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EXPERIMENTAL AND NUMERICAL INVESTIGATION ON FLEXURAL BEHAVIOR OF HIGH STRENGTH REINFORCED CONCRETE BEAM

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ABSTRACT
The use of high strength concrete has become popular in construction work because of its improved strength and durability. High-strength concrete can be used as a substituting material over conventional concrete for structural members. This study describes the flexural behaviour of high strength reinforced concrete beam. The variation of flexural ductility with concrete compressive strength is quite complicated and thus sincerely reviewed in this paper. An experimental and numerical investigation of high strength reinforced concrete beam has been conducted in the present study. Four simply supported beams, having compressive strength of 27.50 MPa, 43.85 MPa, 54.05 MPa and 62.01 MPa, reinforced in top and bottom edges of the beam have been investigated in this study. The beams were tested under two-point loading to reveal their flexural behaviour. Load-deflection diagram and ductility index are the primary parameters that were considered in this study. The ultimate loads that obtained from the experimental results were found to be in good agreement with the numerical results. In addition, this study also compared the theoretical and experimental deflection at the mid-point of the beam. The cracking behaviour of all the beams and the crack width is also reviewed in this paper.

Keywords: high strength concrete; flexural ductility; load-deflection; crack width.

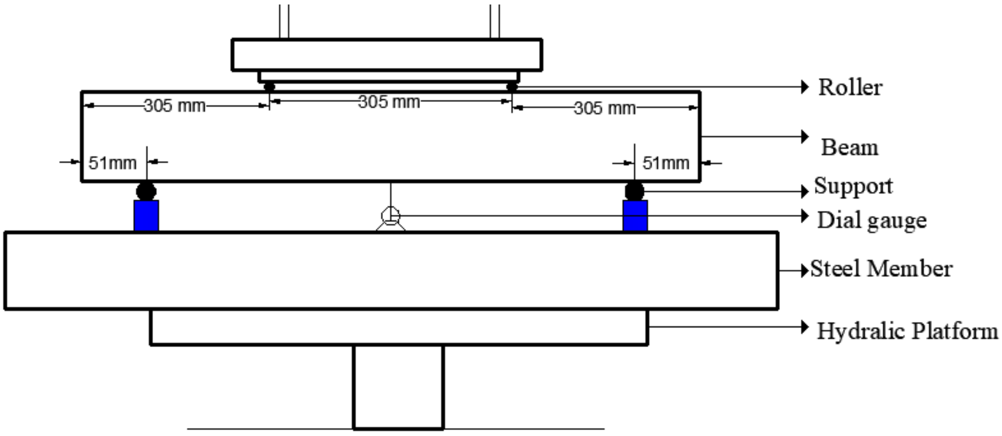
INTRODUCTION

In recent years, because of the advancement of concrete technology, the use of high strength concrete has increased and high strength concrete has been now used in many countries around the world. They also raised the upper limit of the concrete strength in their building code (Pam et al., 2001) to consider the higher strength of modern concrete. The use of high strength concrete can improve the durability of concrete, decrease the shrinkage and creep of the concrete, and reduce the size of the structural member (Lin et al., 1992). Although, in many cases the behaviour of high strength concrete is different from normal strength concrete, therefore high strength concrete should not be treated as normal strength concrete with greater strength. Another problem of high strength concrete i.e. generally more brittle in nature compared to that of normal-strength concrete (Pam et al., 2001). As high-strength concrete is more brittle in nature, their crack does not always occur in aggregate-hardened cement paste interfaces (Ho et al., 2002). It has been found that reinforced concrete beams made of high-strength concrete, if not properly designed, could fail in a brittle manner (Sarkar et al., 1997). As a consequence, in the design of reinforced concrete integrating high strength concrete, meticulous checking of ductility, cracking, and shear strength of the structure is ineluctable.

METHODOLOGY

Four beams were tested under simply supported condition. The dimensions of each beam were 915 mm × 152.4 mm × 139.7 mm. The span length of each beam was 813 mm with 51 mm clearance from the each end to the support. The span depth ratios taken in this study is around 6 which are lower than the previous studies available in the literature. To facilitate the cracking patterns on beam during the application of load, gridding was done. Each unit was 10 mm × 10 mm. The beams were tested under two concentrated loads with a constant moment region. The distance between the two point loads was 305 mm. The deflections were measured at mid-point. The beams were tested under load control condition. The deflection was recorded for each 10 kN increment of load up to failure and their crack pattern was also recorded. The experimental setup of the beam under two point loading are shown in Fig.1. Material properties and the geometric dimensions of the tested beams are shown in Table 1.

Fig. 1:



Experimental setup

Table 1: Material properties and the geometric dimensions of the tested beams

Beam no.	Compressive strength, f'_c (MPa)	Depth of the centre of bottom Steel layer, d (mm)	Depth of the centre of top Steel layer d' (mm)	No. of Bottom Steel, A_s	No. of Top Steel A'_s
B1	27.50	96.3	25.4	2#16	2#12
B2	43.85	96.3	25.4	2#16	2#12
B3	54.05	96.3	25.4	2#16	2#12
B4	62.01	96.3	25.4	2#16	2#12

Experimental Investigation

The main objective of this experiment program is to investigate the flexural behavior of reinforced concrete beam. A total of four small-scale rectangular concrete beams were tested. All of them were reinforced with grade 60 steel. A total of four batches of concrete were used for this study. The designed compressive strengths for four batches were 27.50 MPa, 43.85 MPa, 54.05 MPa and 62.01 MPa. Development of first crack in the beam and fracture of the beam during experiment are shown in Fig. 2 and Fig. 3 respectively.

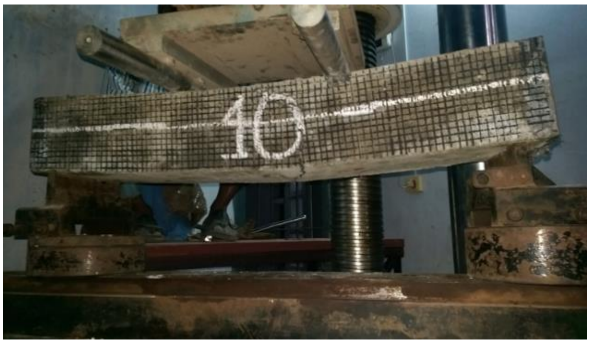


Fig. 2: Development of first crack in the beam   Fig. 3: Fracture of the beam during experiment

All specimens were loaded up to failure using a four-point flexural test under monotonic loading condition. The main variables are the compressive strength of concrete. The overall performance of the tested specimens was evaluated based on the overall flexural behavior.

Numerical Investigation

In this study the beam is analysed by static pushover analysis method due to incremental load application. The reinforcement detailing of the beam is carefully maintained and material property that is used in this program are tried be synchronized with the experimental result. The properties of concrete and reinforcement details used for experiment program were put in SeismoStruct software as shown in Table 2. The two point loading was set in the model of the beam by applying two incremental loads of 10 kN from 305 mm distance of each end of the beam. The two hinge support was placed at the bottom of the beam at 51 mm from both ends. The analytical model of the beam and development of first crack in the analytical model of the beam is shown in Fig. 4 and Fig. 5 respectively.

Table 2: Material properties of the beams for numerical investigation

Material name	Material type	Material properties	Remarks
Concrete 1	Con_ma	f'_c = 15 MPa up to 45 MPa	Used in beam B-1 and Beam B-2
Concrete 2	Con-hs	f'_c = 50 MPa up to 120 MPa	Used in beam B-3 and Beam B-4
Steel	Stl_bl	E = 200071.60 MPa F_y = 462 MPa	Used in all four beams

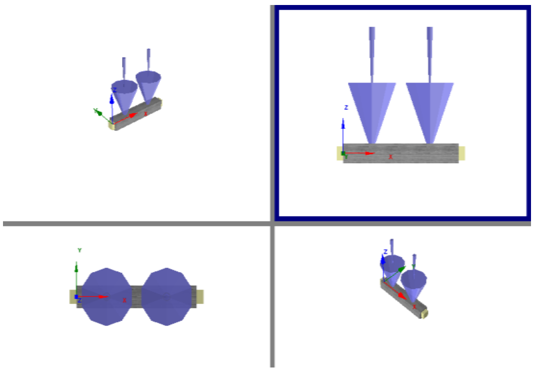


Fig. 4: Analytical model of the beam

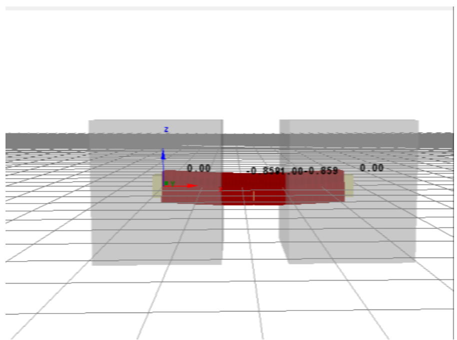


Fig. 5: Development of first crack in the analytical model of the beam

RESULT AND DISCUSSION

The parameters used to evaluate flexural performance were flexural cracking load and ultimate load under the load deflection behaviour, cracking width, ductility index, flexural capacity and deflection under service load.

Load deflection behaviour

Four separate load deflection curves were obtained experimentally and numerically and they are shown in Fig. 6 and Fig. 7. From Fig. 6 and 7 it can be shown that experimental load deflection curve slightly varies from numerical load deflection curve and numerical result shows larger deflection than experimental result except from beam B-1 where the experimental result shows larger value than numerical one.

The comparison of development of first crack loading and ultimate loading between experimental results and numerical evaluation are shown in Fig. 8 and Fig. 9. As seen in Fig. 8 and 9 the cracking load increases with the increase of concrete compressive strength both experimentally and numerically but numerical results showed larger value than experimental results. But the opposite phenomenon occurred in case of ultimate load. Here, experimental results showed larger value than numerical results except for beam B-1 which showed the similar value for both experimental and numerical.

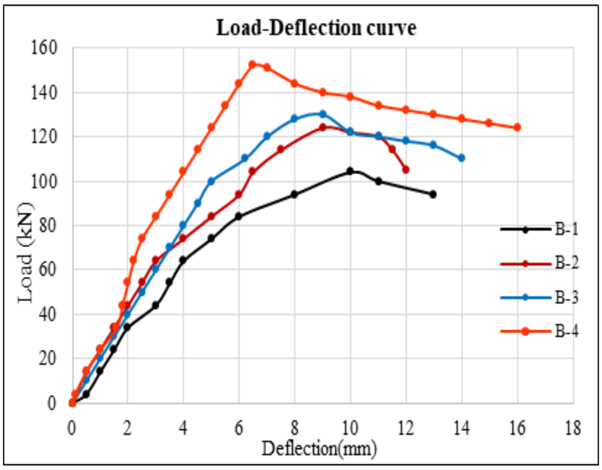


Fig. 6: Load-deflection curve from experimental results

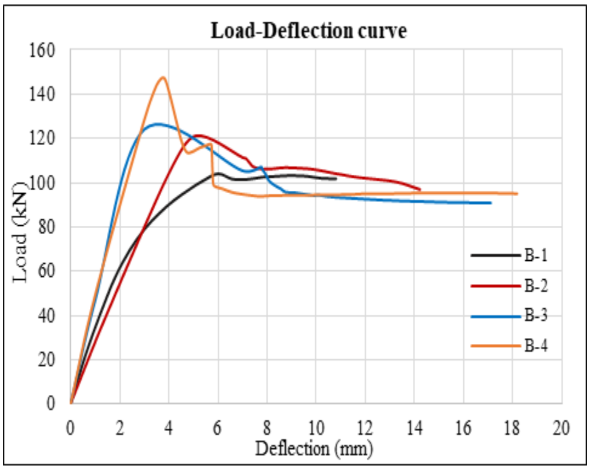


Fig. 7: Load-deflection curve from numerical results

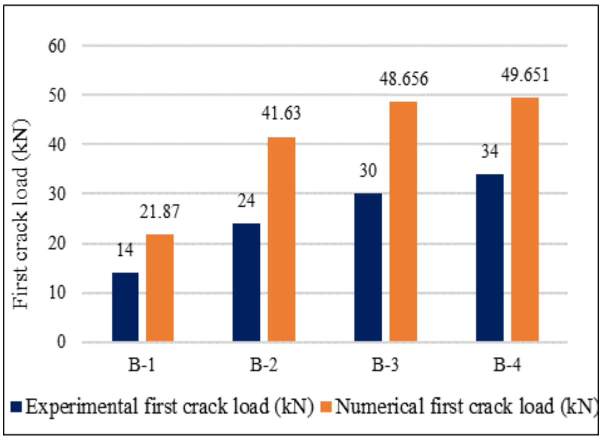


Fig. 8: Comparison of first crack load

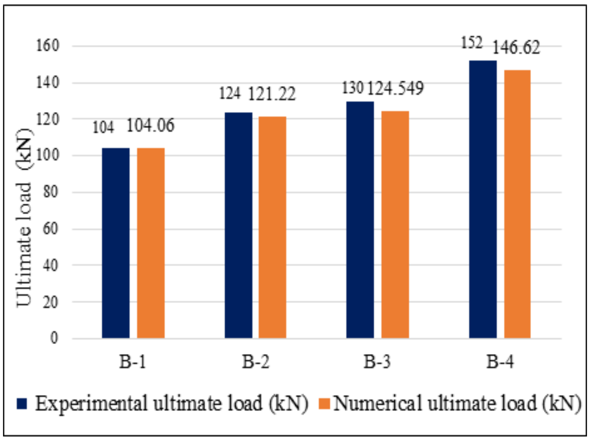


Fig. 9: Comparison of ultimate load

Cracking behaviour

Crack widths were measured at every load interval at the tension steel level and the crack formations were marked on the beam. The crack width at the tensile face was measured at every load stage in all the tests. The cracks forming on the surface of the beams were mostly vertical, suggesting failure in flexure. From experimental investigation it is observed that the crack widths are increasing for higher strength concrete. Though in most codes of practice, the maximum allowable crack width lie in the range of 0.10

to 0.40 mm (Vidivelli and Subbulakshmi, 2016), all crack widths found from the experiments exceed the value recommended in codes.

Table 3: Crack width and numbers of cracks for beam

Beam no	Max crack width (mm)	No. of crack between loading points
B-1	1.0	2
B-2	1.3	3
B-3	3.1	5
B-4	3.9	6

Ductility index

The ductility index (μ_d) was calculated depending on (Δ_{max}/Δ_y), where the deflection at ultimate load (Δ_{max}) is the deflection when the load reached 85% of the ultimate load and (Δ_y) is the deflection when the applied load reached 75% of the ultimate load (Pam et al., 2001). The variation of ductility index of beam both experimentally and numerically are shown in Fig. 10.

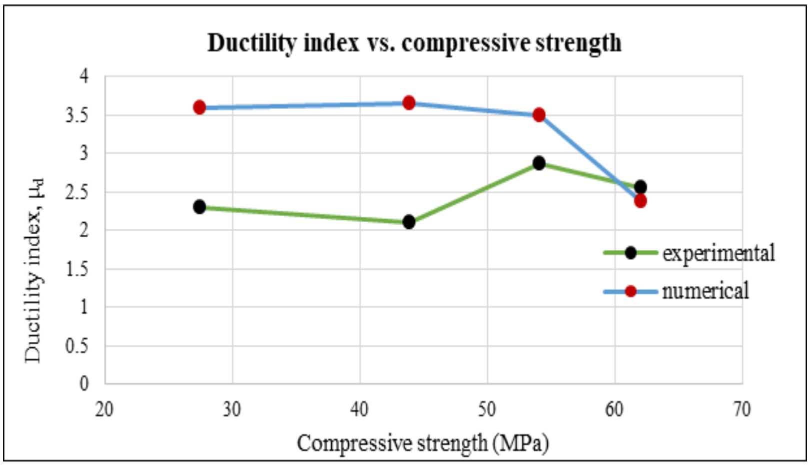


Fig. 10: Variation of ductility index with concrete compressive strength

From Fig. 10 it has been observed that the ductility index of beam showing large variation between the experimental and numerical results and opposite trend in the results. The main reason behind this variation and opposite trend in the result is the inaccuracy in casting of beam with lack of adequate clear cover and lack of required no. of dial gauge to measure the deflection under two point loading. It is known that concrete becomes less deformable and more brittle when its compressive strength increases especially when it is heavily reinforced. This might be the reason behind the decrease in ductility index for higher compressive strength of concrete.

Flexural capacity

Flexural strength of beams are shown in Table 4. From Table 4 it has been observed that the flexural strength of beam increases with the increase in the compressive strength of concrete both experimentally and numerically. This increase in flexural strength is rapid in case of beam B-2 and beam B-4.

Table 4: Flexural strength of beams

Beam no.	Compressive strength (MPa)	Flexural strength (MPa)	
		Experimental	Numerical
B-1	27.5	31.98	32.0
B-2	43.85	38.12	37.27
B-3	54.05	39.97	38.29

B-4	62.01	46.73	45.08

Maximum deflection at service load

Comparison between the calculated ($\delta_{ser,ACI}$), the corresponding experimental deflection ($\delta_{ser,exp}$) and numerical ($\delta_{ser,num}$) at service load are shown in Table 5. From the Table 5 it is observed that ACI 318-11 code expression for E_c value leads to a highly unconservative prediction of ($\delta_{ser,ACI}$) in terms of experimental result. But ACI 318-11 code overestimates the predicted deflection in terms of numerical result except for beam B-3.

Table 5: Experimental, numerical and predicted deflection at service load

Beam No.	$\delta_{ser,exp}$ (mm)	$\delta_{ser,num}$ (mm)	$\delta_{ser,ACI}$ (mm)	$\delta_{ser,exp}/\delta_{ser,ACI}$	$\delta_{ser,num}/\delta_{ser,ACI}$
B-1	3.90	2.00	2.66	1.47	0.75
B-2	3.95	2.30	2.67	1.48	0.86
B-3	4.00	3.80	2.59	1.54	1.47
B-4	3.40	1.90	2.87	1.18	0.66

CONCLUSIONS

The effect of concrete compressive strength on the flexural behaviour of reinforced concrete beam was investigated in this study. The load-deflection curves from the beams obtained experimentally are slightly different from numerical analysis. As concrete compressive strength increases the flexural strength of reinforced concrete beam also increases. The ductility index increases as concrete compressive strength increases for the same ρ up to some limit in terms of experimental results thereafter decreases as f_c' increases. ACI 318-11 code expression for E_c leads to a highly unconservative prediction of deflection at service ($\delta_{ser,ACI}$) in terms of experimental result. The maximum crack width lies in the range of 1.0 mm to 4.0mm which is larger than code suggested value.

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