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Replacement of Deformed Side-Face Steel Reinforcement in Deep Beams With Steel Fibers

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ABSTRACT

The purpose of this study was to quantify the amount of steel fibers needed to supplement the minimum distributed side face reinforcement requirement for deep beams. The ability of steel fibers to supplant conventional reinforcement was quantified in terms of the serviceability performance or maximum diagonal crack width measured during testing. To achieve the goal of this study, the research plan included the fabrication and testing of nine 300 mm wide by 460 mm deep specimens with a shear span-to-depth ratio of 1.8. Experimental variables included the volumetric percentage of steel fibers and transverse web reinforcement. The diagonal crack widths for specimens were compared with one another and this relationship was used to quantify their serviceability performance. Upon completion of the proposed study, the authors observed that the serviceability performance of deep beams reinforced solely with fibers was equivalent to beams reinforced solely with conventional web reinforcement. The performance of beams reinforced with a combination of steel fibers and conventional reinforcement was further improved. These results provide preliminary support for replacing conventional web reinforcement in deep beams with steel fibers.

1. Introduction

A “D-region” (aka “discontinuity” or “deep beam” region) is a portion of a member with a low shear span-to-depth ratio, or $a/d \leq 2$ to 2.5. Alternatively, a member with $a/d > 2$ to 2.5 is referred to as a “B-region” (aka “Bernoulli” or “slender beam” region). Fig. 1 presents an asymmetrically loaded beam with both a deep and slender beam region noted.

A significant difference between a deep and slender beam region is how shear is transferred to the support. The shear resistance of a slender beam region is attributed to the ability of the cross-section to transfer shear across a diagonal crack. Mechanisms to transfer sectional shear include: 1) web reinforcement; 2) aggregate interlock of concrete along a diagonal crack; 3) dowel action of longitudinal reinforcement; and 4) shear capacity of concrete in the crack-free compression zone. Thus, the size and number of side-face reinforcing bars that cross the diagonal crack has a significant influence on the shear resistance of a slender beam region. Deep beams, on the other hand, transfer shear via a compressive strut or “arching action”. Put another way, “deep beams transfer shear to the support by in-plane compressive stresses rather than shear stresses” [1]. These compressive stresses concentrate at the bearing regions. Thus, the shear capacity of a deep beam region is heavily influenced by the compressive strength of concrete at the bearing or nodal regions. The quantity of side-face or web reinforcement, while necessary to resist inclined cracking within the strut, has a much lower influence on the strength of a deep beam [2]. As a result, serviceability requirements, rather than strength requirements, largely dictate the amount of side face web reinforcement required within deep beam regions. Concrete reinforced with steel fibers is known to exhibit improved crack control and ductility properties; however, the addition of fibers has a small influence on compressive strength [3]. Given this fact, the following study was established to investigate whether deep beams reinforced with steel fibers could achieve similar serviceability performance as those reinforced with conventional web reinforcement.

2. Current practice

Current practice dictating the minimum required side face reinforcement in deep beams is relatively similar between the American Concrete Institute (ACI); American Association of State Transportation and Highway Officials (AASHTO); and the International Federation for Structural Concrete (*fib*). All provisions are based on conventional deformed steel reinforcement and do not consider the addition of steel fibers. The minimum web reinforcement requirements in the ACI 318-11 [4] building code, AASHTO LRFD [5] bridge design specification, and *fib* 2010 Model Code [6] are summarized as follow.

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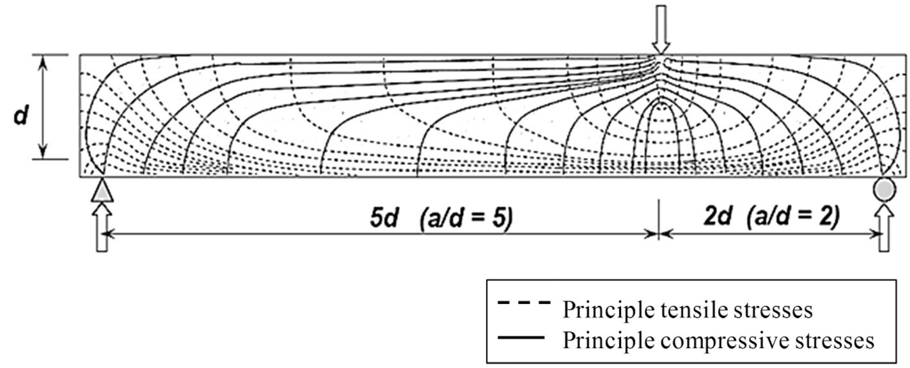

Fig. 1. Asymmetrically loaded beam showing a deep beam (a/d = 2) and slender beam (a/d = 5) [2].

2.1. ACI 318-11 [4]

With respect to deep beams, ACI 318-11 [4], Section 11.7.4 states that the minimum amount of web reinforcement shall not be less than 0.25% in each direction. In the commentary, it is stated that "the steel is provided to restrain the width of the cracks". Based on this comment, the implication is that the reinforcement is a serviceability requirement. This requirement must be satisfied by means of the strut and tie analysis, or otherwise. ACI 318-11, Appendix A requires reinforced struts to be crossed by approximately 0.3% reinforcement or:

$$\sum \frac{A_{si}}{b_s s_i} sin\alpha_i \geq 0.003 \quad (1)$$

where b_s is the width of a strut, A_{si} is the total area of surface reinforcement at spacing s_i in the i-th layer of reinforcement crossing a strut at an angle α_i to the axis of the strut. Fig. 2 illustrates the preceding variables.

According to the code, this reinforcement requirement is "related to the tension force in the concrete due to the spreading of the strut". The implication being that this requirement is needed to maintain the integrity of the strut, i.e. strength. Thus, while not explicitly stated, there is indication that the minimum web reinforcement requirement is needed to both maintain the integrity of the strut and tie model and limit crack widths under service loads.

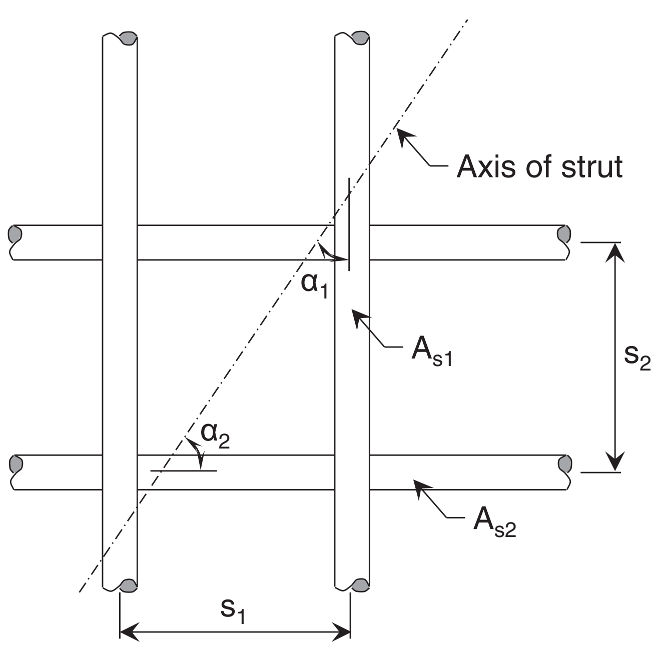

Fig. 2. Reinforcement crossing a strut [4].

2.2. AASHTO LRFD [5]

The minimum reinforcement requirement in AASHTO LRFD [5] is similar to ACI 318-11 [4]. For members designed in accordance with the AASHTO LRFD [5] STM provisions (Article 5.6.3), the reinforcement in the vertical and horizontal directions shall satisfy the following:

$$\frac{A_v}{b_w s_v} \geq 0.003$$
$$\frac{A_h}{b_w s_h} \geq 0.003 \quad (2)$$

where A_h is the total area of horizontal crack control reinforcement within spacing s_h, respectively; A_v is the total area of vertical crack control reinforcement within spacing s_v,; b_w is the width of the member's web; s_v and s_h are the spacing of vertical and horizontal crack control reinforcement, respectively. Fig. 3 illustrates the variables of the AASHTO LRFD [5] provision.

Thus, AASHTO LRFD [5] requires a slightly greater amount of web reinforcement than ACI 318-11. This is reasonable considering that highway structures are typically exposed to the weather and thereby more sensitive to cracking. According to the commentary, "This reinforcement is intended to control the width of cracks and to ensure a minimum ductility for the member so that, if required, significant redistribution of internal stresses is possible." In other words, the requirement is needed for both strength and serviceability.

2.3. fib model code for concrete structures 2010 [6]

The *fib* Model Code 2010 does not explicitly contain minimum web reinforcement requirements for D-regions. However, the code requires beams that contain "shear reinforcement" must have more than approximately 0.1%. This requirement is based on the sectional shear strength of a slender beam and not related to the behavior of a deep beam.

In summary, current design provisions generally recognize the need for a minimum amount of web reinforcement in deep beams. Whether this is needed to maintain strength or serviceability is not clear. Likely, the requirements are based on both. Also, the provisions presented above only pertain to deformed steel reinforcing bars. Comparable provisions do not exist for deep beams reinforced with steel fibers. Researchers [7–10] have studied fiber reinforced deep beams; however, they have not specifically examined the correlation between the fiber percentage and the minimum amount of web reinforcement. A summary of past research follows.

3. Relevant past research

Research of fiber-reinforced concrete generally has focused on the improved strength or ductility characteristics of the material. Research