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A new approach to shear design of slender reinforced concrete members without transverse reinforcement

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ABSTRACT

This paper presents the theoretical development of a new approach to determining the shear capacity of slender reinforced concrete members without transverse reinforcement. Taking into account the very small component of the normal stress of concrete in the tension zone, which is normally neglected when determining the bending capacity, it is assumed that the damage is potentially localized in a narrow band that tends to connect the tips of existing flexural cracks. The width of this band increases with the shear force and decreases with the increase of the bending moment. The shear failure is characterized by the formation of the critical shear crack in the shear band when its width reaches a critical value. With the new approach, the bending moment has a positive influence on the shear resistance of a cross-section, which contradicts most existing shear models. The validation of the new approach against experimental data shows that the proposed method accurately predicts the shear capacity of all investigated types of shear span. The influences of the structural system and load arrangement on the shear response observed from experimental investigations can be well captured.

1. Introduction

Substantial components that contribute to the shear resistance of slender reinforced concrete members without transverse reinforcement have been specified through numerous theoretical and experimental investigations over the last 60 years, as summarised in the Report of Joint ACI-ASCE Committee 445 [1] or in the extensive review of research results performed by Collins et al. [2]. Opinions about the relative magnitude of these contributions and how they act together are, though, strongly diverse. This led to a large number of mechanics-physical based models to describe the shear behaviour, in which according to individual author concepts, for the sake of simplicity, normally only one or two components are considered to be essential and are taken into account in the formulation of the shear model.

In the largest number of mechanics-based models, it is assumed that only the uncracked flexural compression zone is responsible for the shear resistance. Reineck [3] and Sherwood [4] examined the shear force component calculated from integration of the shear stresses over the depth of the compression zone according to bending theory and stated that this component, however, does not significantly contribute to the shear resistance in a slender member without axial compression. In most models of this type, the basic assumption that plane sections remain plane is adopted in determining the depth of the compression zone as well as in the distribution of the concrete normal stress in this zone. Though, to eliminate the shear stress in the web below the neutral axis (thus to consider that shear stress only distributes in the compression zone), Zink [5] and Tureyen and Frosch [6,7] simultaneously assumed a local loss of the bond between the flexural reinforcement and the surrounding concrete in the tension zone. With this assumption, the cross-sections do not remain plane, rather, an inclined compression strut and a constant horizontal tie should be developed, what can contradict the first assumption. Also, relying on the shear resistance of the uncracked compression zone, Park et al. [8–10] described development of the inclined failure surface in this zone through examination the principal stresses, while Zararis and his co-authors [11,12] checked the splitting stress of a fictive round plate having a diameter of the length of the inclined strut in the compression zone for failure in this zone. Since different shear-transfer mechanisms have been recognized, the shear component carried by the uncracked compression zone should not be considered as the only one to carry shear force in a cracked member.

Through the introduction of the average stress–strain relation for the cracked concrete, especially in tension, the Modified Compression-Field Theory (MCFT) developed by Vecchio and

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Nomenclature

a	shear span
b_w	web width
d	effective depth of member
$d_{b,crit}$	critical width of the shear band
d_g	size of the maximum aggregate particles
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of steel
f_c	compressive strength of concrete
f_{ct}	tensile strength of concrete
G_F	fracture energy of concrete
h	depth of member
M	bending moment
M_{cr}	crack moment of the cross-section
n	modular ratio for reinforcement steel
s_{rm}	crack spacing of primary cracks
V	shear force
V_{Rc}	shear resistance provided by concrete
x	cracked concrete section neutral axis depth
x_0	distance from the critical shear crack to the support
x_{crit}	distance from the control section to the support
x'	distance from the peak of the concrete tensile stress to the neutral axis
x''	height of the region with softening of concrete in the tension zone
w_k	crack opening of the primary cracks
ε_{ct}	strain of concrete by reaching the tensile strength
ε_s	strain in longitudinal reinforcing bar
$\rho_{p,eff}$	reinforcement ratio in the effective area of concrete surrounding the reinforcement
ρ_s	reinforcement ratio for the flexural reinforcement
τ_u	allowable shear stress in the critical width of the shear band
τ_{Rc}	relative shear capacity, $\tau_{Rc} = V_{Rc}/(bd)$
σ_1	principal tensile stress in concrete
σ_2	principal compressive stress in concrete
σ_{xm}	average normal stress of concrete within the critical width of the shear band

Collins [13] describes the response of reinforced concrete membrane elements loaded in pure shear or in shear combined with axial stress very well. Having considered the shear transfer by aggregate interlock essential and based on the test results of Walraven [14], a relationship between shear across the crack, crack width and compressive strength is proposed. Obviously, the tensile axial strain reduces the shear capacity of these elements. This mechanism is widely accepted as an important shear-transfer mechanism [1]. The simplification of the MCFT (SMCFT) proposed by Bentz et al. [15] has been included in some recent shear provisions, i.e. CSA 23.3-04 [16], ASSHTO LRFD [17] and *fib* MC 2010 [18]. Applying the MCFT to slender reinforced concrete beams, the authors considered the bending moment and shear force to cause the longitudinal strain in the web [19,20], and hence, to affect shear resistance.

From the other starting point, the Critical Shear Crack Theory (CSCT) developed by Muttoni [21], Muttoni and Ruiz [22] yields, though, very similar equations and predictions for the shear resistance as that of the SMCFT. Having assumed that the critical crack width is proportional to the longitudinal strain in the control depth that can be directly derived from the bending moment, the CSCT also considers the effect of the bending moment on the shear resistance. With some small simplifications, the theory has been adopted by the Swiss Code SIA 262 [23].

With regard to the fact that shear force in flexural members is a result of the change of the bending moment, the co-existing bending moment must affect the shear response of slender members. In this connection, the approaches included in the above-referred theories (MCFT and CSCT) have potential abilities to represent the nature of this behaviour. Taken into account the effect of the bending moment, the physic-mechanics based theories predict the shear resistances not only of the simply supported beams under concentrated loads, but also of simply supported beams under uniform loads with significantly higher shear capacities well [20,15,22]. Furthermore, it is shown that the theories are able to accurately capture most influencing parameters on the shear resistance, such as the compressive strength, reinforcement ratio, effective depth of section (size effect), shear span-to-depth ratio, and aggregate size [21,22,24–26]. In contrast, empirical formulations included in the most used design codes, both in EC2 [27] and ACI 318-08 [28], are not able to capture the possible effect of the co-existing bending moment because they were both calibrated with test data on simply supported beams subjected to one or two-point loading. Evidence of inaccurate predictions with ACI 318-08 for the shear capacity of simply supported beams subjected to uniformly distributed loading can be found elsewhere, e.g. [12].

Taking the effect of the longitudinal strain in the web on the shear resistance into consideration, the predicted shear capacity according to these theories (SMCFT, CSCT) is then lower for members with predominant flexural action, such as regions at intermediate supports of continuous beams, than for members with less flexural action, such as simply supported beams. The experimental investigation performed by Perez et al. [29] on cantilevers under different load arrangements shows, however, that cantilevers under distributed loads fail at significantly higher shear force than cantilevers subjected to one concentrated load. The co-exiting moment at failure is, consequently, higher for cantilevers under distributed loads than for cantilevers under concentrated loads. Another experimental program, which has just been carried out at the Graz University of Technology [30] shows, moreover, that shear force at failure for cantilevers subjected to uniformly distributed load with a longer cantilever arm (thus, with a larger bending moment at failure) is much higher for the same beams with a shorter cantilever arm (thus, with a smaller bending moment at failure). This implies that the moment–shear resistance interaction included in above theories should be re-examined.

In this paper, a new approach to the shear design of reinforced concrete members through introduction of a new criterion for the formation of the critical shear crack is presented. The co-existing bending moment with the corresponding flow of forces and flexural crack pattern is considered to have a decisive influence on the shear behaviour of a member. This approach is limited for slender members ($a/d \geqslant 2.5$) without transverse reinforcement. The verification and validation of the proposed method are performed through comparing the predicted shear capacities with experimental data. To evaluate the quality of the proposed approach in relation to the state-of-the-art, the predicted shear capacity using the proposed method is also compared with some design equations in EC 2 [27], ACI 318-08 [28] as well as with *fib* MC 2010 [18].