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MIXED MODE CRACK PROPAGATION IN REINFORCED CONCRETE BEAMS - EFFECTS OF SIZE AND REINFORCEMENT RATIOS

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Abstract. The mixed mode crack growth in reinforced concrete is studied for effects of size and reinforcement ratios. The beam specimens were reinforced with a single longitudinal bar and no shear reinforcement was provided. In the experimental work, three reinforcing bar diameters i.e. 8mm, 10mm and 12mm were used for the small, medium and large beam specimens respectively. The notch was provided at the quarter span, as it is the region prone for mixed mode crack initiation and propagation. The data from load, CMOD, displacement and strain in steel were useful to understand the behaviour of reinforced concrete in opening and mixed mode. It can be concluded that, the larger beams are more brittle compared to the smaller ones and this observation is consistent with the size effect law for reinforced concrete. It is observed that, the final failure occurs due to propagation of the flexural crack at mid-span and the diagonal tension crack resulting from inadequate shear capacity at the quarter-point position of the beam. This implies that a shear-tension crack develops suddenly leading to a more brittle kind of failure than a pure flexural crack in tension.

1 INTRODUCTION

Civil Engineering structures are commonly subjected to a combination of loads which lead to the development of normal and shear stresses at any given point. This gives rise to mixed-mode fracture conditions at pre-existing cracks and notches. Current design codes for the shear resistance of reinforced concrete are still based on the empirical relations. Under pure shear stresses, cracks tends to propagate primarily in sliding mode. Under mixed mode fracture in reinforced concrete, the determination of crack trajectory until crack instability is more challenging than the opening mode. In this work, an attempt has been made to understand the mixed mode crack propagation in reinforced concrete beams for effects of size and reinforcement ratios.

The work done by researchers on mixed mode studies in reinforced concrete is discussed here. Carmona et al. [1] conducted an experimental program to investigate the mixed mode fracture in reinforced concrete. The tests were designed so that only one single mixed-mode crack generates and propagates through the specimen, as opposed to the usual dense crack pattern found in most of the tests in the scientific literature. These experiments helped to understand the mechanisms of crack initiation and propagation under mixed-mode load conditions. Carpinteri et al. [2] developed the bridge crack model for modelling the propagation of flexural and shear cracks through reinforced concrete beams. They concluded that the diagonal tension failure is an unstable process from shear cracks and provokes the collapse of the element. Carpinteri et al. [3] introduced bridged crack model which is an efficient theoretical and numerical tool for investigating the behavior of structural reinforced concrete (RC) elements in bending. In this work, the three collapse mechanisms flexure, shear, and crushing were considered jointly, so that failure modes could be immediately compared to detect which one of them dominated the related failure load. Carpinteri et al. [4] presented an experimental program to validate a bridge crack model connecting failure modes with cracking process in reinforced concrete (RC) beams. Their experimental program investigated five different reinforcement percentages with four samples each, for a total of 20 beams subjected to three point bending tests. The model unifies the theoretical treatment of yielding, shear, and crushing failures to predict collapse mode transitions and related size effects. Carmona and Ruiz [5] described a simple model, based on the concepts of fracture mechanics, to evaluate the diagonal tension failure load in RC beams without stirrups. The proposed model considers the variables that govern the failure, and includes the bond between concrete and steel. A failure criterion was proposed based on whether the crack reached its critical crack depth. The model reproduces the size effect which has been experimentally observed. Carpinteri et al. [6] studied the failure mode transitions in RC beams. RC beams under flexure show three different collapse mechanisms i.e. tensile, shearing and crushing due to varying mechanical and geometrical parameters. Their results focussed on the prediction of the predominant collapse mechanisms, the failure load as well as the analysis of the mutual transition between the different failure modes by varying the scale, slenderness and percentage of reinforcing steel. Prashanth and Chandra Kishen [7] conducted an experimental study on mixed mode crack propagation in reinforced concrete beams with single longitudinal bar using acoustic emission technique. They concluded that, the acoustic emission data such as events, amplitude, absolute energy were used to understand the crack growth mechanism in opening and mixed mode crack propagation of reinforced concrete beams. The above works are few studies, which have been reported on mixed mode fracture for reinforced concrete beams. The main objective of the present work is to understand the mixed mode crack propagation in reinforced concrete beams and to study the mechanical behavior of different sizes of beams (small, medium and large) with different percentage variation of reinforcement.

2 EXPERIMENTAL PROGRAM

2.1 Materials and mix proportions

Ordinary Portland cement OPC 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 150mm was 51 MPa. All the specimens were cured in water for 28 days. The reinforcement used was 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-length of steel bar prior to casting.

The specimens had a length to depth ratio (L/D) of 4.5, span to depth ratio (S/D) of 4, and notch to depth ratio (a_0/D) of 0.2. The notch was provided at the quarter span (D), as this was the region of crack propagation. The thickness (B) was 50 mm and was kept constant for all sizes of specimens. The beam specimens were reinforced with single longitudinal bar and no stirrups were provided. In the present experimental work, three reinforcing bar diameter of 8mm, 10mm and 12mm were used for each of the small, medium and large beam size specimens. The reinforcement is provided above the initial notch tip. A gap of 12 to 14 mm is provided between the outer edge of steel bar and the notch tip. The details of dimensions of beam specimen of small, medium and large size with single bar of 8mm, 10mm and 12mm are shown in Table 1. The details of geometry of specimen are shown in Figure 1.

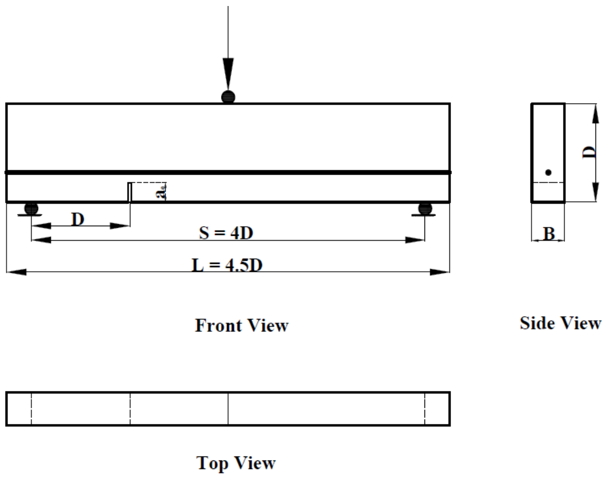

Figure 1: Details of geometry of the specimens

Table 1: Details of dimensions of beam

Beam Size	**D** (mm)	**S** (mm)	**L** (mm)	a_0	ϕ	p_t (%)
S	75	300	337.5	15	8 10 12	1.34 2.09 3.01
M	150	600	675	30	8 10 12	0.67 1.04 1.50
L	300	1200	1350	60	8 10 12	0.33 0.52 0.75

Dimension - **D** -Depth, **S** - Span, **L** - Length
Beam Size - **S** - Small, **M** - Medium, **L** - Large
a_0 is Notch size in mm.
ϕ-Bar diameter in mm.
$p_t(\%)=(A_{st}/BD)*100$

2.2 Testing of Specimens

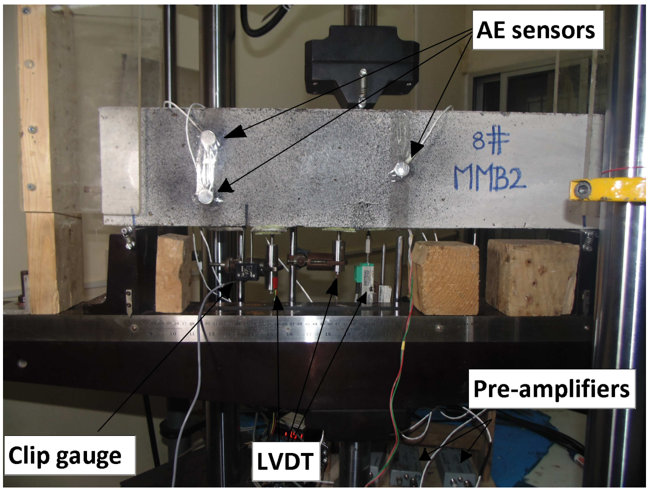

Figure 2: Testing of beam specimen and instrumentation such as clip gauge and LVDT and strain gauge to reinforcement

The specimens were tested in a closed loop servo controlled hydraulic testing machine. The tests were performed in displacement/stroke control at the rate of 0.001 mm/sec. The testing of the beam specimen with the machine and instrumentation are as 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 linear variable displacement transformer (LVDT). The crack mouth opening displacement (CMOD) measurements were taken at the notch provided at quarter span using a clip gauge. An electrical resistance strain gauge of 120 ohms was used to measure the axial strain in the reinforcing bar at the midspan.

3 Results and discussion

3.1 Results from mechanical testing

The experimental data such as applied load, CMOD, mid-span displacement and rebar strain, acquired during the tests are analysed. The present experimental work aims to understand the behavior and the effect of percentage of reinforcement on small, medium and large size specimen on mixed mode crack propagation in reinforced concrete.

Table 2 shows the numerical values at different points to understand the mixed-mode crack propagation for small, medium and large size specimens with different percentage variation of reinforcement.

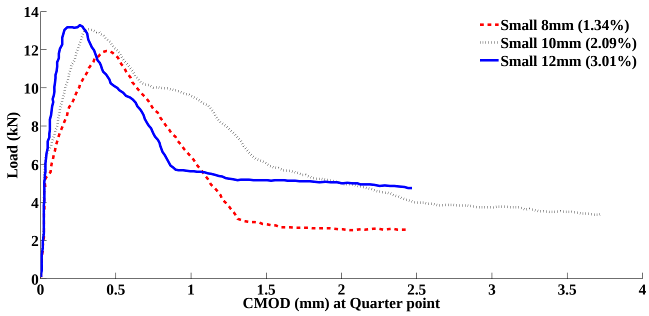

Figure 3: Load versus CMOD at Quarter Point for small size specimens with different percentage variation of reinforcement

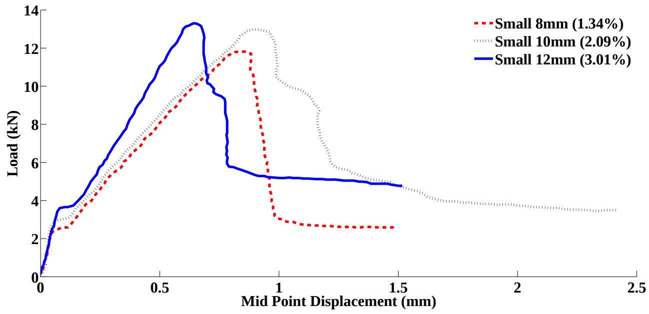

Figure 4: Load versus Mid Point Displacement for small size specimens with different percentage variation of reinforcement

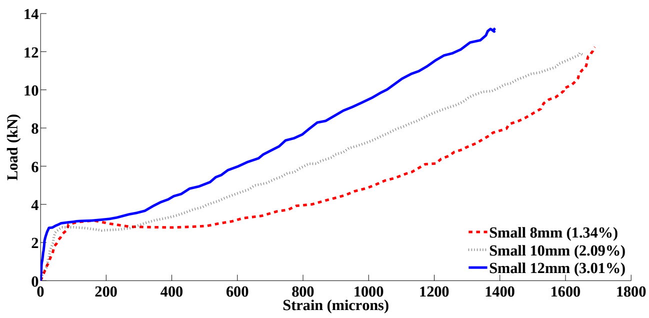

Figure 5: Load versus Strain for small size specimens with different percentage variation of reinforcement

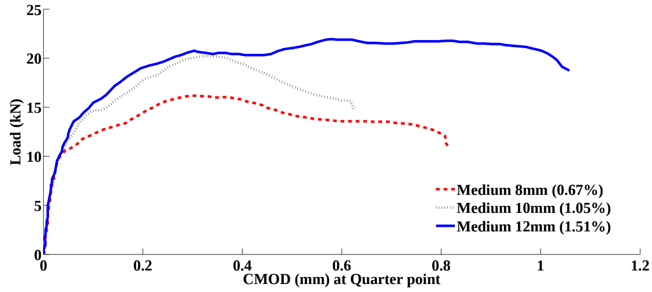

Figure 6: Load versus CMOD at Quarter Point for medium size specimens with different percentage variation of reinforcement

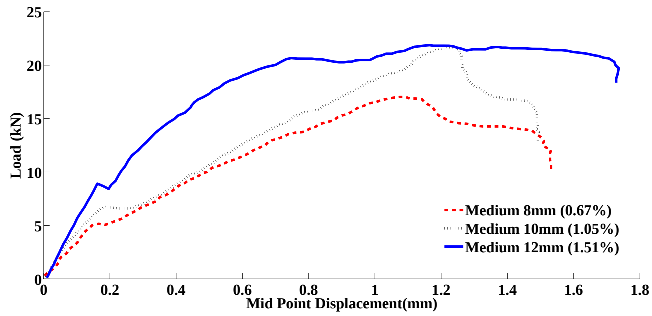

Figure 7: Load versus Mid Point Displacement for medium size specimens with different percentage variation of reinforcement

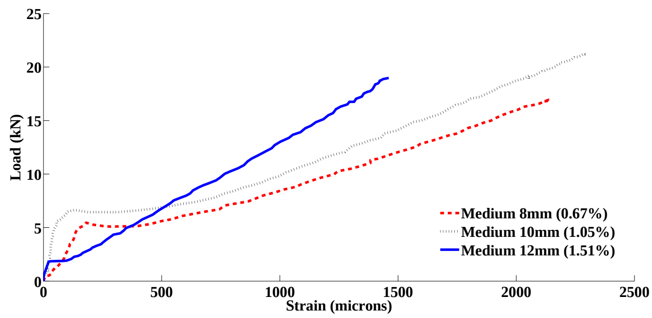

Figure 8: Load versus Strain for medium size specimens with different percentage variation of reinforcement

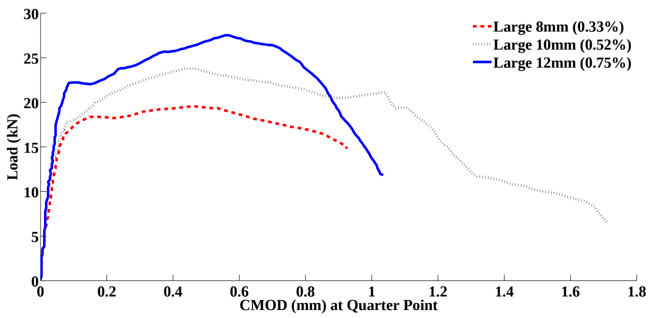

Figure 9: Load versus CMOD at Quarter Point for large size specimens with different percentage variation of reinforcement

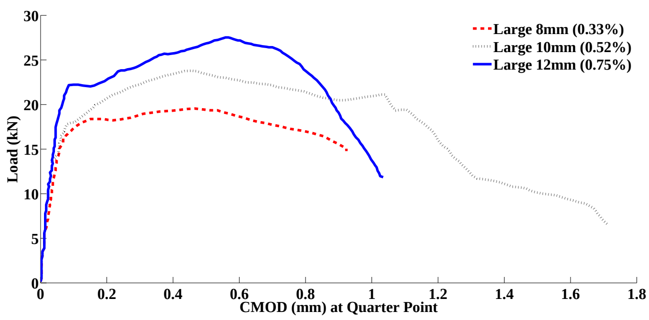

Figure 10: Load versus Mid Point Displacement for large size specimens with different percentage variation of reinforcement

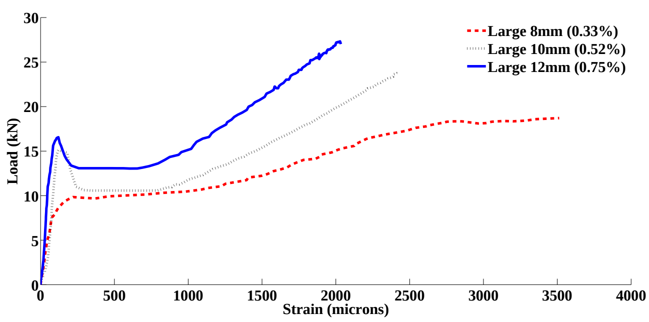

Figure 11: Load versus Strain for large size specimens with different percentage variation of reinforcement

Table 2: Details of test result

Beam size Dia (%)	Max load (kN)	CMOD		Disp	
		M	F	M	F
S08(1.34%)	11.93	0.44	2.43	0.88	1.49
S10(2.09%)	13.07	0.32	3.38	0.92	2.42
S12(3.01%)	13.29	0.26	2.47	0.65	1.52
M08(0.67%)	16.13	0.32	0.81	1.07	1.53
M10(1.05%)	20.42	0.34	0.62	1.23	1.49
M12(1.51%)	21.94	0.58	1.06	1.15	1.73
L08(0.33%)	19.36	0.53	0.92	2.26	2.68
L10(0.52%)	23.79	0.45	1.71	1.87	3.27
L12(0.75%)	27.52	0.56	1.02	2.77	2.89

M - at maximum load in kN
F - at failure in kN

Figures 3 4 and 5 show the plot of load versus CMOD at quarter point, load versus displacement at midpoint and load versus strain respectively for small size specimen with different percentage of reinforcement. The three steel bars with percentage of reinforcement i.e 8mm (1.34 %), 10mm (2.09 %) and 12mm (3.01 %) were considered for the study and comparison is made between them. From the plots of load versus CMOD at quarter point shown in Figure 3, it can be observed that initially the slopes are linear and almost coinciding till a load of 5 kN, after which the beam with greater reinforcement shows higher slope till the peak load indicating a stiffer behavior. After the peak load, the load carrying capacity of specimen decreases with softening behavior. This softening behavior shows the formation of the fracture process zone ahead of the notch at the quarter span region with a lot of microcracking. In the final stage before failure the CMOD increases steadily at constant load indicating that the crack begins to propagate continuously leading to failure. From the plots of the load versus displacement at mid point shown in Figure 4, it can observed that stiffness are almost coinciding till the load of 2.5 kN. After that, the specimen with greater percentage of reinforcement shows higher stiffness till the peak load. After the peak load, the load carrying capacity of all the beams suddenly drops and remains constant with increasing displacements before failure. From the plot of the load versus strain as shown in Figure 5, it can be observed that the strain in rebar does not develop initially and the load is carried by the uncracked concrete. As the concrete cracks, the load is carried by the steel rebar and the strains increase steadily in all the beams. At a given load, the strain is higher in the beam with lower percentage of reinforcement.

Figure 12: Failure pattern for small size with 10mm bar (2.09 %)

Figures 6 7 8 and Figures 9 10 11 show the plot of load versus CMOD at quarter point, load versus displacement at midpoint and load versus strain respectively for medium and large size specimen with different percentage variation of reinforcement. Similar observation as in the case of small beam is seen for the medium as well as large beams. However, from Figures 6 and 9, we see the absence of the softening kind of behaviour in the load-CMOD plots of medium and large beams, respectively but seen in small beams. This indicates that the crack keeps propagating continuously after reaching the peak loads with increasing CMOD. There is no initiation and coalescence of micro-cracking taking place. The values of CMOD at failure are also much lower in the case of medium and larger beams when compared to small beams. This means that the larger beams are more brittle compared to the smaller ones and this observation is consistent with the size effect law for reinforced concrete beams.

Figure 13: Failure pattern for medium size with 8mm bar (0.67 %)

From Figures 3 to 11, it is seen that by increasing the percentage of reinforcement in each of the small, medium and large size beams, respectively the initial stiffness and the peak load increases. There is not much effect on the ductility in the case of mixed-mode fracture and failure of reinforced concrete beams.

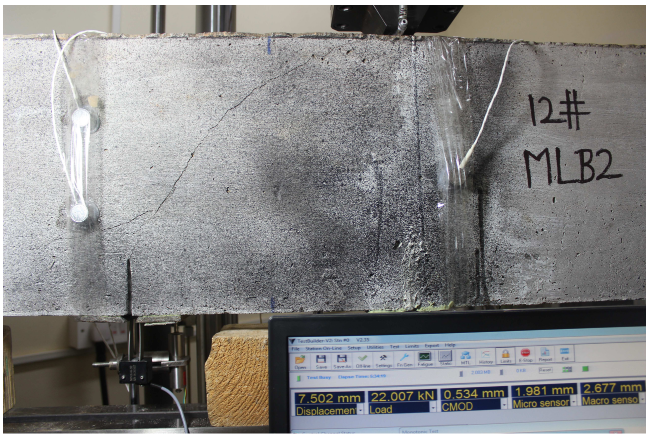

Figure 14: Failure pattern for large size with 12mm bar (0.75 %)

Pictures in Figures 12 13 14 shows the typical failure pattern of the crack in opening mode and mixed mode for small size with 10mm bar (2.09 %), medium size with 8mm bar (0.67 %) and large size with 12mm bar (0.75 %) respectively. The final failure occurs due to propagation of the flexural crack at mid-span and the diagonal tension crack resulting from inadequate shear capacity at the quarter-point position of the beam. This implies that a shear-tension crack develops suddenly leading to a more brittle kind of failure than a pure flexural crack in tension.

4 CONCLUSIONS

The mixed mode crack growth is studied in reinforced concrete to study the effect of size and reinforcement ratios. The beam specimens were reinforced with a single longitudinal bar and no shear reinforcement was provided. In the present experimental work, three reinforcing bar diameter i.e 8mm bar, 10mm bar and 12mm bar is used for the small, medium and large beam specimens respectively, to study the mixed-mode crack propagation with varying reinforcement. The notch is provided at the quarter span, as it is the region prone for mixed mode crack initiation and propagation. The specimen is tested in three point bending under displacement/stroke control in a closed loop servo controlled hydraulic testing machine. The data from load, CMOD, displacement and strain in steel were useful to understand the behaviour of reinforced concrete in opening and mixed mode.

Fom this study, the following conclusions are made:

- The values of CMOD at failure are much lower in the case of medium and larger beams when compared to small beams. This means that the larger beams are more brittle compared to the smaller ones and this observation is consistent with the size effect law for reinforced concrete beams.

- Upon increasing the percentage of reinforcement in each of the small, medium and large size beams, it is observed that the initial stiffness and the peak load increases. There is not much effect on the ductility in the case of mixed-mode fracture and failure of reinforced concrete beams.

- The final failure occurs due to propagation of the flexural crack at mid-span and the diagonal tension crack resulting from inadequate shear capacity at the quarter-point position of the beam. This implies that a shear-tension crack develops suddenly leading to a more brittle kind of failure than a pure flexural crack in tension.

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