

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

A. Aarabzadeh, R. Hizaji

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 concrete 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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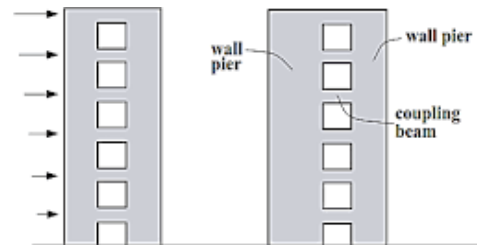


Fig. 1 Beams supported on concrete shear walls



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.

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.

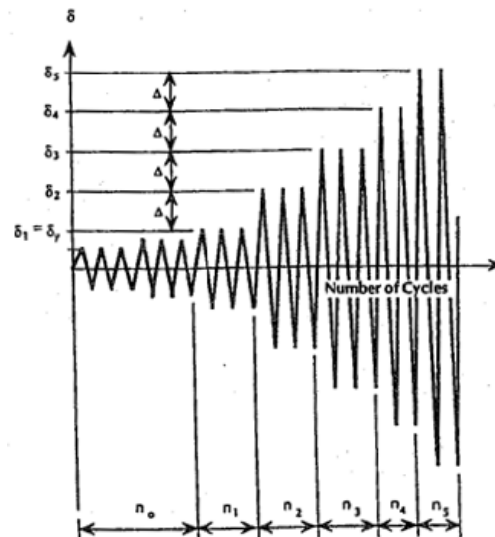


Fig. 6 Deflection history for multiple step test

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.

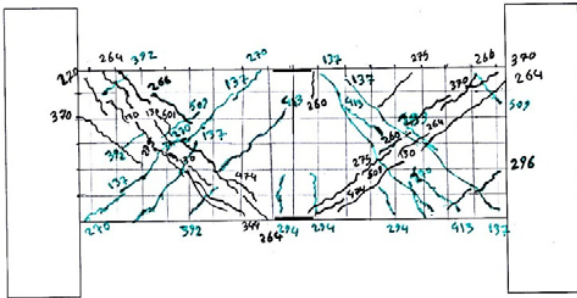
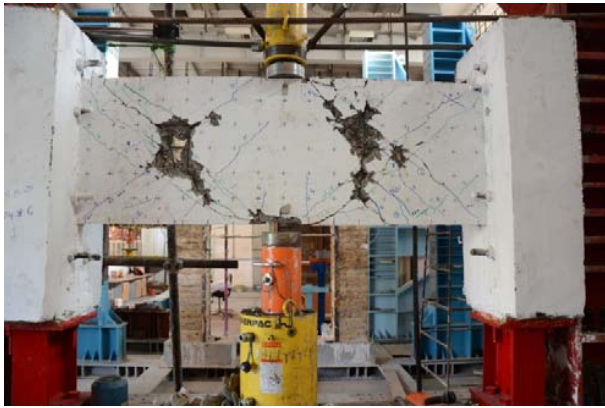


Fig. 7 Crack propagation

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.

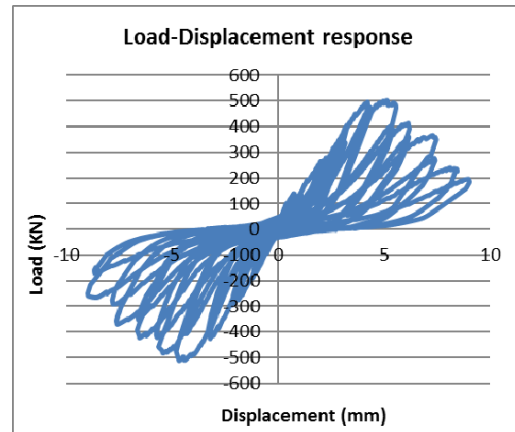


Fig. 8 Load-displacement response

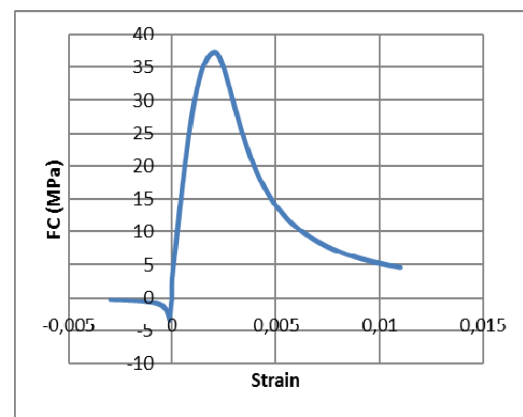


Fig. 9 Stress-strain curve of concrete

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 in final step are also compatible with the experimental results, and this is presented in Fig. 11.

