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Comparison of available shear strength models for non-conforming reinforced concrete columns

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ABSTRACT

Field surveys in the aftermath of major seismic events, laboratory tests and numerical studies outlined that existing reinforced concrete (RC) structures are likely to exhibit premature shear failures. However, a proper quantification of the shear capacity of existing members with seismic details non-conforming to current seismic code is still a challenging task. Several models based on mechanical approaches or experimental observations are available in literature, current standards and guidelines. Nevertheless, the lack of a widely accepted theory often results in the use of old formulations, mainly developed for design purposes, to assess the shear strength of non-conforming RC members. This study investigates the available shear strength formulations. Eight capacity models commonly adopted in the current practice and worldwide standards or guidelines have been assessed comparing the model predictions with a unique database of 180 experimental tests properly selected to be representative of non-conforming RC members. Members with rectangular or circular cross-section, different aspect ratio (i.e. slender or squat) and shear or flexure-shear failure mode have been investigated. Meaningful statistics have been used to quantify the accuracy and the level of safety of each formulation. Several criticisms in the use of the available formulations are herein outlined. Suggestions for the model applicability have been provided in order to drive the reader to select the most appropriate shear strength formulation for assessment purposes. Finally, corrective factors have been calibrated to allow the use of the selected models with specific levels of safety.

1. Introduction

Post-earthquake reconnaissance and numerical studies have shown that the shear failure of RC members may strongly limit the seismic performances of existing structural systems. Recent devastating earthquakes [1–4] outlined that the low amount of transverse reinforcements or the absence of seismic details can be detrimental for the member response. Reverse cyclic actions may strongly degrade seismic capacity of these members resulting in severe diagonal cracking and a sudden drop in the load bearing capacity (see Fig. 1). In many cases, the reduced member ductility, typical of a brittle failure, may lead to a structural collapse with severe consequences in terms of economic losses and life safety. In other cases, the short member length, often related to architectural needs, along with a wrong capacity design may result in a significant structural weakness. This makes the accuracy in the prediction of member shear capacity of paramount importance to properly assess the overall structural performances and design effective retrofit solutions.

Number of shear strength models and design formulations can be found in worldwide codes and guidelines. Commonly, code design formulations [5–9] are based on the truss analogy model, postulated a century ago by Ritter and Mörsch [10,11]. Often, they result in very conservative underestimations of the actual shear strength when used to predict the shear strength of existing members [12]. This is because of the severe limitations on the truss inclination or on the maximum allowed concrete stress used to account for flexural-shear interaction, loss of bond and other non-linear phenomena typical of RC members [13]. It is worth mentioning that those models are commonly suggested in worldwide standards for seismic design of new buildings, where a structural safety higher than existing structures is expected.

Along with the design formulations, refined theories (the Modified Compression Field Theory, MCFT, [14], among many others) were proposed to overcome the deficiencies of the classical

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Fig. 1. Column shear failures after L'Aquila earthquake, 2009, Italy.

theoretical approaches. This model accounts for shear behavior of RC members subjected to a variable stress field considering smeared and fully rotating cracks. Local stresses and strains at cracks are computed based on the stress-strain relationship properly developed for cracked concrete.

In the recent years, several capacity models and simplified formulations have been proposed to improve the accuracy in the assessment of the shear strength of RC members. In particular, the increasing number of available experimental tests allowed the calibration and validation of simplified models suitable for the application in common practice. These models were calibrated matching the mean value of the experimental data. Thus, with respect to design formulations more refined predictions of the experimental response are expected.

Experimental evidences [15–17] showed that non-conforming RC members commonly have a reduced ductility and may suffer premature shear failure. Cyclic loads and the increasing flexural deformations along with seismic detailing non-conforming to current seismic codes [18,19] significantly affect the member lateral response [20]. The reduction of the shear strength for increasing ductility demand could change a ductile flexure failure mode in a more dangerous shear failure, with a sudden drop of the lateral capacity after the flexural yielding (flexural-shear failure according to ACI 318-11 [6]).

These concepts are accounted for in modern capacity models which consider the shear capacity as a function of the ductility demand under reverse cyclic actions. One of the first formulations accounting for the reduction of concrete shear transfer mechanisms during cyclic loadings has been proposed by Priestley et al. [21], known as University of California at San Diego (UCSD) model. Such a model, calibrated on the few available tests on rectangular and circular members, considers that the shear strength is the sum of the concrete mechanisms, the contribution of the transverse steel reinforcement, estimated with a fixed inclination truss analogy, and the contribution of the axial load (accounting for the arch action). Then, the original UCSD formulations have been modified for circular columns (revised UCSD, Kowalsky and Priestley [22]) and shear walls [23]. In particular, the revised UCSD model [22] overcomes the deficiency of the original model, which neglects the effects of member aspect ratio and light longitudinal reinforcement ratio on concrete shear capacity. The revised UCSD model, validated on 38 circular columns with shear and flexure-shear failure mode, is often used in common practice also for rectangular columns [24] and it has been also adopted in several codes and guidelines (e.g. Circ. n. 617 [25] for bridge piers and Caltrans Memo to Designers 20-4 [26]).

Recently, based on large database of experimental tests on RC columns, new models have been formulated to capture the effect of shear strength degradation. Sezen and Moehle [27] and Biskinis et al. [24] assume that the shear strength degradation due to the ductility demand affects both concrete and steel contributions. Sezen and Moehle [27] model focuses on diagonal tension failure and adds the steel contribution, computed with the truss analogy, to concrete contribution, computed using the Mohr's circle approach and including the effect of axial load. The model has been calibrated on 51 experimental tests on rectangular columns mainly exhibiting flexure-shear failure and it is adopted in current standards for the assessment of existing buildings [18,19]. Note that, because of the limited number of tests adopted in model validation, caution is recommended when applying outside the range of test data [28]. In those cases, the ACI 318 [6] or other experimentally validated formulations can be employed.

The empirical model in Biskinis et al. [24] has been calibrated on an a database of 239 experimental tests, including tests on rectangular and circular columns, shear walls and bridge piers, failed both in shear and flexure-shear. Differently from previous models, in Biskinis et al. [24], the diagonal failure of concrete compressive strut, typical of short columns, is also considered. Indeed, two formulations are given for columns shear failure due to diagonal tension and diagonal compression. This model, along with the classic variable truss approach, is suggested in the Eurocode 8 part 3 [29] for assessment purposes.

Alternative to empirical models, a simplified version of MCFT, named SMCFT [30], is suggested in several standards and guidelines [31–33] to estimate the shear strength of RC members. The model simplifies the original theory [14] in the calculation of the inclination of the compressive stresses and in the tensile stress at the peak strength, which can be accurately estimated with simple equations. It assumes that the concrete reinforced in both longitudinal and transverse directions has the ability to resist shear at a range of different possible angles of principal compression by a plastic truss mechanism. Due to the ability of concrete to sustain compressive stresses without crushing and the steel to yield, the shear stresses can be redistributed to different angles. This formulation has been validated on RC panels subjected to shear or combined actions.

This study aims at clarifying the applicability of available shear strength capacity models. The number of available shear strength formulations, the lack of a widely accepted theory and the different databases used for the model's validation creates a lot of uncertainties in the model selection. Often, this results in the use of very conservative mechanical approaches, mainly developed for design purposes, to assess the shear strength of non-conforming RC members. Eight capacity models commonly adopted in the current practice, worldwide standards or guidelines have been assessed. The model predictions are compared with a unique database of 180 selected experimental tests in order to quantify the model accuracy, mean absolute percentage error and level of safety. The scope of this study is to drive the reader (practitioners, researchers or code committees) to select the most appropriate shear strength