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# Evaluating the shear-friction resistance across sliding planes in concrete

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ABSTRACT

Shear friction or aggregate interlock behaviour across sliding planes in concrete is now a well-established area of research. Two separate shear-friction approaches have been developed previously where these separate approaches either quantify the shear transfer capacity for a given crack displacement, normal stress and crack separation (*Walraven Approach*) or quantify the maximum shear transfer for a given crack confinement (*Mattock Approach*). In this paper, these two seemingly disparate approaches are combined to provide sufficient information to simulate all aspects of shear friction in initially cracked planes including a quantifiable failure limit for various crack separations and displacements. The shear friction components of initially uncracked sliding planes are also derived from the analysis of actively confined concrete cylinders and a failure envelope for initially uncracked sliding planes is developed. Hence, this paper provides the technique for determining the shear friction properties not only for initially cracked sliding planes, which have previously been available, but also for initially uncracked sliding planes which were not previously available so that shear-friction theory can now be used for all aspects of concrete.

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## 1. Introduction

Reinforced concrete structures are typically cracked under serviceability conditions and as such sliding planes occur in initially cracked concrete such as across flexural and critical diagonal cracks. When these cracks form, it is known that shear forces can be transferred across the crack primarily in two ways, that is dowel action and shear friction. Shear friction, which is the subject of this paper, is a well-established research area [1–5] with many applications [6–9] and its importance to the behaviour of reinforced concrete is fully appreciated.

The term shear friction was first proposed by Mast [10] and Birkeland and Birkeland [11] to define the frictional resistance of cracks to sliding. Under initially cracked conditions the sliding plane surfaces can be idealised as rough and irregular. These rough, irregular aggregate particles force the sliding planes apart and this separation induces normal stresses in the reinforcement crossing the sliding planes, restricting the opening of the sliding planes. Confinement to the sliding planes provides frictional resistance to sliding and allows the transfer of shear forces across the cracked planes [12–15]. Under high levels of confinement significant shear stresses can be transferred across the crack faces through shear friction (sometimes referred to as "aggregate interlock").

The shear friction parameters of initially cracked planes have been quantified mathematically. Walraven [13] performed a fundamental analysis on aggregate interlock for initially cracked sliding planes where the structure of cracks was assessed at both a macro and micro-roughness level. From this analysis, where it was shown that the macro-roughness of the crack face was the dominant shear transfer mode, the projected contact areas of aggregate bearing on the opposing sliding plane were quantified statistically. The corresponding shear and normal stress transferred across the crack are proportional to the projected contact areas and according to Walraven and Reinhardt [14] are given by:

$$\tau_N = -\frac{f_{co}}{30} + (1.8h_{cr}^{-0.8} + (0.234h_{cr}^{-0.707} - 0.20)f_{cc})\Delta \quad (1)$$

$$\sigma_N = \frac{f_{co}}{20} - (1.35h_{cr}^{-0.63} + (0.191h_{cr}^{-0.552} - 0.15)f_{cc})\Delta \quad (2)$$

where the units are in N and mm, $f_{co}$ is the unconfined compressive cube strength of concrete (referred to as $f_{cc}$ in the original Walraven and Reinhardt equations), $h_{cr}$ (or sometimes referred to as '$w$') is the sliding plane separation, $\Delta$ the relative displacement of the sliding planes, $\sigma_N$ the normal stress and $\tau_N$ the shear stress across the sliding planes. In Eqs. (1) and (2) the original nomenclature used by Walraven and Reinhardt for concrete strength, $f_{cc}$, has been replaced with $f_{co}$ to prevent confusion, where in this paper $f_{cc}$ refers to the confined strength of concrete.

These mathematical expressions, Eqs. (1) and (2), quantify the magnitudes of the shear and normal stress able to be transferred

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