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Prediction of shear strength of reinforced concrete beams using displacement control finite element analysis

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ABSTRACT

This research resulted in the development of a new method for performing displacement control analysis of distributed loads to obtain the ultimate shear strength of structural components. A framework, consisting of several sub-frames, was designed to convert the single displacement applied at the top of the framework to equivalent uniformly-distributed forces applied to the beam. The shear capacity of beams under a concentrated load at mid-span was compared with the shear capacity of a uniform load for four different a/d ratios (3, 4, 5, and 7). The results indicated that the strain in the longitudinal rebar, which is dependent upon the loading condition, strongly impacts the shear strength of a critical section of structural components. The shear strength of the critical section of the R.C. beams studied in this research had uniformly distributed loads that were, on average, 76% greater than the shear strength of the same beam with a concentrated load at mid-span. The shear strength prediction of the AASHTO specification as well as ACI318-14 code were evaluated for beams with shear behavioral mode. A parametric study of 24 RC beams was conducted, and the results indicated that AASHTO's prediction for strain in longitudinal rebar differs about 19%, on average, from the results of the finite element method (FEM). For prediction of the β factor, however, the difference is about 61%. The ACI318-14's formulation for the concrete shear strength (V_c) averages 59% higher than the FEM results for the studied beams.

1. Introduction

For every non-prestressed reinforced concrete element, such as a beam, the shear strength is $V_c + V_s$. The concrete shear strength, V_c, depends on the cross-section dimension, the material properties of concrete, and the amount of longitudinal rebar. ACI 318-14 [1] suggests using Eq. (1) in Section 22.5.5 to calculate V_c for non-prestressed members without axial force, such as beams.

The shear strength of concrete (V_c) is obtained by the minimum value of V_c calculated by Eqs. (1a)–(1c).

$$(1a): V_c = \left(1.9\lambda\sqrt{f'_c} + 2500\rho_w \frac{V_u d}{M_u}\right) b_w d \quad (1b): V_c = (1.9\lambda\sqrt{f'_c} + 2500\rho_w) b_w d \quad (1c): V_c = 3.5\lambda\sqrt{f'_c} b_w d \tag{1}$$

Where f'_c is in psi (1 psi = 0.0069 MPa).

According to Eq. (1a), the shear strength of concrete (V_c) varies along the span of a beam if the ratio of $\frac{V_u d}{M_u}$ changes. If Eq. (1a) doesn't govern, regardless of loading condition, using Eqs. (1b) or (1c) leads to assign only one value of V_c to the entire cross sections of a beam.

The American Association of State Highway and Transportation Officials' (AASHTO) Specification [2] takes a different approach when calculating V_c in Sections 5.8.3.3 and 5.8.3.4., Eq. (2):

$$V_c = 0.0316\beta\sqrt{f'_c} b_v d_v \tag{2}$$

Where f'_c is in ksi (1 ksi = 6.9 MPa).

According to the AASHTO specification [2], the value of β varies when the strain (ε_s) in longitudinal rebar varies, and it is expressed as Eq. (3).

$$\begin{cases} (3a) \quad \beta = \frac{4.8}{1+750\varepsilon_s} \quad \text{For section containing at least the minimum amount of transvers reinforcement} \\ (3b) \quad \beta = \frac{4.8}{1+750\varepsilon_s}\frac{51}{39+S_{xe}} \quad \text{When sections do not contain at least the minimum amount of transvers reinforcement} \end{cases} \tag{3}$$

ε_s is the strain of longitudinal rebar which AASHTO calculates for non-prestressed members without axial load in Eq. (4), as follows:

$$\varepsilon_s = \frac{\frac{|M_u|}{d_v} + |V_u|}{E_s A_s} \tag{4}$$

And S_{xe} is the crack spacing parameter determined by Eq. (5).

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Nomenclature

a	(clear span)/2
$\mathbf{a_g}$	maximum aggregate size, inch (1 in. = 25.4 mm)
$\mathbf{A_s}$	the area of non-prestressed longitudinal tension reinforcement
b or $\mathbf{b_v}$ or $\mathbf{b_w}$	the effective web width taken as the minimum web width within the depth, $\mathbf{d_v}$.
d or $\mathbf{d_v}$	the distance from the extreme compression fiber to the centroid of longitudinal tension reinforcement, inch (1 in. = 25.4 mm)
$\mathbf{E_c}$	modulus of elasticity of concrete
f_1	maximum principal stress
$\mathbf{f'_c}$	the specified 28 days compressive strength of concrete, psi (1 psi = 0.0069 MPa)
$\mathbf{f_{sp}}$	concrete split cylinder strength
h	the height of beam cross section
L	the total length of beam
$\mathbf{M_u}$	the factored moment at section
P	applied load
$\mathbf{P_u}$	ultimate load capacity of beam
$\mathbf{S_x}$	the lesser of either $\mathbf{d_v}$ or the maximum distance between layers of longitudinal crack control reinforcement
$\mathbf{S_{xe}}$	the crack spacing parameter
V_c	the shear strength carried by the concrete cross section
v_{ci}	the shear stress across the cracked interface
V_s	the shear strength carried by the stirrups
V_u	the factored shear force at section under consideration
w	crack width, inch (1 in. = 25.4 mm)
β	the factor indicating the ability of diagonally-cracked concrete to transmit tension and shear
ε_0	concrete strain at peak cylinder stress
ε_1	maximum principal strain values
ε_2	minimum principal strain values
ε_x *or* ε_s	average strain in longitudinal rebar
δ	applied displacement
δ_u	mid-span deflection at peak load
λ	the modification factor reflecting the reduced mechanical properties of lightweight concrete relative to normal weight concrete of the same compressive strength
ρ_w	the ratio of $\frac{A_s}{b_w d}$
θ	the angle of crack inclination

$$S_{xe} = S_x\frac{1.38}{a_g + 0.63} \quad (12\ in. \leqslant S_{xe} \leqslant 80\ in.) \tag{5}$$

Based on AASHTO's general procedure for shear design, the shear strength of concrete largely depends on the strain in the longitudinal rebar, which is changed by the loading condition and moves along the beam span. Therefore, when using AASHTO's equations, rather than only one value for V_c assigned to the entire beam, the value of V_c is calculated for different beam sections, as strain in the longitudinal rebar varies. Thus, designers usually find the most critical section in the structural component and calculate the β factor of that section to check for shear capacity.

Numerous research studies have been conducted on shear strength and the behavior of structural elements. Collins et al. [3] proposed a general shear design method, which was the basis of AASHTO's current shear equations. This method was proposed based on the modified compression field theory (MCFT) that was developed by Vecchio and Collins [4] for reinforced concrete elements subjected to shear. In general, using the shear design method, they proved that when the strain of longitudinal rebar increases, β values decrease, and the angle of crack inclination increases. The MCFT indicated that concrete can carry more shear stress after cracking by aggregate interlock. The shear stress across the cracked interface is expressed by Eq. (6).

$$v_{ci} = \frac{2.16\sqrt{f'_c}}{0.3 + \frac{24w}{a_g + 0.63}} \tag{6}$$

Where "f'_c" is in psi, "w" is in inches, and "a" is in inches. (1 in. = 25.4 mm).

According to Vecchio and Collins [4], the shear strength of reinforced concrete sections depends on the strain of the longitudinal rebar, and the maximum principal strain in a cracked section is determined by the term of the longitudinal rebar strain, as shown in Eq. (7):

$$\varepsilon_1 = \varepsilon_x + (\varepsilon_x - \varepsilon_2)(\cot\theta)^2 \tag{7}$$

Maximum principal stress (f_1) was expressed in the term of v_{ci} in Eq. (8).

$$f_1 = v_{ci}\tan\theta \tag{8}$$

Thus, the shear strength of concrete in the vertical section is:

$$V_c = f_1 b_v d_v \cot\theta \tag{9}$$

The value of β is defined as $\frac{v}{\sqrt{f'_c}}$ and by substitution of Eq. (8) for Eq. (9), we have:

$$V_c = \beta\sqrt{f'_c}\, b_v d_v \quad (f'_c \text{ in psi}) \tag{10}$$

Collins et al. [3] compared the general method of predicting shear capacity with experimental test results and reported that the average ratio of experimental shear strength to predicted shear strength was 1.39. This reveals that the general shear design underestimates the shear capacity of structural components by 39 percent. The AASHTO specification [2] adopted this method, which introduced a shear design methodology.

Shear behavior of large concrete beams reinforced with high-strength steel was studied by Hassan et al. [5]. They investigated and compared the effects of using Grade 100 and Grade 60 (conventional) steel, and found that ignoring the high strength characteristic of the material could provide unreliable predictions of the ultimate load-carrying capacity and the mode of failure. Shioya et al. [6] performed experimental tests on large-scale reinforced concrete beams in order to discover beams' shear strength and their associated size effects. The shear strength of a reinforced concrete beam without shear reinforcement gradually decreases as the effective depth of a beam increases. Research performed by Sherwood et al. [7] demonstrated that the width of a member does not have a significant influence on the shear stress at failure. The shear behavior of reinforced concrete deep beams was investigated by M. D. Brown and O. Bayrak [8]. They performed a series of tests to study the impact of load distribution and shear reinforcement on the behavior of the beams. Their results indicated that differences in load distribution affects the failure mode, crack pattern, ultimate strength, and strain distribution within the beams. Zararis and Zararis [9] presented an analytical theory for shear resistance of reinforced concrete beams subjected to uniformly distributed loads. They concluded that the shear strength of beams, both slender and deep, under a uniform load is much higher than the shear strength of beams under a loading arrangement of two concentrated loads at quarter points. The fallacy of the truss analogy in the design of web reinforcement consisting of bent-up bars was discussed by Neville and Taub [10]. They studied the influence of anchorage and cutoff of the tension steel on the shear strength of reinforced concrete beams. The shear strength of pre-stressed concrete elements was investigated by some researchers to assess design codes [11,12].