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ORIGINAL ARTICLE

Behavior and shear design provisions of reinforced concrete D-region beams

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Arch action

Abstract This paper studied the behavior and shear design provisions of D-regions in reinforced concrete (RC) normal-size beams. In D-regions, the load is transferred to the support mainly through arch action mechanism associated with nonlinear strain distribution, while in B-regions, the strain is linear. Shear design for B-regions follows the conventional sectional method (CSM), while the strut and tie modeling (STM) approach has been introduced for D-region recently. Depending on the shear span to depth ratio, normal-size beams may contain both B-regions and D-regions, thus, creating a unique class of beams. The impact of the shift in the shear design provisions from CSM to STM has not received enough attention. The study involved testing eight reinforced concrete beams with and without stirrups having various flexural reinforcement ratios loaded under a shear span to depth ratio less than two, to create D-regions. The beams were simulated numerically via nonlinear finite element (NLFE) for verifications. Comparisons of results were made among those obtained from the experimental program, STM, CSM, and NLFE. The study provided some insight into the behavior of these regions and compared the prediction capability of the numerical methods. Finally, the study pointed to potential shortcomings that may arise when this class of beams is designed on the basis of STM.

1. Introduction

Shear design provisions in many building codes, nowadays, distinguish between regions in normal-size beams, depending on the shear span to depth ratio. Regions in short spans are classified as D-regions where the D stands for deep or disturbed; for these regions, the load transfer is assumed to follow arch action mechanism and the strain distribution across the section is nonlinear. On the other hand, longer shear spans carry load by beam action and are referred to as B-regions, where the B stands for beam or for Bernoulli, who postulated the linear strain distribution in beams. Regions in RC beams where the shear span is less than twice the depth are considered to be dominated by arch action and thus defined as D-regions (ACI-318, 2008; SBC 304, 2007) as shown in Fig. 1

D-regions in conventional normal-size beams may not satisfy dimension limitations of deep beams regarding the total

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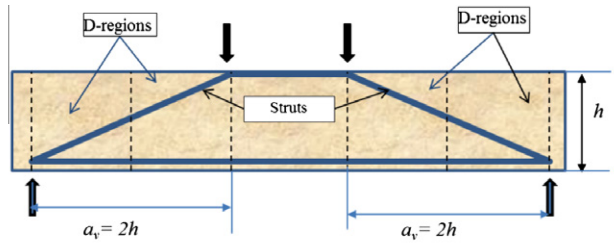

Figure 1 D-regions in normal beams when shear span, $a_v \leqslant 2h$, (after *Fig. RA.1.2* of ACI-318-08).

clear span to depth ratio of four as defined by Section 10.7.1(a) of ACI-318-08; therefore, situations may arise where both B-regions and D-regions coexist in a single beam which produces a unique class of beams. Shear design of reinforced concrete beams has been on the basis of conventional sectional method (CSM) until recently when the strut-and-tie modeling (STM) approach was introduced for D-regions, though the latter remains within the appendix of the code (ACI-318, 2008; SBC 304, 2007).

In the CSM, shear strength in reinforced concrete conventional beams, V_n in most reinforce concrete design codes (SBC 304 (2007), ACI-318-08, Eurocode 2 (2004)) is assumed to be the summation of contributions of concrete and stirrups as

$$V_n = V_c + V_s \tag{1}$$

Where, V_c, is the concrete contribution usually expressed as a function of key variables, (ACI-426, 1987; ACI-445, 1998):

$$V_c = f(\rho, f'_c, \frac{a_v}{d}, d) \tag{2}$$

The stirrup contribution to shear strength, V_s, is affected by the longitudinal spacing of stirrups, s, legs area, A_v, yield strength, f_{yv}, and orientation and expressed as

$$V_s = \frac{A_v f_{yv} d}{s} \tag{3}$$

This approach has been criticized as being not intuitively related to physical behavior (Hawkins et al., 2005) and that the empirical equations have a large degree of scatter (ACI-445).

A strut and tie model (STM) is made up of struts and ties connected at nodes as shown in Fig. 2. The governing provisions of this approach consist of dimensioning rules, concrete efficiency factors, reinforcement limits, and anchorage requirements. Extensive research has been conducted on these critical elements (Rogowsky and MacGregor, 1986; Foster, 1998; Kuchma et al., 2008; Brown and Bayrak, 2008a, among others). The safety in the STM approach is contingent on the appropriateness of the stress limits in codes of practice and that the structure is sufficiently ductile to allow the load to be supported in the manner selected by the designer (Kuchma et al., 2008).

The impact of the shift in the shear design provisions from CSM to STM for the class of beams having both B-regions and D-regions has not received enough attention. The overall design of beams should satisfy all fundamental criteria including strength and ductility. Relevant provisions with respect to these criteria along with the overall behavior are the focus of this study.

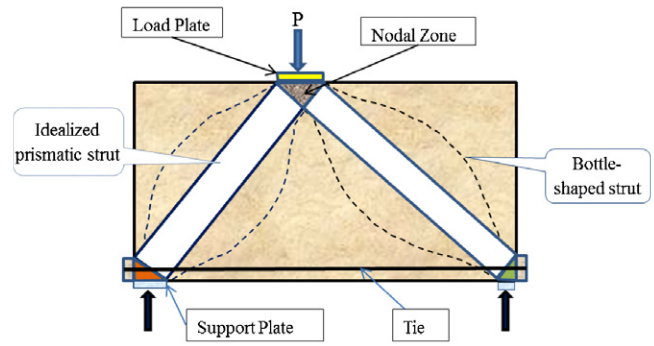

Figure 2 Basic strut-tie model components (*after Fig. RA3.3* in ACI-318-08).

The study involved testing eight full-scale reinforced concrete beams with and without stirrups under a shear span to depth ratio less than two in order to create D-regions. The beams differed in the amount of flexural reinforcement ranging from minimum to maximum. The beams were also simulated numerically via nonlinear finite element (NLFE). Comparisons of results were made among those obtained from the experimental program, STM, CSM, and NLFE. Results were discussed, and conclusions were drawn.

2. Experimental program

2.1. Specimen design

Two groups of beams were tested: KQ series having four beams without stirrups, and MH series having four beams with stirrups. The specimens were constructed to a nominal thickness of 400 mm, a width of 200 mm, and a total length of 3.2 m. They were designed with four reinforcement ratios chosen to cover the practical spectrum of flexural reinforcements, the lowest was slightly above the code minimum and the largest was slightly above the recommended maximum reinforcement ratio.

Five rebar sizes were used as shown in Fig. 3. with the following yield strength: 8 mm (f_y = 450 MPa), 12 mm (f_y = 450 MPa), 14 mm (f_y = 633 MPa), 18 mm (f_y = 549 MPa), 22 mm (f_y = 534 MPa). Average concrete strength at 28 days from standard specimens, f'_c, was 30 MPa for MH series and 27 MPa for kQ series. The beams were simply supported and loaded by two-point load such that a_v/h = 1.75, making the shear span qualify for the D-region definition.

2.2. Experimental setup

The specimens had a clear span of 3.0 m and subjected to point loads at a shear-span, a_v, of 700 mm. The concentrated loads were applied through steel bearing plates in a displacement-controlled manner. The total load was recorded from the machine head as well as from load cells at each point load. Electrical strain gauges were placed on bottom rebars of flexural longitudinal reinforcement. Vertical displacement measurements were recorded at the midspans. Each specimen was loaded with several load increments up to failure. During the loading the cracks were visually traced and marked and photographed at the end of the test. Continuous recording of displacements and reinforcement strains and incremental loads were provided throughout the loading history.