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General solution for shear strength estimate of RC elements based on panel response

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ABSTRACT

The capacity of structural systems subjected to shear loads commonly distinguished by discontinuities such as point loads or supports, or abrupt changes of cross section, where complex fields of stresses and strains are generated, is vital information for design. Four structural systems that present stress concentration due to applied shear loads are commonly short walls, deep beams, corbels and beam-column joints. In the present work a model is developed to predict the shear capacity of these elements based on a panel model that considers average strain and stresses in a reinforced concrete orthotropic material, which covers the section of the structural element subjected to stress concentration. In addition, the panel element complies with the longitudinal equilibrium, by equalizing the applied axial load with the internal stresses of the structural element, requiring constitutive material laws for both concrete and steel reinforcement. The original model that has shown good shear strength prediction requires solving the non-linear equation of vertical equilibrium. Thus, this work eliminates the need to solve the iterative problem for the capacity estimation of four possible limit states (failure of concrete in tension and compression, and yielding of longitudinal web and boundary reinforcement). For that, an expression is calibrated for the strain of the model with respect to relevant parameters, for each limit state, that allow the generation of a non-iterative model. The model results in an average predicted capacity over experimental capacity ratio, V_{model}/V_{test}, of 1.0 and a COV of 0.25, with similar performance for all four structural systems. When comparing these results with the general model that requires an iterative method, a similar performance is observed, with an average strength ratio and COV of 0.98 and 0.23, respectively. Likewise, in comparison with the ACI 318, the latter shows worse predictions (on average 24% lower) and with greater scatter (on average 28% higher). The expression in AASHTO code presents better correlation than ACI with predictions closer the proposed model.

1. Introduction

The capacity of structural systems subjected to shear loads is hindered by discontinuities such as point loads or supports, or abrupt changes of cross section, where complex fields of stresses and strains are developed. The shear loads, for these cases, generate a diagonal compression stress field in the concrete from the point of application of the load to the support, which is balanced by the tensile forces generated in the reinforcement and, to a lesser extent, in the concrete. Four structural systems that commonly present stress concentration due to applied shear loads are short walls (common in nuclear plants, facades and at the parking level in buildings), deep beams (coupling beams), corbels (elements that support beams, transferring loads to columns in precast systems) and beam-column joints (continuity element in frame structures).

Several models have been developed to calculate the shear capacity of structural systems, which are separated into two groups: theoretical and empirical (or semi-empirical). The empirical models are based purely on the correlation of experimentally determine capacities with respect to an expression with relevant parameters of the phenomenon (e.g., concrete compression strength, reinforcement yielding, aspect ratio). Expressions of this type were incorporated in the 60s on the ACI 318 standard [1] to estimate shear capacity, which were developed after the 1955 air-force warehouse shear failure [2]. However, these types of expressions are limited based on the experimental data used for the calibration. Due to this limitation, in ACI 318 of 1995 [3] a large number of over 40 expressions for shear strength estimation for different elements and load types have been included, which makes imperative to develop models with a theoretical basis that allow covering a broad spectrum of structural elements and parameter ranges [4]. The

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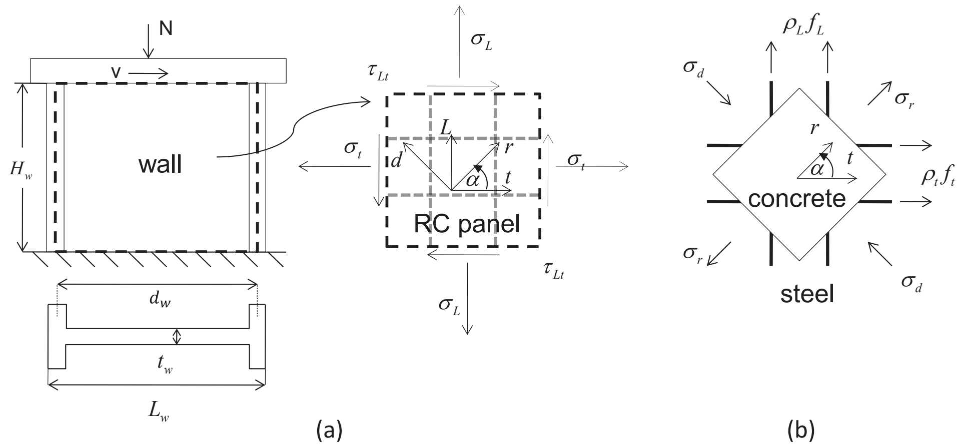

Fig. 1. Short wall – (a) Stress resultants in L–t coordinates, and (b) Stress resultants in principal direction d–r coordinates, including distributed reinforcement (after [9,10]).

understanding of shear response improved considerable with the development of panel constitutive law for cracked reinforced concrete. One of the first complete approaches was the Modified Compression Field Theory [5]. This model uses a rotating-angle modeling approach to describe the evolution of concrete average stress field that rotates as the external actions change, provided that the principal concrete stress direction coincide with the principal strain direction. Constitutive stress-strain models for materials are applied along the principal directions of the strain field in order to obtain the stress field associated with the principal directions. One of the relevant considerations of the panel or membrane model is the incorporation of the compression softening effect. The softening effect is mainly a reduction in the compressive stress of concrete along the principal compressive direction undergoing tensile strains in the other principal direction. The application of this and other membrane models has led to development of finite element formulation for detail reinforced concrete elements or structural analysis (e.g., Vecchio [6]), but also to simplified approaches for shear strength estimation (e.g., Collins et al. [4]).

Regarding theoretical models or based on the physics of the problem, there are two of the most accepted models to predict the shear capacity of structural elements: (i) softened truss or panel model (e.g., Hsu and Mo [7], Collins et al. [4]), and the softened strut-and-tie model (e.g., Hwang et al. [8]), some of them originally applied for walls. The softened truss model differs from the strut-and-tie model by the way the reinforcement and concrete stresses are incorporated in its formulation. The softened truss model assumes that each point of the structural element meets the stress equilibrium with a uniform distribution of stresses and strains. In contrast, softened strut-and-tie model simulates the force distribution in the structural element, with diagonal compression struts that represent the compressive stresses generated in concrete and tensile tensors that represent the stresses induced in the reinforcement. Thus, the model equilibrium is satisfied by the joint action of the strut-and-tie (lattice) system. The softened truss model presents a relatively simple formulation, where the hypothesis of uniform stresses simplifies the analysis. On the other hand, although the strut-and-tie model analyzes the phenomenon with a more convincing concept of stress flow, its formulation is more complex and highly dependent on the expression used to define the cross-sectional area of the compression strut.

In the present work, a closed-form solution (series of expressions that require no iterative numerical procedure for the strength estimate) for a softened truss model applicable to short walls, deep beams, corbels and beam-column joints is developed, based on the formulation proposed by Kassem and Elsheikh [9], originally for short walls, and which has been modified to generalize it and make it applicable to more structural systems [10–12]. Finally, the results of the modified model are compared with experimental results of the literature and with the code expressions of the ACI 318. The relevance of the article is not only showing that a simple material formulation based on general principles can correctly predict the shear strength of reinforced concrete elements for a large database (635 tests), but also that the iterative procedure (nonlinear equilibrium equation) can be avoided after a fitting analysis that keeps three main parameters such as axial load, material strength and principal concrete stress/strain direction, maintaining the main physics of the problem, such as the shear equilibrium equations, compatibility and material constitutive laws.

2. Base model and previous modifications

The base model developed by Kassem and Elsheikh [9], called the fixed-angle panel model, considers a softened truss model to estimate shear capacity for short walls. Geometrically, the model is detailed as shown in Fig. 1, where a short wall of height H_w, length L_w, effective length d_w (horizontal length of the short wall between the centroids of the boundary elements or calculated as $0.8L_w$ for non-barbell walls) and thickness t_w is subjected to an axial load N and another shear V. The short wall is analyzed as a panel element, in which the forces are uniform with respect to its axes. Two coordinate systems are considered, the "L–t" axes that follow the orientation of the longitudinal and transverse reinforcement of the structural element (Fig. 1a), and the "d–r" axes inclined at an angle α representing the slope of the compression diagonal strut developed in concrete (the angle represents the concrete stress principal direction) or principal strain direction angle (Fig. 1b), which is named in this article as principal direction angle. Thus, the normal stresses (σ_L, σ_t) and shear stress (τ_{Lt}) of the structural element are defined by the stresses of the coordinate system "L–t", calculated according to the responses of the distributed longitudinal reinforcement ($\rho_L f_L$) and distributed transverse reinforcement ($\rho_t f_t$), defined by their steel ratio (ρ_L, ρ_t) and average steel reinforcement stress (f_L, f_t) in the L or t direction, and the principal concrete stresses of the compression (σ_d) and tension (σ_r) directions that are in the coordinate system "d–r". All stresses are considered as average values within the panel.

For its formulation, the work by Kassem and Elsheikh [9] applies the equations of equilibrium of the system, strain compatibility and constitutive laws of both concrete and reinforcing steel. For this, it imposes a fixed angle for the principal strain direction that coincides with the principal concrete stress direction. This angle is determined as the one that better predicts the shear capacity of short walls for a database of 100 tests.