI: 10.13189/cea.2021.091314

Acoustic Emission Signal Application on Damage Evaluation of RC Beam-Column Joint under Monotonic Loading

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Received January 29, 2021; Revised July 27, 2021; Accepted August 19, 2021

Cite This Paper in the following Citation Styles

(a): *[1] Md Nor N., Jalilluddin A. M., Mohamad M. Z., Mat Saliah S. N., Ibrahim A., Abd Ghani K. D. , "Acoustic Emission Signal Application on Damage Evaluation of RC Beam-Column Joint under Monotonic Loading," Civil Engineering and Architecture, Vol. 9, No. 5A, pp. 121 - 127, 2021. DOI: 10.13189/cea.2021.091314.*

(b): *Md Nor N., Jalilluddin A. M., Mohamad M. Z., Mat Saliah S. N., Ibrahim A., Abd Ghani K. D. (2021). Acoustic Emission Signal Application on Damage Evaluation of RC Beam-Column Joint under Monotonic Loading. Civil Engineering and Architecture, 9(5A), 121 - 127. DOI: 10.13189/cea.2021.091314.*

Abstract Beam-column joint in reinforced concrete (RC) structure is a critical element that needs to be monitored continuously throughout its service life. The beam-column connection acts as the core component that receives moment transfer from adjacent elements. Consequently, the integrity of the RC beam-column joint reduces when subjected to load over time. This study investigates the damage of RC beam-column joint subjected to static load until failure using acoustic emission (AE) signal strength. The size of the RC joint sample was composed of 300mm x 200mm x 600mm, 200mm x 200mm x 1200mm and 1500mm x 500mm x 300mm for beam, column and foundation respectively. The vertical loading was applied to the beam at 530 mm distances from the column surface. Four sensors were used at specified positions at the beam and column surfaces. It was found that the increment of load intensity results in intensified acoustic emission signal strength.

Keywords RC Beam-Column Joint, Signal Strength, Acoustic Emission Technique, Damage Evaluation

1. Introduction

One of the critical reinforced concrete (RC) structural components is the beam-column joint that transfer moments from other elements connected to it. Simultaneously, the service life of an RC beam-column joint is limited due to depreciation, wear and tear, increased load, and changes in usage [1].

There are three broad categories of beam-column joints in RC structure where the exterior beam-column joint is highly influenced by external loadings. Furthermore, most of the RC beam-column joint majorly fails at the joint region due to development of shear crack. Hence, early detection of the crack occurrence should be implemented in order to maintain its integrity. Furthermore, inadequate reinforcement detailing in the RC structure will also affect the occurrence of damage [2 - 4]. Once damage occurs, the life span of the RC beam-column joint decreases, reducing the integrity of the RC beam-column joint.

Acoustic emission (AE) technique is one of the most extensively utilized non-destructive testing (NDT) methods in structural health monitoring. Many studies have thoroughly reported on structural health monitoring adopting the AE method [5–7]. This is attributed to the high sensitivity of the equipment to detect the early development of cracks and damages [8]. In fact, AE is a reliable method where a strong correlation between the AE activities and the damage progression were observed [9]. It is also potential in examining the level of damage in cementitious composites [10-11].

Thus, employing AE is vital to assess in regards to the structural integrity by identifying the occurrence of damages over time. Monitoring micro-cracks is often overlooked and undetectable by naked eyes where the AE can achieve the purpose [12]. Moreover, NDT approach is an alternative way to observe the damages without causing any damage to the structures. As a result, the goal of this research is to look into the crack propagation in the RC beam-column joint when it is monotonically loaded to failure on the beam using AE technique.

2. Experimental Study

2.1. Sample Specification

The RC beam-column joint sample was prepared and designed in accordance to Eurocode 2 with concrete grade C40. The concrete design was based on a ratio of 1:2:3 (cement: fine aggregate: coarse aggregate) with water to cement ratio of 0.46. The RC beam-column joint was made from beam, column and foundation with the size of 300 mm x 200 mm x 600 mm, 200 mm x 200 mm x 1200 mm and 1500 mm x 500 mm x 300 mm, respectively. The beam was constructed at the middle of the column and the column was erected at the centre of the foundation.

There were four stages of the construction of the RC beam-column joint specimens. The first stage was the construction of the foundation. The foundation was reinforced with 16 mm diameter high yield steel bars with 80 mm centre to centre (c/c) followed by 100 mm centre to centre (c/c) spacings as the bottom layer and upper layer, respectively. The bars were placed at the bottom of the foundation with a concrete cover of 25 mm.

The second stage was the construction of the column. Four 20 mm diameter high yield steel bars and 8 mm mild steel bar as link was designed for the column. The spacing between the links was 150 mm centre to centre. The third stage was the construction of the beam designed with two 12 mm diameter high yield steel bars procured to strengthen the tension and compression zone of the sample beams. The links was mild yield steel of 8 mm diameter with the spacing of 150 mm was used. Fourth stage was the assembling of formworks for the entire beam-column joint specimen. Conventional simple joint connection was used in the RC beam-column arrangement. Fig. 1 shows in detail the beam-column joint connection for the investigation.

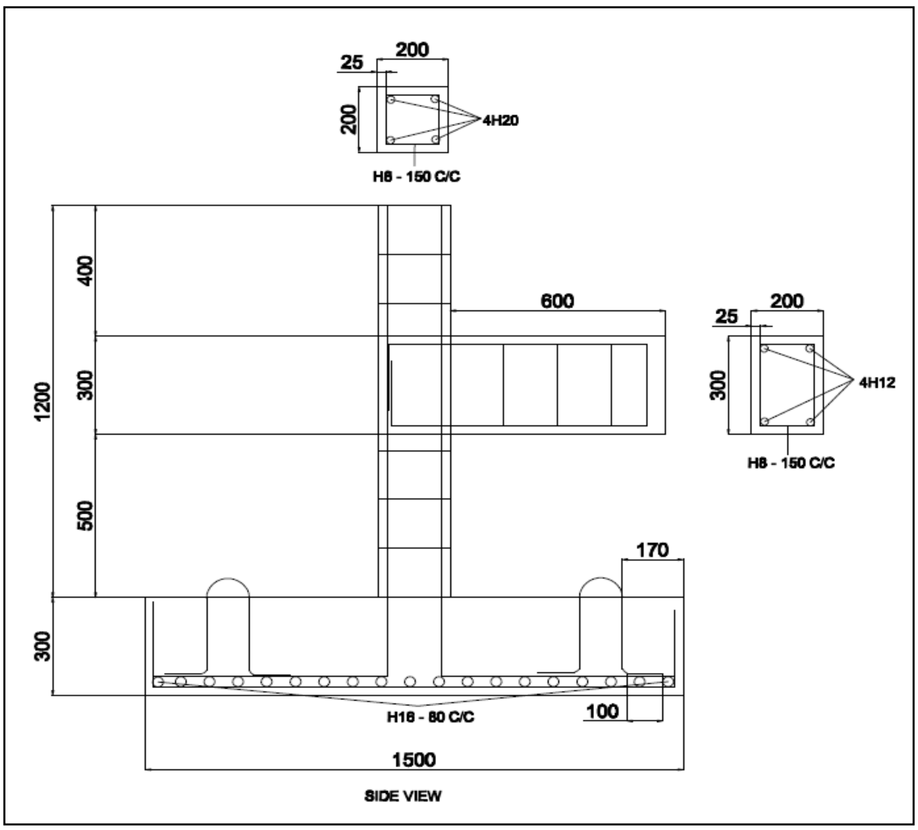

Figure 1. Details of the RC beam-column joint (all dimension measured in mm)

2.2. Test Setup

The RC beam-column joint was monotonically loaded to failure using Universal Testing Machine (UTM) with the capacity of 1000 kN. A constant load rate of 0.002 mm/s was used throughout the testing. Fig. 2 illustrates the position of the applied load on the beam at a distance of 530 mm from the column surface. To avoid the joint transforming to bracket or corbel during the placing of load, the effective length was needed to be acquired of the load placement. According to Singh et al. [13], the optimum value to place the load was based on the shear span/ affective depth ratio (a/d) with the ratio a/d must be greater than 2. In this study, the a/d was 2 which complied to the justification of Singh et al. [13].

2.3. AE Instrumentation

The AE type AMSYS-6 used in this study was provided by Vallen Systeme, Germany. The threshold was set to 40 dB with the AE wave velocity of 4000 m/s in the AE hardware to remove the background noise (i.e. machineries appliances and ambient noise) [14]. Four sensors VS75 - V with frequency range between 20 – 100 kHz were fixed on specified locations. Magnetic clamp with two legs of magnet was used to hold the sensor at the center of magnetic clamp. Then the legs were attached to two 2 mm steel plate that glued on the surface of RC beam-column joint specimen. High vacuum grease was applied between the sensor and the RC beam-column joint surface that act as a couplant. One sensor was attached at mid-height to one side of the beam surface with the distance of 30 mm from the tip of the beam edge and named as CH5. This channel was placed at below the beam to solve the difficulties such as the location of load applied and to simulate the real situation whereby presence of slab at the above part of the beam.

Three remaining sensors were attached at the center of the column width with the distance of 210 mm named as CH6, 550 mm named of CH7 and 950 mm named of CH8 from the top edge of the column. Fig. 3 and Fig. 4 show the schematic arrangement of the sensor on the RC beam-column joint and experimental set up for AE monitoring on RC beam-column joint. The sensors were connected using a cable to the pre-amplifier with the gain of 34 dB. Then, the cable was connected to the ASIP-2 board. From the ASIP-2 board, it was connected to a computer for AE data acquisition. In this study, only AE signal strength collected from all channels was analysed to evaluate the crack behaviour of the sample.

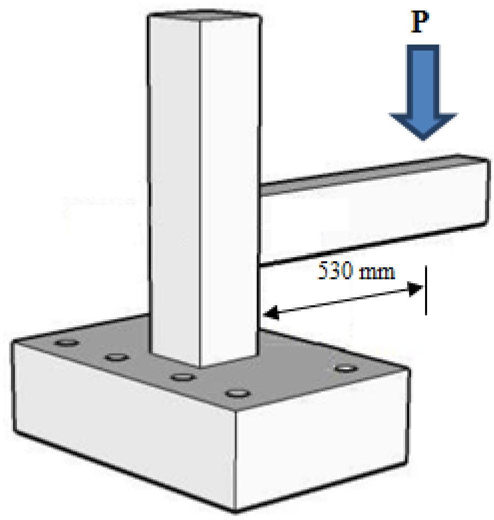

Figure 2. Schematic drawing of RC beam-column joint sub-assemblages

2.4. Visual Observation

Crack appeared during testing was retrieved by visual observation. The crack was mapped on a grid paper and redrawn on the RC beam-column joint surface when the load stopped. The crack which mapped on the grid paper was numbered as 1 and onwards. During the mapping process, the first crack that appeared on the surface of the specimen was identified. Torchlight was used to detect the crack initiation especially the occurrence of hairline crack [12].

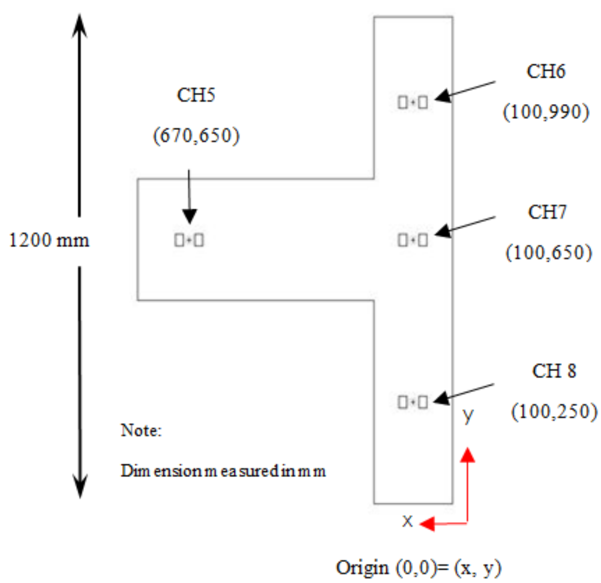

Figure 3. Schematic diagram location of the sensors

Figure 4. Experimental setup

3. Results

3.1. Visual Observation of the RC Joint Sample

The RC beam-column joint was tested using UTM machine and subjected to monotonic load. It can be remarked that the ultimate load of the RC beam-column joint was 46.16 kN. When the load reached 21.55 kN at 168 seconds, the first crack was visible and marked as number 1, as shown in Fig. 5. The first crack was observed to appear vertically at the joint between the beam and the column. It indicates that when the load is approximately 47% of the ultimate load, the first crack occurred and can be visualised using naked eyes. Then, more cracks were developed at the joint and designated as 2 to 4. The first diagonal crack designated as crack 5 occurred at the column as shown in Fig. 5. The crack was observed when the load reached 39.48 kN or 86 % of the ultimate load at 327 s which propagated approximately 45^0 to the plane. The crack was then increased as the load increased. Similar crack pattern was also identified by Fadwa et al. [15].

At 355 s, a single vertical crack occurred at the beam, designated as 6. It was located at 270 mm from the joint, which occurred at centre between the column face and the point load. The crack was propagated from the top of the beam. Then, when the load reached 92 % of the ultimate load or 42.53 kN, the crack was propagated from crack 6 to nearly mid-depth of the beam and designated as 8. It was noted at time 404s. When the load increased, more cracks were developed. The cracks were seen to be more evident at the column and the joint of the RC beam-column joint.

Figure 5. Crack pattern on the RC beam-column joint

3.2. Signal Strength of RC Beam-Column Joint

Fig. 6 depicts the correlation between signal strength, load and time when the beam of the RC beam-column joint was applied with a monotonic vertical point load. Meanwhile, Fig. 7 shows the relationship between signal strength and time corresponding to the crack modes of the joint sample. The signal strength was analysed from channels 5 (CH5), 6 (CH6), 7 (CH7) and 8 (CH8).

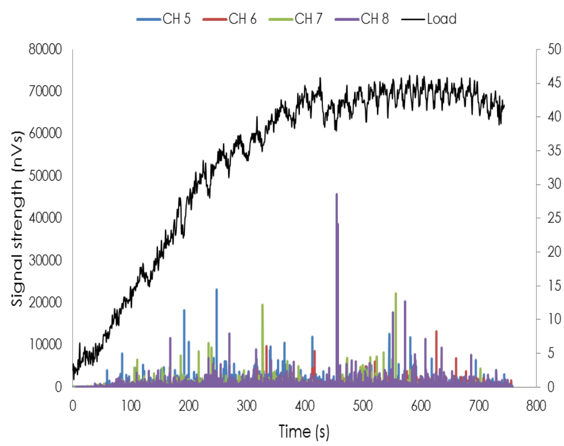

Figure 6. Relationship between signal strength, load and time

Generally, several crack modes were identified based on the relationship between signal strength and time corresponding to the crack modes that appeared on the RC beam-column joint. For instance, in Fig. 5 and Fig. 6, when load subjected to the beam of from 0 kN to 12 kN, the crack nucleation that was not visible with naked eye was identified. Only one peak signal strength was noticed from time 0 s to 168 s (Fig. 7) captured by CH5 with the signal strength of 7950 nVs at time 85 s. The peak signal strength attained can be considered as the nucleation of crack which generated in the RC beam-column joint. According to Md Nor et al. [16] and Abdul Kudus et al. [17], the identification of crack existence corresponds to the peak observed from the signal strength. Moreover, Shield [18] stated that a major peak in AE signal preceded the crack. Hence, it is relevant to consider the signal strength of the 7950 nVs as the nucleation of crack that might occur in the joint of the RC beam-column.

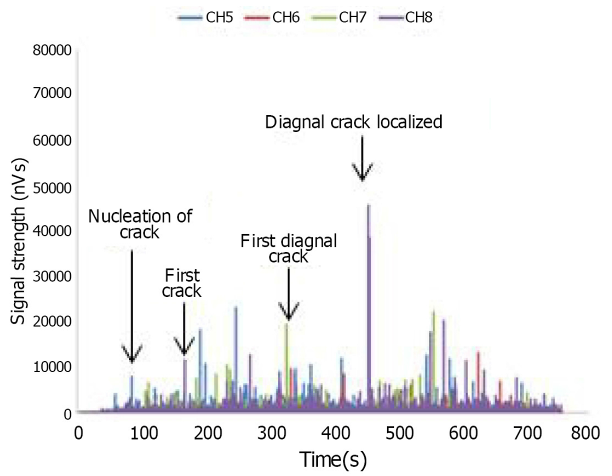

Figure 7. Relationship between signal strength and time for all channels

The occurrence of the first crack at the joint was visually observed when the load reached 21.55 kN at time 168 s. The signal strength was 11600 nVs captured by CH8. It indicates that the signal strength increased as the crack occurred which generated high stress at that particular location. Md Nor et al. [16], Md Nor et al. [19], Wan Ahmad et al. [20], Bourchak et al. [21] and Mat Saliah et al. [22] confirmed that the presence of cracks in the structure is linked to high signal strength. Logically the crack happened at the joint will be captured at CH7 because it is very near to that occurrence of crack. But in this situation, CH5 was still captured the signal strength from first crack but the value was not so high compared that at CH8. This might be come from inhomogeneous condition of concrete inside the RC beam-column joint sample. For example, the segregation of aggregate inside the concrete that may slowdown the transient wave and reduce the signal strength of the AE data. But it was counter back by the nearest channel that captured the high signal strength. In this case CH8 captured the high value of signal strength for the first crack.

At time 248 s, peak signal strength was noticed with the value 23100 nVs. The peak signal strength was collected by CH 5 which is located close to the joint. The progression and propagation of the crack in the RC beam-column joint is the factor contributing to the high signal strength.

The first diagonal crack with an angle approximately 45^0 to the plane of the column was identified at time 327 s. The load of 39.48 kN was induced high signal strength of 19500 nVs. The signal strength was collected from CH7. When load reached 40.63 kN, a single vertical crack appeared on the beam with signal strength of 10500 nVs at time 365 s. The crack was initiated from the compression region of the beam. However, when the load reached 42.53 kN, the crack propagated to the tension part. The signal strength was increased to 11900 nVs as the length of the crack increased.

The second diagonal crack at column was identified and produced highest signal strength of 45700 nVs at time 455 s. The load at 455 s was 41.58 kN. At this time, a loud noise can be heard that might be attributed to the progression of the diagonal crack in the RC beam-column joint. Then, it generated more diagonal cracks in the column and the cracks were localised.

Table 1 shows the summary of the AE signal strength corresponding to the time, load, crack type and channel (CH). From the summary, it is found that the CH8 captured more peak signal strength than other channels. The nucleation of crack, first crack, flexural or vertical crack, and diagonal crack were identified as the four main outcomes of crack development. From the four crack modes, the diagonal cracks were dominant. Most of the diagonal cracks were captured by CH8, because the CH8 or sensor 8 is located at the column hence recorded more signals than other channels.

Table 1. The summary of the AE signal strength, time, load, crack types and channel

Time (s)	Load (kN)	CH	Signal Strength (nVs)	Crack modes
85	12	5	7950	Nucleation of crack
168	21.55	8	11600	First crack
202	31.85	7	8470	Flexural vertical
224	29.37	7	10400	Flexural vertical
229	30.90	7	9380	Flexural vertical
327	39.48	7	19500	Diagonal crack
365	40.63	5	10500	Flexural vertical
377	41.39	7	4960	Flexural vertical
403	42.53	5	11900	Flexural vertical
446	39.86	8	38600	Diagonal crack
455	41.58	8	45700	Diagonal crack

3.3. Relationship between Cumulative Signal Strength and Time for All Channels

Fig. 8 shows the cumulative signal strength for all channels with respect to time. From the graph, CH8 produced highest cumulative signal strength compared to other channels, because CH8 is located at mid-width of the column and 250 mm from the foundation. This channel was not near to the concentration of the crack occurrence in the joint area of the sample. It depends on the material of the concrete itself such as segregation of the material that can slowdown the wave and decrease the signal strength. But can support the nearest channel as long the channel location 1 m from other channel. Hence, it would have captured the highest signal strength that released by the cracks. The peak cumulative signal strength for CH8 is 3.99 x 10^6 nVs.

The second highest cumulative signal strength was captured by CH5. The cumulative signal strength value is 3.08 x 10^6 nVs. The CH5 was located at one side of the beam, close to the point load. When load is applied to the beam, the CH5 captured signal from the crack activity in the beam. CH7 produced the third graph of cumulative signal strength with the value of 2.40 x 10^6 nVs. The CH7 was located close to the joint of the RC beam-column. Meanwhile, the CH6 was produced little cumulative signal strength of 1.71 x10^6 nVs. The CH6 was located at 650 mm from the foundation.

From these values of cumulative signal strength, the location of the channels is important to capture signal released from the crack [12, 19–21]. At the same time, the motion of the wave induced by the crack is also to be taken into consideration.

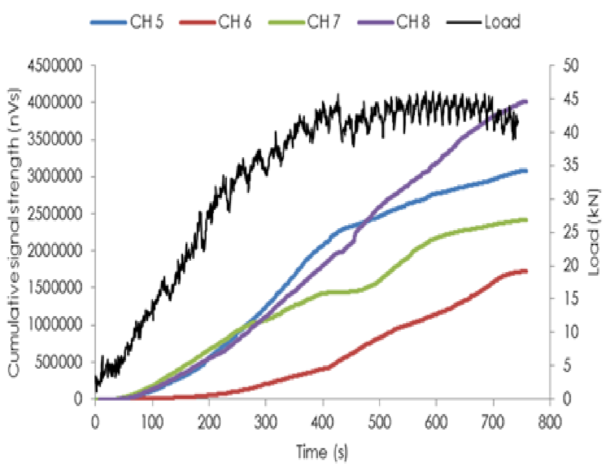

Figure 8. Cumulative signal strength and load with respect to time for all channels

4. Conclusions

AE is a practical approach in monitoring the fracture mechanisms of RC structural elements explicitly. Higher monotonic load intensity increases the AE activities. It can be observed that most of the crack in the RC beam-column joint was concentrated at the central area of the joint sample. Four types of cracks were identified with reference to the signal strength. The cracks progressed from crack nucleation to first crack, first diagonal crack, and localised diagonal crack. Cracks were also discovered to evolve in three distinctive stages. It began with flexural cracks in the early stages and progressed to mixed mode cracks with broader flexural crack coverage in the second stage. The final stage reveals that diagonal cracks appeared massively before the RC beam-column joint failed.

Acknowledgments

The authors would like to express their gratitude to the Ministry of Education (MOE) for funding the research works under Grant No. RAGS/1/2014/TK02/UITM/19. Acknowledgement is also conveyed to Universiti Teknologi MARA, Cawangan Pulau Pinang for offering the facilities to complete the laboratory works.

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