Addressing Punching Failure

Considerations to Prevent Premature Concentric Punching Shear Failure in Reinforced Concrete (RC) Two-way Slabs

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Two-way slabs are unique to Reinforced Concrete (RC) construction. The most common type, due to its ease of forming and speed of construction, is the flat plate, a slab of uniform thickness supported by columns without beams, drop panels or capitals. Flat plates are common in building construction, and can also be found as deck components in waterfront piers and wharves.

The design of RC flat plates is generally governed by serviceability limits on deflection, or by the punching shear capacity of the slab at the slab-to-column interface or at locations of concentrated loads. In practice, for the specific case where the transfer of unbalanced moment to the column is minimal, most punching failures look alike: a pyramid or truncated cone of slab remains around the column as the slab is loaded to failure. Punching may occur before (brittle) or after (ductile) a yield line mechanism has formed in the slab around the column. Brittle punching is undesirable because there is little warning of the impending failure.

For about 50 years, ACI 318 has used the equation $V_n = 4\sqrt{f'_c}b_o d$ (where f'_c is the specified compressive strength of concrete, b_o is the critical perimeter measured at $0.5d$ from the column face, and d is the effective depth of the flexural reinforcement in the slab) for the nominal concentric punching shear capacity of two-way RC slabs. This expression was first introduced in the 1963 code following recommendations provided by ACI Committee 326 (Shear and Diagonal Tension) and is based on subtle modifications to a design procedure developed by Moe (1961).

The ACI 318 equation (V_{ACI}) has served the profession well. However, with the increasing use of higher strength steels and concretes, the equation is facing increasing scrutiny from researchers and practitioners because (1) it does not include a factor for the effect of the slab flexural reinforcement ratio, ρ, on the slab punching capacity; and (2) average shear stresses significantly lower than $4\sqrt{f'_c}$ at punching have been reported by several researchers for test slabs with $\rho < 1\%$ and also for slabs with $d > 8$ inches.

This article discusses qualitatively the relevance of these "perceived" deficiencies in the ACI 318 punching shear equation, highlighting its shortcomings and suggesting ways to improve the existing code provisions. This discussion concerns the concentric punching shear capacity only and does not include the effects of transferring unbalanced moments. However, the concepts suggested here can be readily extended to the moment transfer situation by use of the interaction relationship discussed in R11.11.7.2 of ACI 318.

Reinforcement Ratio Effect and Interaction Between Shear and Flexure

The absence of a ρ term is often cited as a major deficiency by those who claim that the ACI 318 equation does not predict the punching shear capacities of test slabs as accurately as other equations that explicitly include this variable. This claim is, however, unfounded. Alexander and Hawkins (2005) reminded the profession that the ACI 318 equation was never intended to be used as a shear capacity predictor. Instead, it is a *design* equation aimed at precluding a brittle punching shear failure before the slab develops its flexural capacity. Its use *assumes* that the slab has already been properly designed for flexure.

The interaction between the transferred shear, V, and the shear associated with the flexural capacity of the slab, V_{flex}, as envisioned by Moe (1961), is qualitatively shown in *Figure 1*. The unbroken straight black line and the unbroken black curve represent conditions for a flexural failure and a shear failure, respectively. When the designer provides the proper amount of flexural reinforcement to resist the demand, the flexural capacity matches the design load. V_{flex} plots as a straight line against the flexural load capacity because it is the product of the slab design load and the area tributary to the column. Point A represents the "balanced failure" point; i.e., the point where the slab fails simultaneously in flexure *and* shear. To the right of point A, $V > V_{flex}$; i.e., shear failure governs. To the left of point A, $V_{flex} < V$; i.e., flexural failure governs.

The latter is the target failure zone for designers. To allow full moment redistribution and the development of sufficient slab deformation to warn of any impending failure, Moe recommended that the slab be *designed* for $V = 1.1\,V_{flex}$. Thus, the intersection of the steeper straight line with the shear design curve leads to a slight reduction in shear capacity (point B). The plateau B-D is equivalent to the nominal punching shear capacity, V_{ACI}. In practical terms, the design envelope O-B-D separates flexural from shear failures, confirming that even though the ACI 318 equation is not explicitly set up in terms of ρ, it is tacitly based on a term (V_{flex}) that accounts for ρ.

Punching of Slabs with Low Reinforcement Ratios and the Issue of Ductility

The effect of ρ on slab punching capacity has been discussed in the past by many researchers. Intuitively, a decrease in ρ should lead to a reduction in the depth of the compression zone available to resist transverse shear, and also to an increase in the width

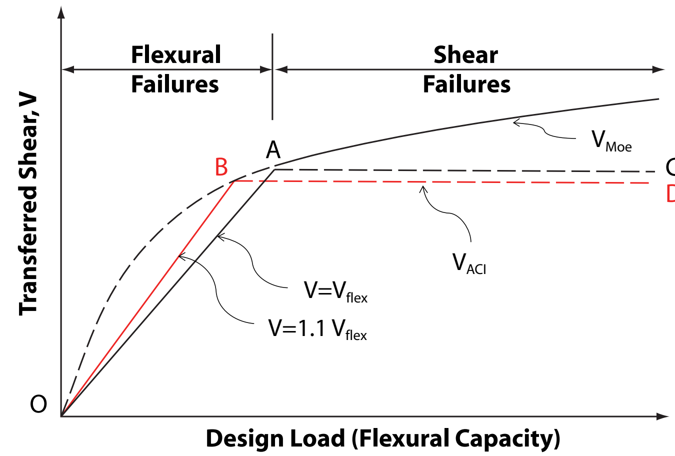

Figure 1: Slab design rationale. (After Moe (1961) and Alexander and Hawkins (2005)).

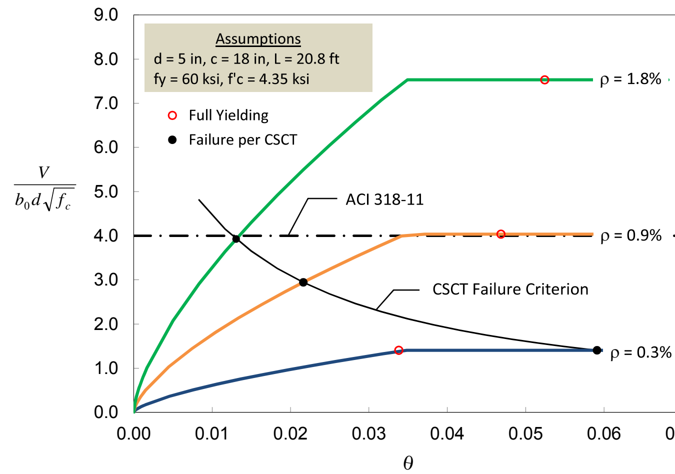

Figure 2: Relationship between V, V_{ACI} and V_{flex} for slabs with varying ρ.

of flexural cracks near the column. The increase in crack width should result in a reduction in aggregate interlock and dowel action. The combination of those three effects should lead to a reduction in the punching shear capacity. Even though punching shear tests of slabs with low ρ are few – the vast majority have been performed on slabs with fairly large amounts of flexural reinforcement to avoid flexural failure – there is experimental evidence (Criswell 1974, Guandalini et al 2009, and Widianto et al. 2009) indicating that two-way RC slabs with ρ < 1% may fail at shear stresses lower than $4\sqrt{f'_c}$ and display little ductility prior to punching. The problem is exacerbated when *d* > 8 inches (Guandalini et al 2009). With the use of higher strength steels and higher strength concretes, many flat slabs now have ρ < 1%.

The fact that a slab with low ρ can fail at a shear stress less than $4\sqrt{f'_c}$ may seem to create the need for a new equation for V_n. Such a "necessity" is, however, unjustified because, as shown by Peiris and Ghali (2012), as long as the slab is properly designed for flexure, the slab will reach V_{flex} *before* it punches. Hence, the maximum shear that can be transferred by a slab with a low ρ is likely to be that associated with the flexural capacity of the slab. That shear can be calculated from a yield line analysis assuming a concentric mechanism centered on the column or concentrated load; or, if using a finite element program, by extracting the shear associated with the applied load on the slab at its flexural capacity.

Historically, the mode of failure of RC two-way slabs tested in the laboratory has been determined by comparing the failure load *V*

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against V_{flex}, with the latter determined from yield line analysis. Brittle shear failure occurs if $V/V_{flex} < 1$, whereas the failure is driven primarily by flexure if $V/V_{flex} > 1$. Additional refinements, to account for strain hardening effects and in-plane restraint effects, have been proposed to establish the brittle versus ductile slab failure mode boundary. Whether an RC two-way slab falls into either category depends primarily on ρ, f'_c, and the geometric characteristics of the slab-column connection. Increased ductility is expected in slabs with larger V/V_{flex} ratios, but at the expense of a punching capacity reduction. For V/V_{flex} higher than 1.1 – i.e., low ρ – Moe's theory assumes that such failures should be preceded by significant deflection increases due to extensive yielding of the slab reinforcement surrounding the column.

Unfortunately, direct comparisons between V and V_{flex} do not necessarily define whether a slab will deform significantly prior to punching. Experience shows that it is incorrect to assume that satisfying $V = V_{ACI}$ will result in markedly increasing deflections or rotations at a slab-column connection before punching occurs. The reason is shown in *Figure 2*, where the shear force-rotation responses per the Critical Shear Crack Theory (CSCT) of Muttoni (2008) are shown for three slabs having identical geometries and differing ρ values. Muttoni's theory is probably the most accurate punching shear response predictor available. Black solid circles represent punching failures per the CSCT failure criterion. Red empty circles signal full yielding of the slab based on a yield line analysis and assuming a line of contra-flexure in the slab at 0.22 times the distance between columns. The yield line capacity is that for a local failure mechanism centered on the column, and is less than the mechanism associated with full yielding of the slab reinforcement.

The slab with ρ = 0.3% was expected to reach V_{flex} at a strength substantially less than V_{ACI}. Punching failure in this case is driven by flexure, and the slab displayed considerable rotation before punching. The response of the slab with ρ = 0.9% shows that even though V_{flex} was expected to match V_{ACI}, punching occurred prematurely, in a brittle fashion, prior to developing the full local flexural capacity. This result highlights the inadequacy of defining a slab failure mode using a strength-based approach only; it implies that reaching V_{flex} is not enough by itself to prevent premature punching failure. The response of the slab with ρ = 1.8% shows that this slab is expected to punch at a load similar to V_{ACI}, and well below V_{flex}, with no ductility whatsoever prior to punching.

The most significant limitation of using the V/V_{flex} approach to separate shear and flexure-driven failures is that attention is concentrated on the load-resisting aspects of the slab response, and not on the associated deformations. In 1963, the primary structural design emphasis was on the accurate evaluation of strength, with little attention paid to deformations; let alone the fact that none of the slabs examined by Moe corresponded to the $V/V_{flex} > 1.0$ case, as noted by Widianto et al (2009). In fact, excluding footings, none of the test slabs considered by Moe had ρ < 1%.

The situation is even more serious for earthquake-resistant design. Even though concentric punching is linked mainly to gravity loading conditions, the associated deformability issues can be invoked to attempt addressing those in the presence of lateral loads. Experiments have shown that the ductility under lateral loading increases as V/V_{ACI} decreases. Today, the basic concepts of seismic design, including the need for ductility and what ductility means, are widely understood and used. For performance to be acceptable in medium and high seismic design categories (SDC), the flexural strength must be maintained through displacements that are several times those at yielding of the flexural tension reinforcement. For one-way action, there is always ductility when the flexural strength is achieved prior to the shear strength. Shear failure following development of the flexural strength is only likely if the flexural reinforcement undergoes rapid strain hardening. Even then, the deformations have increased sufficiently that adequate warning has been provided of the impending failure. Unfortunately, for two-way action in slabs, deformations do not start to develop rapidly once the flexural strength is reached at the slab-column interface, and the use of low reinforcement ratios in that region does not ensure ductility.

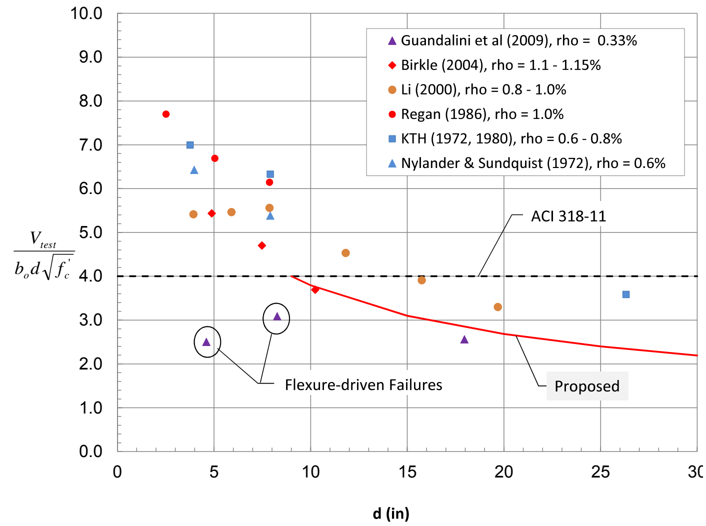

Figure 3: Observed size effect on RC two-way slab punching capacity.

These observations suggest supplementing the ACI 318 equation with a design provision that explicitly addresses minimum deformability requirements for RC two-way slabs to delay premature concentric punching failure. One possible approach is a re-arrangement of Muttoni's CSCT based on a target ratio of slab rotation at ultimate to slab rotation at first yield. Once the ductility shortage is identified, the most practical solution is the addition of shear reinforcement. However, designers should never use a punching shear strength greater than that for the development of a local yield line mechanism centered on the column. Guidance to evaluate V_{flex} for isolated slab-column connection tests and for slab systems is provided by the ACI-ASCE State-of-the-Art Report on punching of slabs (1974).

Size Effect

Another key consideration for reliably predicting the shear capacity of two-way slabs is the so-called size effect. *Figure 3* shows the effect of increasing the slab effective depth on the normalized punching capacity ($4V_{test}/V_{ACI}$) for selected test results extracted from the ACI 445 Punching Shear Test Databank (Ospina et al. 2012). The shear capacity of two-way slabs decreases as the effective depth increases. Shear capacities less than $4\sqrt{f'_c}$ develop for $d > 8$ inches. The reduction in strength is substantial, especially if the slab is lightly reinforced. These observations suggest the effects of low reinforcement ratio and increasing slab depth are in large measure additive. Both are detrimental to the shear capacity of the slab. *Figure 3* shows that reasonable punching shear capacity estimates result for slabs with $d > 8$ inches if V_{ACI} is multiplied by $3/\sqrt{d}$ (with d in inches).▪

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