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Failure Mechanism in Fixed-Ended Reinforced Concrete Deep Beams under Cyclic Load

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***Abstract*—**Reinforced Concrete (RC) deep beams are a special type of beams due to their geometry, boundary conditions, and behavior compared to ordinary shallow beams. For example, assumption of a linear strain-stress distribution in the cross section is not valid. Little study has been dedicated to fixed-end RC deep beams. Also, most experimental studies are carried out on simply supported deep beams. Regarding recent tendency for application of deep beams, possibility of using fixed-ended deep beams has been widely increased in structures. Therefore, it seems necessary to investigate the aforementioned structural element in more details. In addition to experimental investigation of a concrete deep beam under cyclic load, different failure mechanisms of fixed-ended deep beams under this type of loading have been evaluated in the present study. The results show that failure mechanisms of deep beams under cyclic loads are quite different from monotonic loads.

***Keywords*—**Deep beam, cyclic load, reinforced concrete, fixed-ended.

I. Introduction

GENERALLY reinforced concert beams are classified as ordinary and deep beams as depending on their span to depth ratios. When the ratio of span to depth of beams is large, the structural behavior is characterized by flexural actions, whereas with decreasing this ratio, the transversal stiffness will be considerable. According to the ACI 318-14 [1], the beams, whose span to depth ratios are less than 4, are categorized as deep beams. However, the behavior of beams is also influenced by the other factors such as concrete strength, reinforcement characteristics, support conditions, and manner in which the load is applied. Also, ACI 318 has recommended strut-and-tie method for designing the simply supported deep beams, but currently, there are no design documents written specifically for the RC deep beams with end conditions either fixed or partially fixed.

It is considered that the fixed-ended or partially fixed-ended conditions in RC deep beams are more likely to occur in actual structures than simply supported end conditions. For example, in buildings, the coupling beams in shear walls are effectively fixed ended, and the fixity will be provided by transverse walls as shown in Fig. 1. Other examples of fixed or partially fixed end conditions are deep beams supported on heavy columns, and continuous deep beams supported with columns as depicted in Fig. 2.

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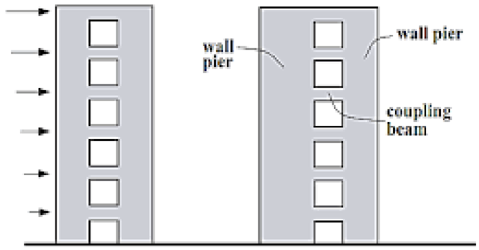

Fig. 1 Beams supported on concrete shear walls

Fig. 2 Continuous deep beams supported on concrete columns

In the past, considerable research works have been made on simply supported concrete deep beams, but fixed ended supported conditions have scarcely been investigated [2]. Two reasons may be given for this situation: first, fixed-ended conditions are extremely difficult to create in a laboratory; and second, fixed-ended conditions introduce additional parameters which already add more complexity to the structural behavior of RC deep beams [3].

Regarding the recent tendency for the application of deep beams, possibility of using fixed-ended deep beams has been widely increased in structures. Therefore, it is obvious that it needs to investigate about this structural element in more detail. Due to probable architectural requirements of columns elimination or structural failure of them, this kind of beams may be suffered of cyclic loads during earthquakes. First, different failure modes of fixed-ended deep beams under monotonic loads have been discussed in the present paper. Following, its failure mechanism is described under cyclic loading. Moreover, experimental results of a specific sample under cyclic load, which is suggested by ATC-24 code, have been illustrated.

II. Modes of Failure in Fixed-Ended Deep Beams

Three different modes of failure were identified for the RC fixed-ended deep beams in the literature [3]. The parameters which are more important in failure modes are: a) the amount of top and bottom reinforcement, b) the concrete strength, c) the shear span to depth ratio, d) the amount of web reinforcement, e) the overall geometry and the position of loading. Thus, the failure modes are described in the following [3]:

A. Flexure plus Shear Failure Mode

This type of failure occurs in the beam with minimum amount of top reinforcement about 0.002 bd, where b and d are beam thickness and effective depth, respectively. The failure occurs when the major diagonal and flexural cracks are formed together with crashing concrete at the ends of major diagonal cracks.

B. Shear Failure Mode

The shear failure mode occurs in the absence of flexural cracks at the fixed ended supports. In this mechanism, after the formation of initial flexural cracks at the mid span of beam, the diagonal cracks appeared and caused the excessive spalling and crashing of the concrete at the edges of the loading patch and the lower corner of beam.

C. Bearing Failure Mode

Reinforcement concrete deep beams with fixed ended supports vulnerable to bearing failure under the load batch, when the area of loading is not enough, and the stress will exceed the capacity of concrete. This failure is basically a local failure and it is preventable, with suitable detailing around the loading area, so the load can be distributed into the body of beam without overstressing locally.

III. Size of Models

The size of specimen is one of important parameter in the laboratory. According to study of Noor and Boswell [4], with decreasing the size of specimen, concrete strength and improvement coefficient will be increased, particularly in specimen less than 100×50 mm size. Also, the results of experiments show that the scaling about 1/6 to 1/8 has 15% error, but in the scaling which is less than 1/6, there is no difference between the specimen and main model [4]. Generally, in the laboratory, huge size of specimen has some limitations for testing, so the maximum length of specimen that may be chosen about 2 to 2.5 meters will be suitable in laboratory. According to these reasons, maximum length of specimen is chosen as 226 cm. This size of specimen is executable and also is less than 1/6 because of scaling and it does not have any error in results.

IV. Detail of Tested Specimen

A. Geometry

The detail of fixed-ended deep beam that is tested in this paper is shown on Fig. 3. The size of this specimen is selected as compatible for the instrument of structural laboratory. The span of beam is 1680 mm, the high is 600 mm, and the thickness is chosen 75 mm. Also, the columns with 290×500 mm cross section and 1150 mm length are used for the supports of this beam. The last research of the authors [5] has shown that this size of columns can provide enough rigidity of supports that has a behavior of fixed-ended deep beam [5]. For preventing of bearing failure mode and avoiding of crashing concrete under applied load, two plates with 150×75 mm size and 10 mm thickness on the top and bottom of beam are on the applying load location. Each of these plates is anchored with 8T10 bars to the body of beam.

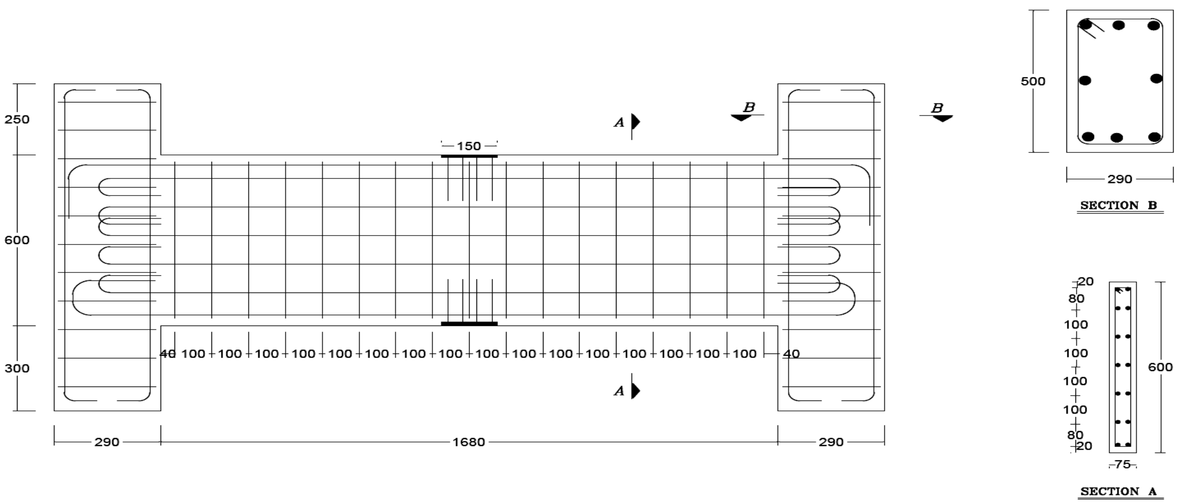

Fig. 3 Detail of tested of deep beam

B. Property of Materials

The concrete compressive strength of standard cube on the day of test is 43.8 MPa, and the details of reinforcement and their properties are given in Table I and Fig. 4.

According to the previous research of the authors [5], the backside of columns should be connected to the reaction frame with high strength bolts as shown in Fig. 5. For this reason, eight bolts size M27 are used with 880 MPa yielding stress. Also, according to Fig. 5, two hydraulic jacks and load cells are used for applying cyclic load; one of them at the top of beam and another one in the bottom of beam (Fig. 5).

TABLE I
REINFORCEMENT PROPERTIES

	Location of bars	Number, Type & size	As (mm^2)	Fy (N/mm^2)	E (N/mm^2)
Main reinforcement	Top	2T16	201	410	208
	Bottom	2T20	314	555.9	217
Web reinforcement	Horizontal	2R6	32.67	374.27	205
	Vertical	2R6	32.67	374.27	205
Anchoring of top & bot plates		8T10	78.5	506.8	211

Fig. 4 Detail of reinforcement in deep beam

C. Setup of Test

Fig. 5 Detail of test setup

To record the displacements of this beam, five LVDTs are used. Two LVDTs are utilized for the midspan of beam at the top and bottom, another two are used at the bottom of beam in 500 mm distance from supports, and the last one controls the displacement of beam in the out of plane direction.

V. LOADING ALGORITHM

In this research, cyclic load has been applied to the mentioned specimen according to the ATC-24 standard [6]. The recommended loading (deformation) history by this standard consists of stepwise increasing cycles (multiple step test) as illustrated in Fig. 6.

According to this algorithm, at first step, the displacement equal to $1/3\delta_y$ should be applied in three cycles, then in the next three cycles, the displacement is increased to $2/3\delta_y$. In the next step, displacement is increased to δ_y. After that in each step, the displacement Δ that is equal to δ_y will be added until the failure mechanism of beam. In this test, δ_y is 1.2 mm, so the first cycle should begin with 0.4 mm.

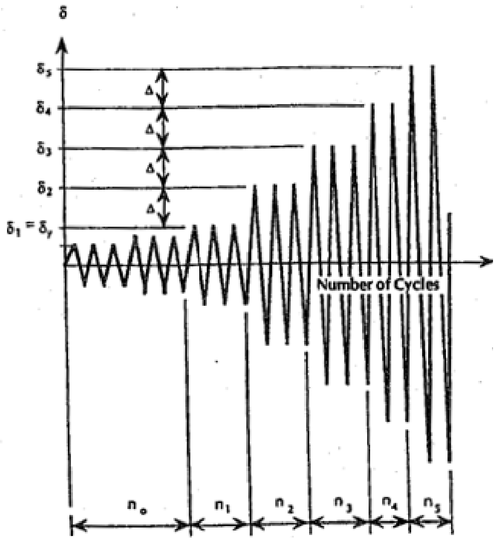

Fig. 6 Deflection history for multiple step test

VI. TESTING PROCEDURE

A. Algorithm of Cracking

In this test, the first cyclic of load did not make any crack in the beam. But, at the second cycle, first crack was appeared in the 137 KN and 130 KN loads from top and bottom of beam, respectively. With increasing load in continuing cycles, more cracks appear. Finally, after 10 cycles of load, failure occurred, and the capacities of this beam were 510 kN and 501 kN under load from top and bottom, respectively. Fig. 7 shows the crack pattern in this beam.

B. Experimental Results

According to the literature [3], when deep beams are failed under statically loads, the main cracks are created along the diagonal struts, but this test reveals that the diagonal cracks are crossed together orthogonally. This decreases the strength of concrete struts, and finally the capacity of deep beams under cyclic load will be decreased about 18% in comparison with the same beam under statically load.

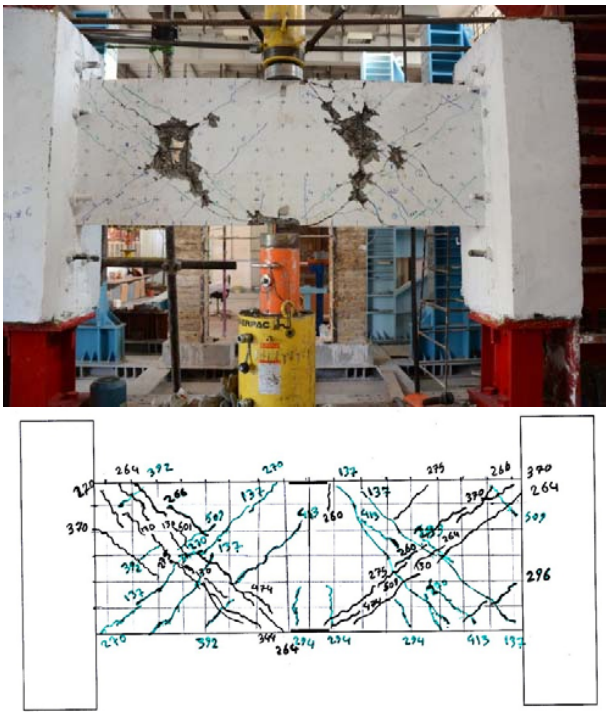

Fig. 7 Crack propagation

According to analytical method [7], the capacity of this beam under statically load is 560.4 kN, but as the experimental result shows, the capacity is reduced to 510 kN. This reduction in capacity may be due to the effects of orthogonal cracks in diagonal concrete struts, because the yield stress of bars did not change considerably in cyclic loading. In the other hand the experimental results have 8.99% error with the analytical method. The results of this test show that by applying reduction factor in strength of concrete struts, the analytical method will be used to achieve the capacity of deep beams. This reduction factor obtains roughly 0.73 for the cyclic load that is introduced in this paper.

C. Load-Displacement Response

The load-displacement curves that are obtained from the experimental results can reveal the behavior of beam; Fig. 8 shows the load-displacement response under cyclic load. This figure shows that rapid of load in each cycle causes to decrease the stiffness of beam specially in final cycles. Also, according to the load-displacement curve, the maximum displacement is 4.4 mm at the maximum capacity of beam.

VII. Finite Element Modeling

A. Material Property

In this stage, tested beam is modeled in ANSYS program [8]. In the modeling procedure, the nonlinearity of materials is considered. The solid 65 elements are used for concrete, and the stress-strain curve is obtained according to the research of Bai and Au [9] as shown in Fig. 9.

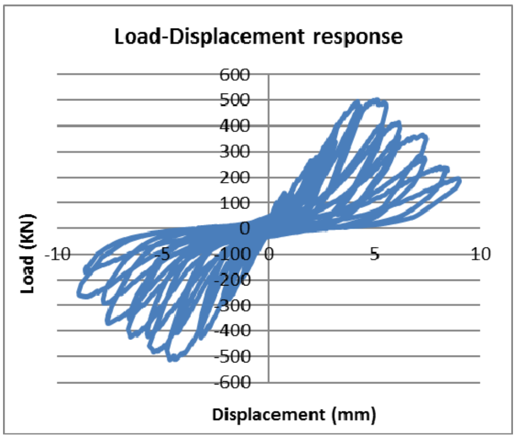

Fig. 8 Load-displacement response

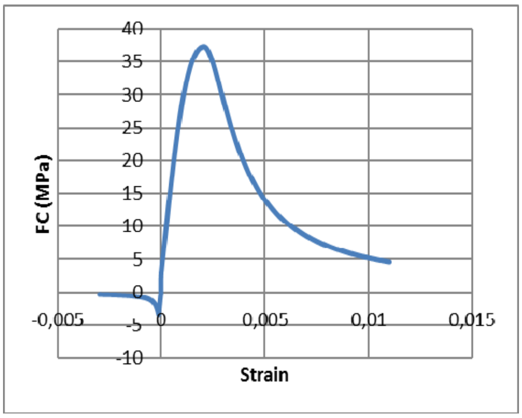

Fig. 9 Stress-strain curve of concrete

According to Fig. 9, the standard cylindrical compressive strength of concrete is 37.23 MPa that is 0.85 of concrete compressive strength of standard cube of tested beam (i.e. 43.8 MPa). The shear transfer coefficient is 0.2 when the concrete crack is open and 0.9 when the concrete crack is closed. All of steel bars are modeled by Link 8 with the results of tension test property.

B. FE Modeling

In the modeling of this beam, the concrete is modeled by solid 65-element, steel bars are modeled by Link 8, and the bearing plates are modeled by shell 181 elements. The 3D finite element of tested beam is shown in Fig. 10.

C. Results of Analysis

Nonlinear analysis has been made on the modeled beam by applying cyclic load as mentioned before. According to this analysis, the capacities of this beam are obtained 584 kN and 568 kN under the load from top and bottom, respectively. The cracks pattern of this beam in final step are also compatible with the experimental results, and this is presented in Fig. 11.

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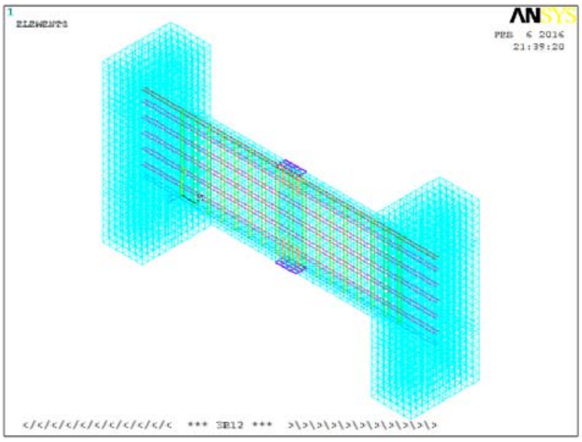

Fig. 10 3D FE modeling of tested beam

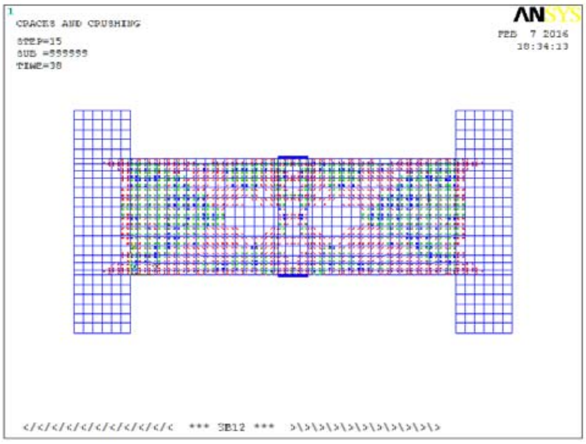

Fig. 11 Cracks pattern of concrete beam

VIII. Conclusion

According to this study, the following points can be concluded:

1) The capacity of concrete deep beams under cyclic load reduced about 18% in comparison under static load.
2) The analytical method can be used for calculating the capacity of deep beams by applying 0.73 reduction factor in the strength of concrete struts.
3) In the concrete deep beams under cyclic load, the diagonal cracks from top and bottom loads crossed each other orthogonally.
4) The load-displacement curve shows the shear behavior of concrete deep beam.

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