

Cyclic Flexural Behavior of Reinforced Concrete Beams

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Abstract: The present study aims at investigating the cyclic flexural behavior of reinforced concrete beams with varying depths. Five reinforced concrete beams with beam depth ranging from 250 mm to 750 mm were tested under reversed cyclic loading and the influence of beam depth on the flexural strength and ductility of reinforced concrete beams was investigated. In addition, OpenSees was used to model the test specimens and the analytical results were compared with the experimental results. It is shown that there is no apparent size effect on the normalized ultimate flexural strength of the tested beams, while for the displacement ductility factor, a significant size effect is observed. Load-deflection hysteric curves of test specimens obtained by the fiber-based element of OpenSees with Concrete03 and Hysteric models are in good agreement with those from experimental tests.

1 Introduction

The size effect has been experimentally evidenced for most brittle types of failures of plain and reinforced concrete members, for example, shear and torsional failure of beams, punching shear failure of slabs and pullout failure of bars etc. [1, 2]. In addition, the effect of size on flexural behavior of reinforced concrete beams was also investigated [3-9]. Early work on flexural behavior of reinforced concrete beams indicated that there was no apparent size effect on flexural strength and rotational capacity [3, 4]. Appa et al. [5] and Yi et al. [6] reported from their studies that size effect is significant for both flexural strength and ductility. Most of the research on under-reinforced concrete beams confirmed the existence of size effect on rotational capacity [7-9]. Some researchers also investigated behavior of over-reinforced and prestressed concrete beams failing due to concrete compressive failure and found that significant size effect on rotational capacity or ductility of beams exists [10-12].

However, most of the studies reported in the literature are concerned with the size effect of flexural behavior of reinforced concrete beams that contain only tensile reinforcement and are subjected to monotonic loading. In reinforced concrete moment-resistance frames, the cross section of the beam end to resist the positive and negative moment induced by lateral earthquake and vertical loads, locates in the potential plastic hinge region where sufficient ductility and rotational capacity is required. Therefore, a better understanding of size effect on flexural

behavior of doubly reinforced concrete beams subjected to cyclic loading is necessary to ensure the safety of reinforced concrete structures.

In view of this, the influence of beam depth on the cyclic flexural behavior of RC beams was investigated experimentally in this study. Besides, nonlinear analysis of test specimens was carried out using OpenSees models.

2 Experimental Program

2.1 Test Specimens and Material Properties

In total, five specimens with beam depth ranging from 250 mm to 750 mm were tested under reversed cyclic loading. The specimens used in the experimental program consisted of two beam elements with identical section cast integrally with a stub as the column element at mid-span. The details of specimens are shown in figure 1 and table 1.

All specimens were cast from the same batch of concrete supplied by a local ready-mix plant. Concrete cubes of 150×150×150 mm³ were casted along with the specimens, and compressive strength tests were performed at time of cyclic loading tests. Hot-rolled deformed bars with diameters of 12, 20, 22 and 25 mm were used as longitudinal reinforcement giving longitudinal reinforcement ratios of 1.08 % and 0.69%, respectively. Hot-rolled plain bars with 6, 8 and 10 mm diameters were used as vertical stirrups, with a constant transverse reinforcement ratio equal to 0.52%. Properties of steel bars are presented in table 2.

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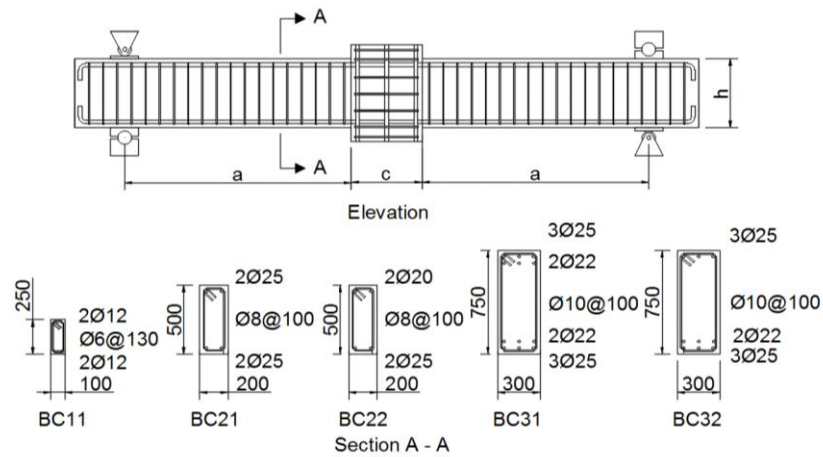


Figure 1 Details of test specimens (mm)

Table 1 Parameters of specimens

Specimen	Dimension (mm)				Concrete cubic strength f_{cu} (MPa)	Longitudinal rebar ratio (%)		Stirrups ratio ρ_{sv} (%)
	Width b	Depth d	Effective depth d_0	Span a		Top bar ρ_s	Bottom bar ρ_s'	
BC11	100	250	210	3	73.6	1.08	1.08	0.52
BC21	200	500	456	3	73.8	1.08	1.08	0.52
BC31	300	750	688	3	72.0	1.08	1.08	0.52
BC22	200	500	456	3	73.8	1.08	0.69	0.52
BC32	300	750	688	3	72.0	1.08	0.69	0.52

Table 2 Properties of steel bars

Diameter of steel bar (mm)	Yield strength (MPa)	Tensile strength (MPa)
6	407	578
8	467	507
10	384	535
12	420	618
22	423	598
25	470	660

2.2 Loading Protocol and Test Setup

Figure 2 shows the planned loading protocol for the reversed cyclic loading test. Each specimen was subjected

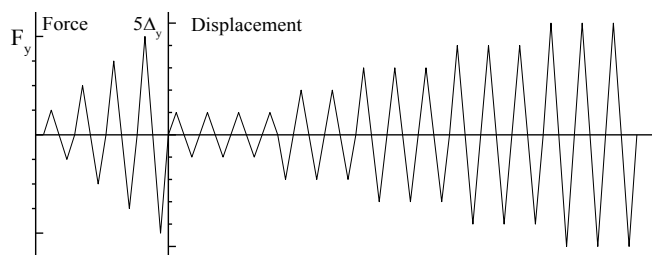


Figure 2 Loading protocol

to progressively increasing load cycles. After yielding of tensile reinforcement, progressively increasing displacement cycles were applied until the specimen failed completely. For each displacement step, three fully reversed cycles were applied. The test setup is shown in figure 3.



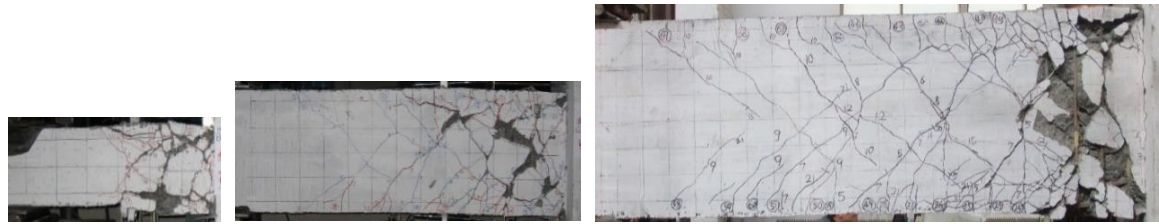
Figure 3 Test setup

3 Test results and Size Effect

3.1 General Behavior

Similar failure patterns were also observed in other specimens regardless of specimen sizes. Flexural cracks were firstly observed at sections adjacent to the central stub. The failure of the specimen resulted from the

yielding of tensile reinforcement followed by the crushing of concrete. Figure 4 shows the typical failure patterns of Specimens BC11, BC21 and BC31 at the end of the test.



(a) Specimen BC11

(b) Specimen BC21

(c) Specimen BC31

Figure 4 Failure patterns of specimens

3.2 Test Results

Test results are listed in table 3, in which the ductility factor for each specimen is calculated by

$$\mu = \Delta u / \Delta y \quad (1)$$

Where μ is the displacement ductility factor, and Δy and Δu are displacements at yield load and ultimate load, respectively.

Table 3 Experimental results

Specimen	Loading direction	At yield		At ultimate		Ductility factor μ
		Moment M_y [kN.m]	Displacement Δy [mm]	Moment M_u [kN.m]	Displacement Δu [mm]	
BC11	+	17.46	3.32	20.12	29.23	8.80
	-	17.42	3.00	20.29	-	-
BC21	+	194.14	7.55	235.48	43.46	5.76
	-	192.30	7.62	223.43	-	-
BC31	+	656.43	13.01	754.49	65.11	5.00
	-	652.31	19.03	752.41	-	-
BC22	+	190.05	8.97	236.00	46.83	5.22
	-	114.70	4.66	137.68	-	-
BC32	+	662.22	12.24	779.62	59.16	4.83
	-	481.04	9.40	533.01	-	-

3.3 Size Effect

The normalized flexural ultimate strength, m , for each specimen is calculated by

$$m = \frac{M_u}{f_{cu} b d} \quad (2)$$

Figure 5 shows the variation of normalized flexural strength with beam depth. As shown, there is no apparent

size effect on the normalized ultimate flexural strength of the tested beams. Figure 6 plots the ductility factor varying with the depth of beams. For beams with symmetric longitudinal reinforcement, i.e. Specimens BC11, BC21 and BC31, the ductility factor decreases with increase of the depth of beams exhibiting a significant size effect. However, for beams with unsymmetric longitudinal reinforcement, i.e. Specimens BC22 and BC32, the size effect cannot be confirmed due to the insufficiency of test data.

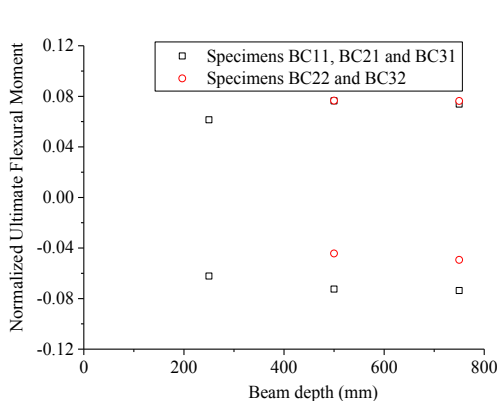


Figure 5 Normalized ultimate flexural moment

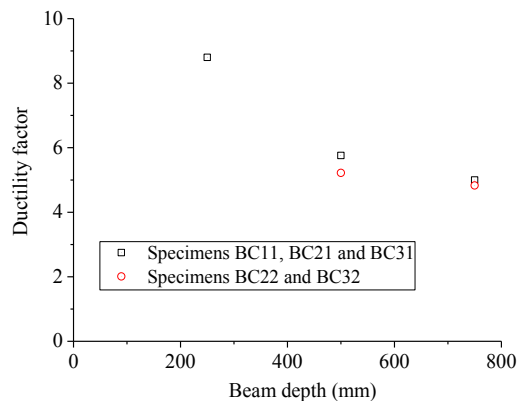


Figure 6 Ductility factor

4 OpenSees Modeling

4.1 The FE Model

Nonlinear analysis of the cyclic experiments was conducted by using OpenSees software which is based on fiber based finite element analysis. In the analysis, the

influence of shear deformation was considered, whereas the slippage of reinforcement was ignored.

The uniaxial material concrete03 for concrete and the hysteretic model for reinforcement provided in OpenSees, as shown in figures 7 and 8, were used to simulate the nonlinear behavior of concrete and reinforcement, respectively. Detailed information of the FE models and the analysis of test specimens can be found elsewhere [13, 14].

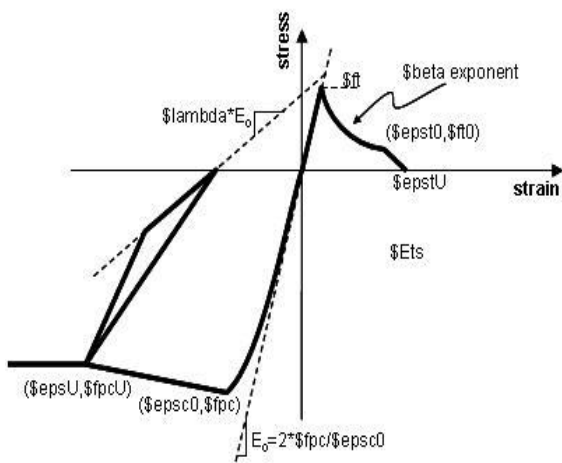


Figure 7 Concrete 02 model

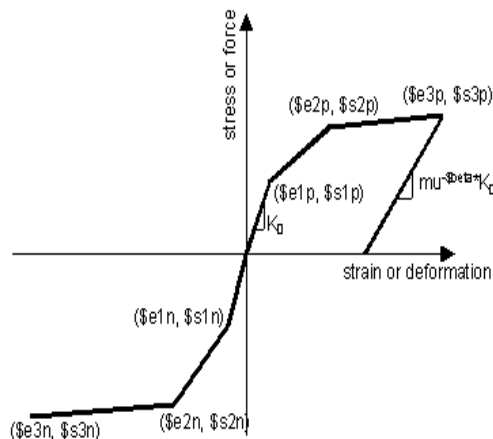


Figure 8 Hysteretic model

4.2 Analytical Results and Comparison

Figure 9 shows the load-deflection hysteric curves of Specimens BC11, BC21 and BC31 obtained from the experiments and analysis by OpenSees. As can be seen,

the results of the analysis are in good agreement with the experimental results, and the pinching effects of experimental curves are well captured by the FE analysis. The fiber-based element of OpenSees with Concrete03 model and Hysteretic steel bar model is suitable to simulate cyclic behavior of RC beams and is able to consider the pinching effect.

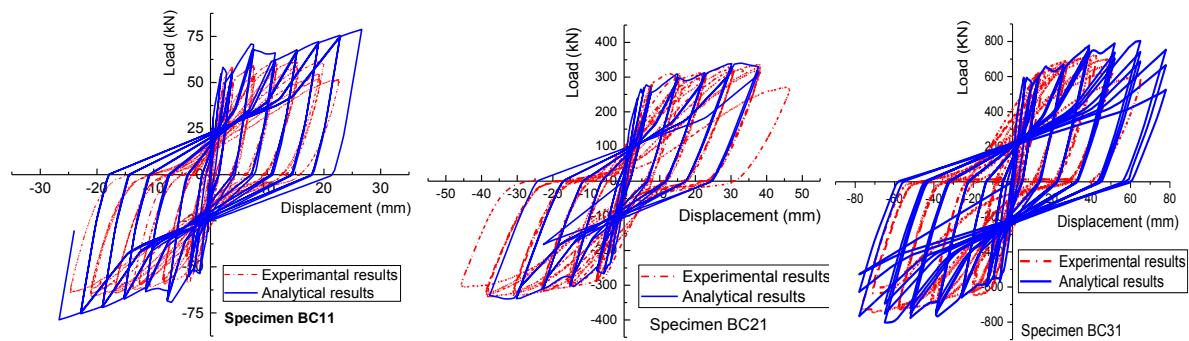


Figure 9 Comparison of load-deflection hysteric curves

5 Conclusion

Based on the present study, the following conclusions may be drawn:

- (1) Test results show that there is no apparent size effect on the normalized ultimate flexural strength of the tested beams.
- (2) For the displacement ductility factor, a significant size effect is observed experimentally in beams with symmetric reinforcement.
- (3) The load-deflection hysteric curves obtained by the OpenSees analysis are in good agreement with those from experimental tests. It is found that the fiber-based element of OpenSees with Concrete03 and Hysteric models is suitable to simulate cyclic behavior of RC beams and is able to consider the pinching effect.

Acknowledgement

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