Engineering Structures 117 (2016) 71–85

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental verification of strut and tie model for HSC deep beams without shear reinforcement

Ahmed B. Shuraim [a,1], Ahmed K. El-Sayed [b,c,*]

[a] Department of Civil Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia
[b] Center of Excellence for Concrete Research and Testing, Department of Civil Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia
[c] Housing and Building National Research Center, Giza, Egypt

ARTICLE INFO

Article history:
Received 2 February 2015
Revised 1 March 2016
Accepted 1 March 2016

Keywords:
Shear strength
Reinforced concrete beams
Strut and tie model
Deep beams
High strength concrete

ABSTRACT

The strut and tie model (STM) has emerged as an alternative effective design methodology particularly for D-regions and complex structural concrete members. This paper verifies the applicability of STM for predicting the shear capacity of high strength concrete (HSC) deep beams without web reinforcement. A total of 18 deep beams were constructed and tested in four-point bending up to failure. The test variables included the longitudinal reinforcement ratio, the shear span to depth ratio, and the beam depth. The load carrying capacity of the beams was predicted using STM. The accuracy of the predictions was examined considering two critical assumptions related to the upper strut height. The predicted load carrying capacity of the beams was compared with the experimental values. The results of the comparison indicated that the two assumptions of the upper strut height showed good prediction capability of the test results for HSC deep beams without shear reinforcement capturing the effects of the test variables.

1. Introduction

Shear design provisions in many building codes, nowadays, distinguish between regions in any reinforced or prestressed concrete beam, depending on the shear span to depth ratio. Regions in short spans are classified as D-regions where D stands for discontinuity 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 B stands for beam or Bernoulli, who postulated the linear strain distribution in beams. A structural concrete member can consist entirely of a D region; however, more often D and B regions will exist within the same member or structure. Deep beams are a typical example of D regions where the shear span is less than twice the depth as shown in Fig. 1 and the load transfer is dominated by arch action [1–3].

Generally, the ultimate shear strength, V_u, of reinforced concrete deep beams can be determined by two different approaches: sectional approach and member approach. The sectional approach is based on empirical equations derived by fitting the equations to the experimental results, whereas the member approach is based on the strut and tie model (STM). The sectional approach was found often not to yield meaningful results for such beams [4]. Therefore, most of the design codes have replaced the sectional design procedures of deep members by STM. In 2002, the ACI 318 building code [5], for example, has replaced the sectional method, described in earlier codes, by STM for designing reinforced concrete deep beams. The Canadian Standard CSA-A23.3-04 [6] as well as the Eurocode [2] recommends the STM for designing deep members. In this model, the struts and ties are 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 [7–22]. 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 [13].

Reinforced concrete deep beams have a wide range of applications in structural engineering, such as pile caps, foundations, bridge girders, offshore structures, and transfer girders in tall buildings [23]. According to span-to-depth ratio, the strength of deep beams is usually controlled by shear rather than flexure if normal amounts of longitudinal reinforcement are used [24].

* Corresponding author at: Center of Excellence for Concrete Research and Testing, Department of Civil Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia. Tel.: +966 11 469 6345.

E-mail addresses: ashuraim@ksu.edu.sa (A.B. Shuraim), ahelsayed@ksu.edu.sa (A.K. El-Sayed).

[1] Tel.: +966 11 467 7004.

http://dx.doi.org/10.1016/j.engstruct.2016.03.002
0141-0296/

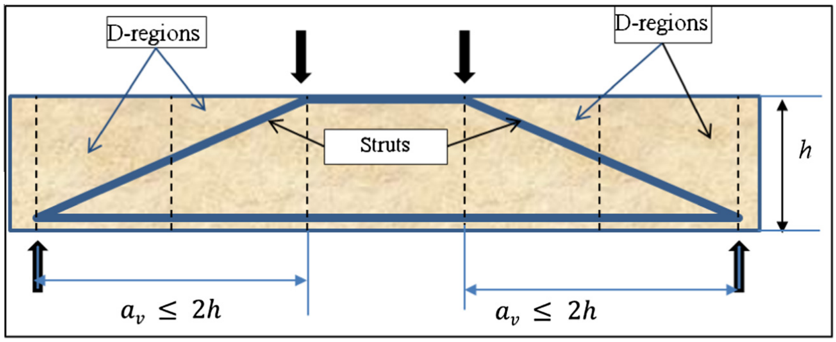

Fig. 1. Deep beam as a typical example of D-regions, $a_v \leqslant 2h$.

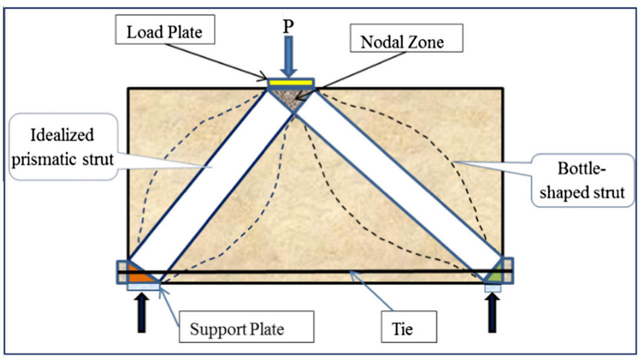

Fig. 2. Basic strut and tie model components.

Although there is a significant amount of research work available in the literature on the strut and tie modeling, there is a little experimental validation of that model for deep beams without stirrups particularly for beams with high strength concrete (HSC). One feature of HSC is the more brittle failures of beams constructed using such a concrete when compared with normal strength concrete beams. It should be noted that the STM is based on the lower bound theorem of limit analysis. The applicability of this theorem in terms of STM for reinforced concrete members is based on the plastic behavior of the reinforcing steel. The brittle nature of concrete makes the use of this theorem for reinforced concrete members is not an ideal solution. Therefore and to account for the brittle nature of concrete, most of the STM design methods recommend reducing the concrete compressive strength of the member by reduction factors. Coupling the brittleness of HSC and lack of shear reinforcement, the applicability of STM needs to be verified for HSC deep beams without shear reinforcement. This investigation focuses on evaluating the shear strength of deep beams without web reinforcement using concrete strength of 55–60 MPa. This concrete strength represents the lower class of HSC and is commonly used in HSC applications in the local construction industry. The experimental shear strengths of the beams are compared with the predictions using STM. The results of the comparison are presented and discussed.

2. Strut and tie model approach for deep beams

Fig. 2 shows STM for a deep beam under concentrated load while Fig. 3 shows STM for a deep beam under two concentrated loads, similar to the beams tested in this study, along with the geometrical notations. STM in Fig. 3 consists of top horizontal strut connected with two inclined struts which in turn connected together with horizontal tie. All of these components were connected to each other by four nodes. The geometry and capacity of the different components of STM are discussed in the following sections.

2.1. Concrete struts

The depth of the top horizontal strut, h_t, is generally taken as the flexural compression depth, c, (distance from extreme compression fiber to neutral axis). By considering a parabolic distribu-

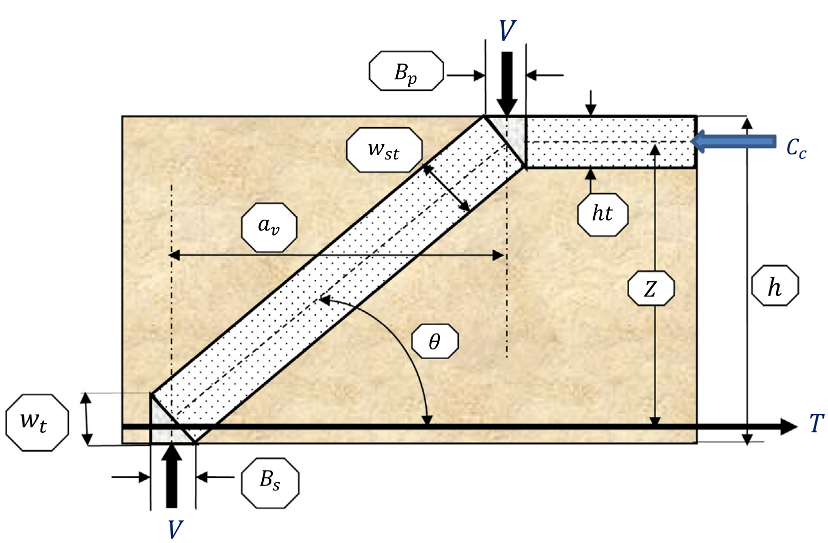

Fig. 3. Schematic representation of strut and tie model showing notations.