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Modeling of shear deficient beams by the mixed smeared/discrete cracking approach

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Abstract This paper presents an analytical study on the modeling of shear critical reinforced concrete beams modeled using the finite element method. The paper investigates two modeling strategies; the first of which is the well established smeared cracking modeling approach. Experimental test results from a wide range of beams tested by other researchers were used for model verification. This paper presents a mixed modeling approach in which the smeared cracking model was used in conjunction with discrete cracking planes to model the concrete continuums in an effort to reach a better correlation with the experimental data. This is achieved by introducing a specific plane inclined at angles in a specified range determined as a result of matching these models' behavior with behavior monitored in the experimental work at the suspected plane of failure for shear critical beams. Analytical results have shown that the proposed modeling approach is capable of better simulation of the observed experimental response in terms of strength and stiffness, as well as capturing the post-peak response of the tested beams. Errors have been calculated between analytical and experimental results; these errors are also acceptable within the bounds of the engineering judgment. Finally the mixed smeared/discrete cracking model is validated and can be used with a high degree of confidence to conduct further parametric studies.
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Introduction

In the early 1900s, many methods were developed with the aim of investigating the most realistic load transfer method from loading plates to supports starting with Ritter (1899) who first used truss models as conceptual tools in the analysis and design of reinforced concrete beams.

Talbot (1909) confirmed this finding and pointed out the fallacies of such procedures as early as 1909 in talking about the failure of beams without web reinforcement. Based on 106 beam tests, it was concluded that the shear stress is greatly

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influenced by reinforcement ratio, beam span and other parameters which affect the stiffness of the beam. In beams without web reinforcement, beam shear resistance depends upon the quality and strength of the concrete. The stiffer the beam the larger the transverse stresses which may be developed. Short, deep beams give higher results than long slender ones, and beams with a high percentage of reinforcement give higher results than beams with a small reinforcement ratio.

Kani (1964) reported a more realistic approach in which the beam segments between the inclined flexural cracks act analogous to tooth in the comb thus behaving like a cantilever. Collins and Mitchell (1974) based on the Wagner theory developed a method for determining the inclination of the principal stress "θ" applicable over the full loading range for members subjected to torsion. This procedure is called the "compression field theory (CFT)". Later, Vecchio and Collins (1986) presented the Modified Compression Field Theory (MCFT) extending the first theory to members subjected to shear.

The MCFT is a further enhancement of the CFT that accounts for the influence of the tensile stresses in cracked concrete that was ignored in truss models. Belarbi and Hsu (1994, 1995) developed a procedure called the Rotating Angle Softened Truss Model (RA-STM) to account for tensile stresses in diagonally cracked concrete. Like MCFT, this method assumes that the inclination of the principal stress, θ, coincides with the principal strain direction. Vecchio 2001, held an analytical investigation using finite element analysis (FEA) as an extension of MCFT; the hybrid crack shear slip formulation is found to accurately model the divergence of stress and strain directions, providing an improved representation of behavior. He also found that predictions of shear strength and failure mode are significantly influenced in some cases. Sahibzada Farooq et al. (2013), developed the compressive force path (CFP) method to explain shear behavior of reinforced concrete (RC) beams identifying types of beams according to its shear span-to-depth ratio.

From all previous researches, it became clear that one of the major disadvantages of shear critical reinforced concrete elements is that failure occurs due to one single crack with approximately no significant damage in the rest of the reinforced concrete element [1], which makes it difficult to develop a model with the whole element stiffness to resist a failure due to this single crack without predicting at least an approximate failure surface with the aim of getting close to the realistic ductile behavior of the element monitored through previous experimental works. This study will investigate a different approach in modeling shear critical reinforced concrete elements.

Reference experimental investigation

Deep beams with variable web reinforcement [2]

Test specimen description

Test specimens consisted of sixteen simply supported concrete deep beams with different properties tested by *A. Arabzadeh, R. Aghayari and A. Rahai* in 2011[2]. They were classified into four series according to the type of their web reinforcing. All specimens had a rectangular cross-section with 80 mm × 400 mm. Their overall and effective spans were 1600 mm and 1200 mm, respectively. Fig. 1 and Table 1 give additional details of the specimens.

Phase one: Series **A** consists of six deep beams with variable transverse steel bars and uniform spacing.

Phase two: Series **B** consists of three deep beams with variable transverse steel bars concentrated at the center of shear span.

Phase three: Series **C** consists of four deep beams reinforced by variable longitudinal and constant transverse web reinforcements.

Phase four: Series **D** consists of three deep beams reinforced by diagonal steel bars which are placed perpendicular to the expected diagonal cracks.

Materials

Concrete. The concrete was prepared by Type II Portland cement and river fine aggregate. Maximum aggregate size was 12.5 mm and the slump was approximately 90 mm. The concrete strength was defined based on the average value of three standard cylinders (300 × 150 mm).

Reinforcing steel. The longitudinal steel reinforcement consisted of 12D (12 mm diameter), 22D (22 mm diameter) and 25D (25 mm diameter) deformed steel bars, and also steel shear reinforcement included 6D (6 mm diameter) smooth round bars. Mechanical properties of used steel bars are indicated in Table 4.

Beam specimens with variable web reinforcement ratio and shear span-to-depth ratio [3]

Test specimen description

Ten deep beams under four point bending were constructed and loaded to failure by *J. Dedios*, *A. Lubell* in 2008 [3]. These beams were designed considering variation of longitudinal reinforcement ratio, shear span-to-depth ratio and presence/omission of transverse web reinforcement. The strength of longitudinal reinforcement was studied through comparison against specimens with normal strength reinforcement. Other parameters shown to influence the performance of non-slender beams, such as concrete strength, transverse web reinforcement distribution, spacing between bars and reinforcement development lengths were designed as constant.

Longitudinal Reinforcement Type: (**M**): for high strength ASTM A1035 reinforcing steel and (**N**) for grade 400R reinforcing steel.

Transverse Reinforcement: (**S**): for specimens with web reinforcement and (**W**) for specimens without web reinforcement.

Shear Span-to-Depth Ratio: (**1**): for a/d = 1.19, (**2**) for a/b a/d = 1.78 and (**3**) for $a/d = 2.38$.

Percentage of Longitudinal Reinforcement: (**1**) for 1.15%, (**2**) for 1.13%, (**3**) for 2.29% and (**4**) for 1.77%.

The experimental program was divided into two test phases as follows.

Phase one specimens. Six beams were reinforced longitudinally with high strength steel and contained normal strength transverse web reinforcement and two specimens were built with main longitudinal and transverse reinforced normal strength steel reinforcement. These eight beams were further divided

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