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A STUDY ON THE FRACTURE OF REINFORCED CONCRETE BEAMS UNDER SHEAR USING THE AE TECHNIQUE

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Abstract. Reinforced concrete structures deteriorate under service conditions due to various factors including loading, environment etc. The failure associated with these structures could be either due to flexure, shear, torsion or a combination of these. Understanding the brittle failure due to shear is of practical importance due to increased use of beams having large depths. Hence, in this study, the acoustic emission (AE) technique is used for monitoring the behaviour of reinforced concrete specimens which fail by shear. The AE data of events, absolute energy and time are analysed to understand the fracture process and energy released. It is seen that, the events of higher energy are located in the region where actual failure took place by the formation of diagonal tension crack due to shear. Thus, the critical failure path in RC beams can be identified through the events of higher energy.

1 INTRODUCTION

Reinforced concrete structures deteriorate under service conditions due to various factors including loading, environment etc. The failure associated with these structures could be either due to flexure, shear, torsion or a combination of these. Understanding the brittle failure due to shear is of practical importance due to increased use of beams having large depths. Hence, in this study, the acoustic emission (AE) technique is used for monitoring the behaviour of reinforced concrete specimens which fail by shear.

Various researchers have attempted to study the fracture behavior in reinforced concrete under shear. Bazant and Kim [1] have studied the size effect in shear failure of longitudinally reinforced concrete beams. Their test results have indicated a significant size effect and a rational mechanics-based formula was derived considering the effect of steel ratio and shear span. Bazant and Kazemi [2] presented size effect on diagonal shear failure of beams without stirrups. The beams were geometrically similar and the test results indicate a significant size effect and showed a good agreement with the Bazant's law for size effect. Muttoni and Ruiz [3] investigated the shear strength of beams and one-way slabs without stirrups based on the opening of a critical shear crack. A rational model accounting for shear-carrying mechanisms after the growth of crack was developed to estimate the shear strength of members without shear reinforcement. Syroka and Tejchman [4] carried out experimental investigations for size effect in reinforced concrete beams failing by shear. The size effect in concrete beams with steel bars was in agreement with the size effect law by Bazant. Slowik [5] investigated shear failure mechanism and shear capacity in longitudinally reinforced concrete beams without transverse reinforcement. It was shown that the effective length-to-depth ratio had a considerable influence on the contributions to the shear resistance mechanism and thus the ultimate shear capacity. Carmona and Ruiz [6] presented bond and size effects on the shear capacity of RC beams without stirrups. The results of their model provide an understanding of the influence of steel-to-concrete bond on the shear strength and the size effect exhibited in test results and its asymptotic behavior.

Various researchers have attempted to study damage and fracture using acoustic emission. Oh and Kim [7] have identified and characterized various damage characteristics of concrete structures due to cracking which arises under different loading conditions. Carpinteri et al. [8] presented damage analysis of reinforced concrete buildings by the acoustic emission technique. The observed proportionality between the rates of recorded AE activity from the cracks and the measured crack growth rates confirms significantly the effectiveness of the AE technique for damage evolution assessment in structural elements. Aldahdooh et al. [9] investigated and evaluated the damage in reinforced concrete beams with varying thickness using the acoustic emission technique. The results showed that as the level of damage increased, the values of all AE parameters increased and all AE parameters increased with increasing beam thickness. Vidyasagar et al. [10] have carried laboratory investigations on concrete fracture using acoustic emission technique. The results of AE statistics have revealed interesting features of the various stages of stress induced micro fracturing and growth leading to the failure of plain concrete and RC beams.

In this study, the acoustic emission (AE) technique is used for monitoring the behaviour of reinforced concrete beams with different percentage of reinforcement, which fail by shear. The AE data of events, absolute energy with time are analysed to understand the fracture process and energy released.

2 EXPERIMENTAL PROGRAM

2.1 Materials and mix proportions

Ordinary Portland cement (OPC) of 53 grade is used in casting of concrete specimens. Locally available natural sand and crushed granite (of maximum size 12.5 mm) are used as fine and coarse aggregates, respectively. The concrete mix design is done using the ACI method and the mix proportion of cement, fine aggregate and coarse aggregate obtained is 1:1.86:2.61 by weight. A water to cement ratio of 0.54 is used throughout the entire mix. The average compressive strength of companion cubes of dimension 150 mm was 51 MPa. All the specimens were cured in water for 28 days. The reinforcement used were high yield strength deformed steel bar of grade Fe500 with the tested yield stress of 550 N/mm^2. An electrical resistance strain gauge of 120 ohms is mounted at mid-span on the steel bar prior to casting.

The dimensional details of reinforced concrete beam specimen are shown in Figure 1. The thickness of beams were 50 mm. The beam specimens were reinforced with single longitudinal bar and no shear reinforcement (stirrups) were provided. In the reinforced concrete specimens, three reinforcing bar diameter i.e 8mm, 10mm and 12mm were used. The percentage of reinforcement is calculated as p_t (%)= $A_{st} * 100)/BD$. The reinforcement is provided above the initial notch tip. A gap of 12 to 14 mm is provided between the outer steel bar and the notch tip.

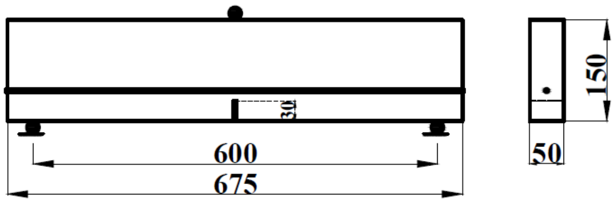

Figure 1: Reinforced concrete beam specimens

2.2 Testing of Specimens

The specimen are tested in a closed loop servo controlled hydraulic testing machine. The tests are performed under CMOD control with the rate of opening of 0.001 mm/sec. The testing configuration of the beam specimen and instrumentation used are shown in Figure 2. An in-built load cell of 35 kN was used for measuring the load. The load point displacement is measured at the midspan using LVDTs. An electrical resistance strain gauge of 120 ohms was used to measure the axial strain in reinforcing bar at the midspan.

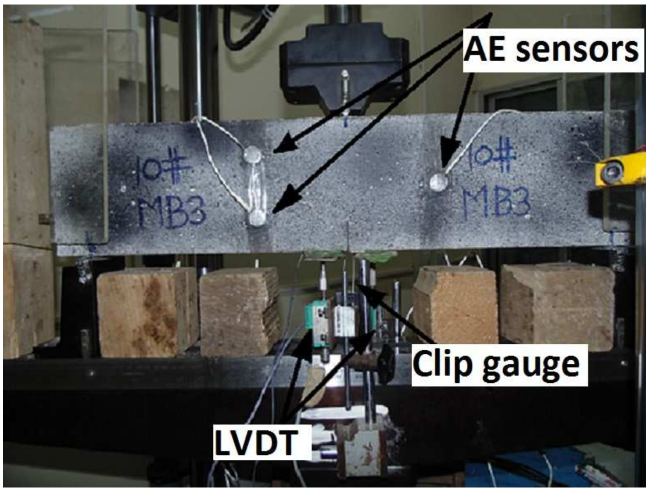

Figure 2: Testing configuration of beam specimen and instrumentation (clip gauge, LVDT and AE sensors)

The details of AE sensor location used for acquisition of AE data are shown in Figure 3. In order to understand the behavior of reinforced concrete specimens and to obtain a 3D location of AE-events, six AE-sensors are mounted on the specimen in a triangulation scheme with three sensors in the front and three on the back face as shown in Figure 3 to capture the cracking and fracture processes. The AE data such as hits, events, absolute energy, signal strength, spatial positions, amplitude and time are simultaneously acquired using data acquisition system during the experiments.

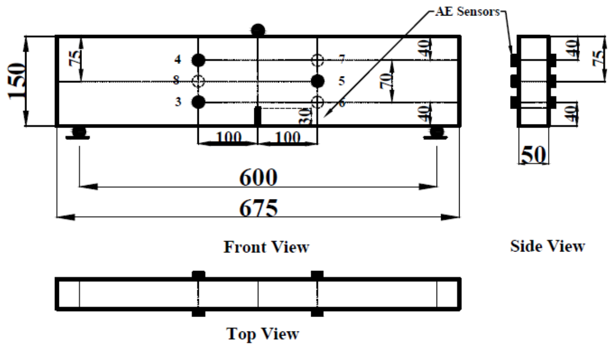

Figure 3: AE sensor location for the reinforced concrete beam specimens

The resonant type differential sensors R6D, having a diameter and height of 19 mm and 22 mm, respectively with an operating frequency of 35 to 100 kHz are used in the experimental work. High vacuum silicon grease has been used as couplant. The AE signals are amplified with a gain of 40 dB using a (PAC) pre-amplifier. An eight-channel AE-WIN for SAMOS E2.0 (Sensor based Acoustic Multichannel Operating System), developed by Physical Acoustics Corporation (PAC)-USA has been used for AE data acquisition. A threshold of 40 dB, which is normally used for concrete is adopted.

3 Results and discussions

3.1 Results from mechanical testing

The present experimental work aims to understand the behavior of reinforced concrete beams with different percentage variation of longitudinal reinforcement and designed to fail under shear. The experimental data such as load, CMOD, mid-span vertical displacement and strain, acquired during the tests are analysed. Load versus CMOD, load versus mid-span displacement, load versus strain and load versus time are plotted for beam specimens with different percentage variation of reinforcement. Here, three single longitudinal reinforcement steel bars were used i.e 8mm, 10mm and 12mm and comparison is made between them to study the effect of reinforcement on their behavior.

From the plots of the load versus CMOD for reinforced concrete beam specimens as shown in Figure 4, it can be observed that the slopes are linear and almost matching until the load of 4 kN, after which snap through behavior was observed. (Snap through behavior was less for 10mm (1.05 %) and 12mm (1.51 %) and more for 8mm (0.67 %) specimen). For reinforced concrete beam specimens, an increase in percentage of reinforcement has shown corresponding increase in the linear stiffness and peak load. Upon reaching the peak load, the specimens of 10mm (1.05%) and 12mm (1.51 %) failed suddenly due to formation of diagonal shear cracks. For specimen of 8 mm (0.67 %), on reaching the peak load, the continuous yielding and elongation of reinforcing bar took place before final failure due to shear.

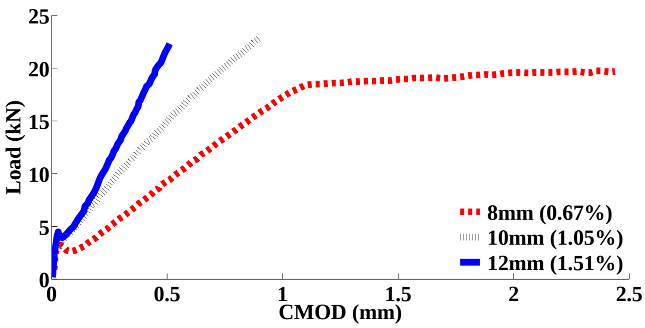

Figure 4: Plots of load versus CMOD for reinforced concrete beam specimens with different percentage variation of reinforcement

Figure 5 shows the plots of load versus mid-span displacement for reinforced concrete beams with different percentage variation of longitudinal reinforcement. From these plots, it can be seen that the initial stiffness of all the beams are almost the same since they are made up of the same concrete mix. The reinforcement does not come into effect upto a load of 4 kN for beams beyond which a snap through behavior occurs wherein the load drops and then increases. At this stage, the load is transferred by the concrete to the reinforcement. The slope of the load displacement plot now changes showing a stiffer behavior for beams having higher reinforcement percentage. Ductile behavior is seen in reinforced concrete beams with the lowest reinforcement. For the other reinforced concrete beams having a higher reinforcement percentage, a sudden failure is observed due to the formation of diagonal shear cracks. The cracks formed at final failure in reinforced concrete beam specimens are shown in Figures 6, 7 and 8 respectively for three beams with varying percentage of reinforcement. It is clearly seen from these failure images that all the beams have failed by the formation of diagonal shear cracks.

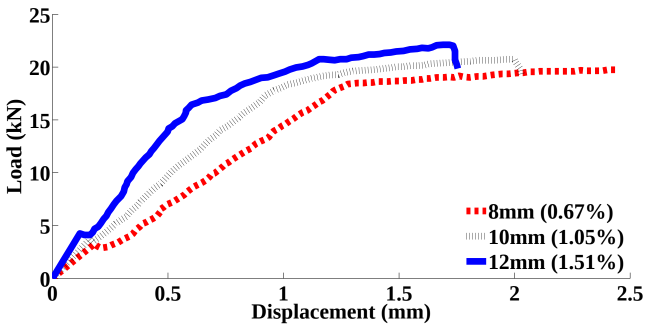

Figure 5: Plots of load versus displacement for reinforced concrete beam specimens with different percentage variation of reinforcement

Figure 6: Failure pattern for reinforced concrete beams of 8mm (0.67%)

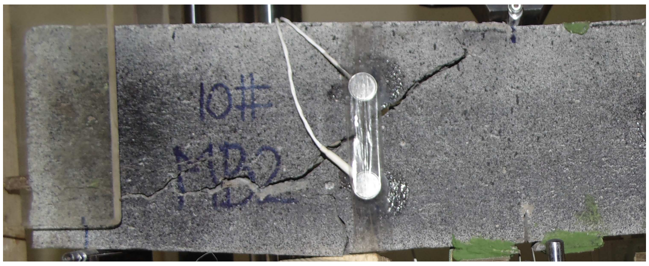

Figure 7: Failure pattern for reinforced concrete beams of 10mm (1.05 %)

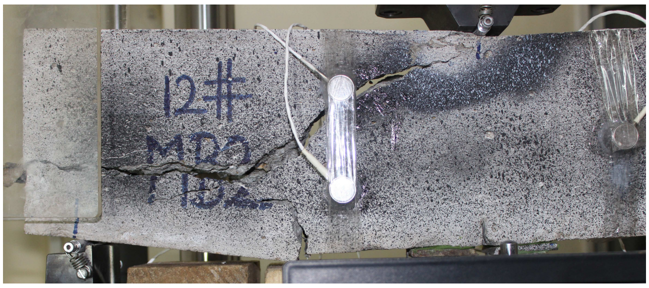

Figure 8: Failure pattern for reinforced concrete beams of 12mm (1.51%)

Figure 9 shows the load versus longitudinal strain in the reinforcements for reinforced concrete beam specimens. It is seen that the strain values at failure are inversely proportional to the percentage of reinforcement i.e higher is the failure strain values for lower percentage of reinforcement in the beams. This is consistent with the CMOD behavior reported earlier. As the strain in reinforcement increases the crack widths increase leading to larger CMOD values at failure.

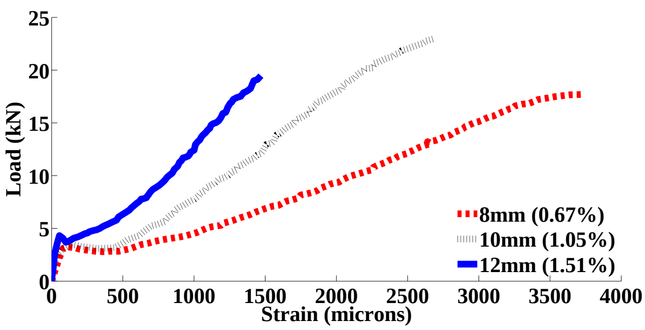

Figure 9: Plots of load versus strain for reinforced concrete beam specimens with different percentage variation of reinforcement

Figure 10 shows the variation of load with time for reinforced concrete beam specimens with different percentage of reinforcement. It is seen that for beams specimen with lower reinforcement, there is a long plateau in the load carrying capacity for considerable amount of time indicating that these beams behaved in a ductile manner suffering large strains in the reinforcement with corresponding increase in displacements. With larger amount of reinforcement, the beams failed in a brittle manner in a shorter time duration by the formation of diagonal cracks in the shear span of the beam.

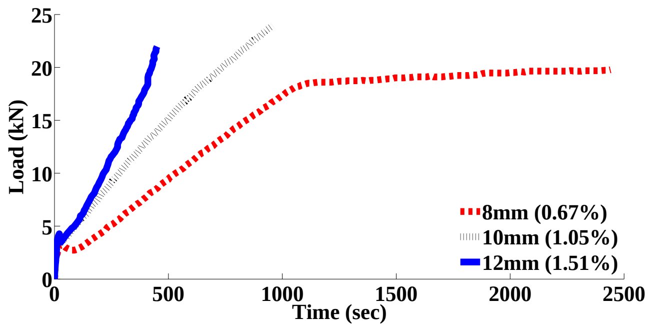

Figure 10: Plots of load versus time for reinforced concrete beam specimens with different percentage variation of reinforcement

Tables 1 and 2 shows the numerical values of the CMOD, displacement and maximum load at the first kink and at the ultimate load. In this table, the corresponding values for plain concrete beams of beam sizes are also shown. The numerical value of CMOD and displacement at the first kink indicates when the load gets transferred to the reinforcement. It is seen that the CMOD values at first kink in reinforced and plain concrete beams match closely. However, the mid-span vertical displacement values of reinforced beams are slightly higher than the corresponding plain concrete ones due to the presence of reinforcement which enhances their stiffness. The ultimate value of CMOD and displacement indicates the maximum displacement/ ductility of the reinforced concrete beam specimen before failure.

Table 1: Details of test results at first kink for reinforced concrete beams

Beam rebar (mm (%))	CMOD (mm)	Disp (mm)	Max load (kN)
8(0.67%)	0.031	0.17	3.26
10(1.05%)	0.025	0.16	3.46
12(1.51%)	0.028	0.11	4.49
PCC	0.044	0.080	-

Table 2: Details of test results at ultimate for reinforced concrete beams

Beam rebar (mm (%))	CMOD (mm)	Disp (mm)	Max load (kN)
8(0.67%)	2.43	2.42	19.69
10(1.05%)	0.89	2.00	22.83
12(1.51%)	0.51	1.73	22.31
PCC	-	-	4.00

3.2 Results from acoustic emission

The AE events and absolute energy are obtained from the AE sensors during the tests on reinforced concrete beams of three different sizes and percentage of reinforcement.

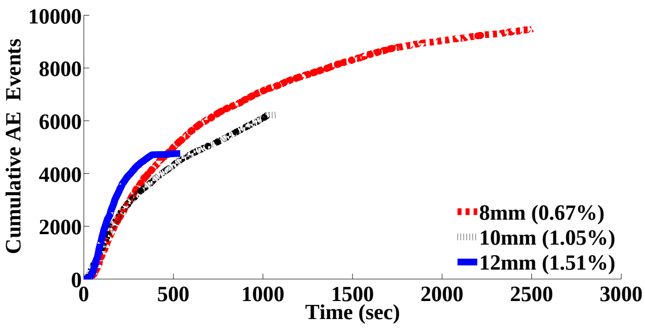

Figure 11: Plots of cumulative events versus time for reinforced concrete beams with different percentage variation of reinforcement

Figure 11 shows the plots of cumulative events with time for reinforced concrete beam specimens with different percentage variation of reinforcement. The following observations are made from these plots:

- It is seen that the beams having smaller percentage of reinforcement develops higher cumulative AE events than those having larger amount of reinforcement. This is due to the formation of a larger number of micro-cracks within the domain of the mid-span region of the beam wherein the sensors are located.

- Initially, the rate of increase in cumulative AE events is high. This is due to the formation of large number of micro-cracks in concrete before the load is transferred to the reinforcement. Once the reinforcement comes into effect, the longitudinal strains on it increases and lowers the micro-cracks formation in concrete as reflected by lower rate of increase in the AE events.

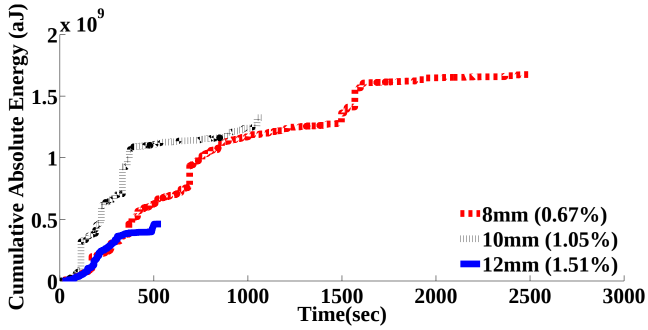

Figure 12: Plots of cumulative absolute energy versus time for reinforced concrete beams with different percentage variation of reinforcement

Figure 12 show the plots of cumulative absolute energy with time for reinforced concrete beam with different percentage variation of reinforcement. The following observations are made:

- The beams having lower percentage of reinforcement showed larger release of acoustic energy than those with higher reinforcement. This is due to the ductile behavior of these beams wherein the beams failed after undergoing large strains in the reinforcement before failure which occurred after a considerable amount of time.

- There is a sudden increase in absolute acoustic energy at different time instances in all the beams. This is due to the coalescence of small micro-cracks to form a larger crack. There is a larger spike in the acoustic energy just before failure indicating the propagation of a major crack.

The picture in Figure 13 shows the AE events location at failure for reinforced concrete beam specimen with 10mm bar (1.05%). Figure 14 show the location of events having absolute energy levels greater than 10^6 aJ and those lying between 10^5 and 10^6 aJ for a typical reinforced concrete beam with 10 mm rebar. As seen from this figure, most of the lower energy events are concentrated in the mid-span region wherein a notch was provided in the lower part of the beam. However, an interesting observation is that, most of the higher energy events are located in the region indicated by a best fit line passing through them. This best fit line indicates critical failure path i.e the location where actual failure took place by the formation of the diagonal tension crack due to shear (as seen in Figure 7). Thus, AE events and energy could be used to indicate the possible failure location in health monitoring of structural elements.

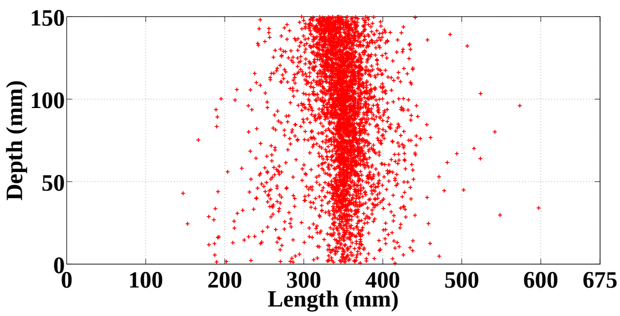

Figure 13: Picture showing AE events location at failure for reinforced concrete beam of 10mm (1.05%)) specimens

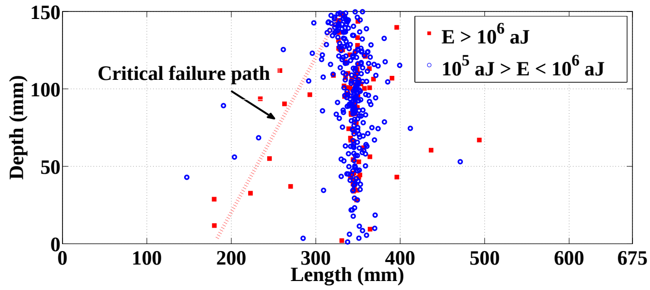

Figure 14: Picture showing events with classification of absolute energy for reinforced concrete beam of 10mm (1.05%)

4 CONCLUSIONS

In this study, the AE technique has been used for monitoring the behavior of reinforced concrete specimens with different percentage of reinforcement which fail by shear. The specimen were tested in three point bending under CMOD control in the closed loop servo controlled hydraulic testing machine. The data from load, CMOD, displacement and strain in steel on beam specimen were useful to understand the mechanical and fracture behaviour of reinforced concrete which failed by shear.

From this study, the following conclusions are made:

- The cumulative AE events are much higher in larger beams when compared to smaller beams. This is due to larger ligament length of concrete along the crack path. More number of micro-cracks form along the crack path as reflected by the number of AE events.

- The beams with lower percentage of reinforcement showed larger release of acoustic energy than those with higher reinforcement. This is due to the ductile behavior of these beams wherein the beams failed after undergoing large strains in the reinforcement before final failure which occurred after a considerable amount of time.

- The events of higher energy are located in the region where actual failure took place by the formation of diagonal tension crack due to shear. Thus, the critical failure path in RC beams can be identified through the events of higher energy in structural health monitoring programs.

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