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A REVIEW ON SHEAR FRICTION MODELS

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Abstract---The strength of the interfacial shear between concrete cast at different times is of great importance for ensuring the consistent behaviour of RC composite elements. Prefabricated beams with monolithic slabs, bridge decks reinforced by adding a new layer of concrete, repairing and reinforcing existing concrete structural elements by adding a new layer of concrete is examples of reinforced concrete composite elements. This article briefly discusses several approaches to predicting the shear strength of a reinforced concrete beam. The shear friction theory/model is one of the approaches adopted in design standards for predicting strength under longitudinal shear between concrete elements cast at different times and same time. This article presents a review of the literature on structural expressions for shear friction, such as the innovative concept of the friction shear theory, proposed by Birkeland and Birkeland in 1966. A "modified version" was proposed by Mattock and Hawkins in 1972; Incorporation of concrete strength in 1978 by Loov; the "sphere model" developed by Walraven in 1987; and considering all effects like the influence of cohesion, friction and dowel action are specifically identified by Randl in 1997.

Keywords---Interfacial shear strength, shear friction theory, longitudinal shear strength, cohesion, friction, dowel action.

I. INTRODUCTION

Reinforced concrete bridge decks, RC slabs, are often reinforced by the addition of a concrete overlay. The sheathing of beams and RC columns is also widely used in strengthening operations. In these situations, the interfaces between concrete and concrete play an important role in assuming the monolithic behaviour of the resulting RC Composite Element. Due to the complexity of shear transfer mechanisms, shear design procedures have been the subject of intense research for more than 100 years. There are several approaches for predicting the shear strength of RC members. They are Truss model, Plastic theory, Compression field theory, Shear friction theory and Segmental approach.

The truss model is based on the truss model 45^0, in which the contribution of transverse reinforcement to shear capacity is determined by quantifying the expansion of a critical diagonal crack, and the specific contribution to shear capacity is equal to that at which the diagonal of the crack forms. Later, the truss model was improved by applying a plastic theory, which allows to vary the angle of a critical diagonal crack, and determining in such a way that the destruction of the cross section is such that the load causing the diagonal cracking coincides with the load causing slip along the inclined crack.

As an alternative to the truss model and plasticity theory, compression field theory uses the condition of deformation in concrete to determine the inclination of a diagonal crack and takes into account the total contribution of concrete to shear capacity by determining the average principle of tension in concrete with cracks, which includes both surface stresses cracks and between cracks. The segmented approach is an approach based on mechanics for the analysis of reinforced concrete based on well-established mechanics of the interaction of particles. This model can be applied to determine a wide range of behaviour including bending strength, short term and long term deformation of the traditionally reinforced and pre-stressed beams and columns, as well as crack width and the distance between cracks.

II. SHEAR FRICTION.

The theory of shear friction suggests that the mechanism for transferring shear forces at the interface between concrete and concrete, which is simultaneously subjected to shear, and compression, is ensured only by friction. A simple "saw teeth model" is commonly used to illustrate the basic principles of this theory, which is shown in Figure 1. The effects of both transverse reinforcement crossing the interface and normal stresses in the shear plane are considered.

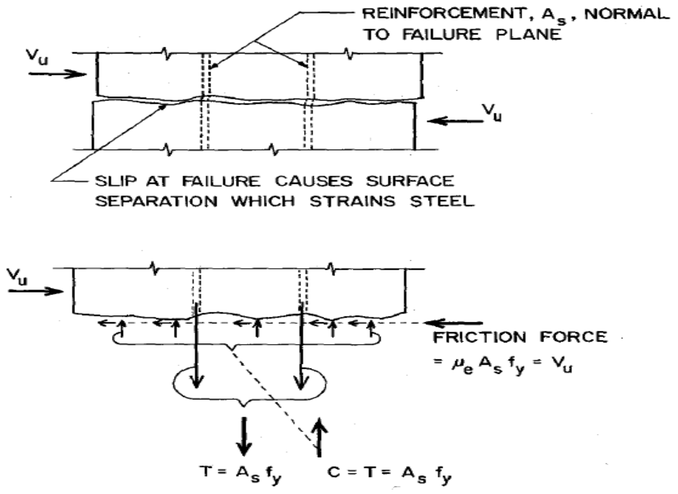

Figure 1 Schematic representation of Shear-friction principle (Extract from Shaikh (1978))

Several design expressions were proposed for predicting the ultimate stress of the longitudinal shears at the interface between concrete and concrete. Few of the studies are Anderson (1960), Mattock and Kaar (1961), Birkeland and Birkeland (1966), Birkeland (1968), Mast (1968), Hofbeck, Ibrahim, Mattock (1969), Mattock and Hawkins (1972), Mattock (1974, 1981, 1994, 2001), Mattock Li and Wang (1976), Raths (1977), Shaikh (1978), Loov (1978), Walraven (1981, 1987), Mau and Hsu (1988), Lin and Chen (1989), Tsokantas and Tassios (1989), Patnaik. (1992, 2000, 2001), Loov and Patnaik (1994), Randl (1997, 2013), Kan and Mitchell (2002), Papanicolaou and Triantaphyllou (2002), Mansour, Vinayagam and Tan (2008), Santos and Julio (2009), Rahal (2015).

Among them are five of the most significant contributions are theory of shear friction proposed by Birkeland and Birkeland in 1966, the “modified version” of Mattock and Hawkins in 1972, the inclusion of concrete strength by Loov in 1978, the “sphere model” developed by Walraven in 1987, and considering all mechanisms in design expression proposed by Randl 1997. These five theories are explained below.

Birkeland and Birkeland (1966) were the first to propose a linear expression to evaluate the ultimate longitudinal shear stress of concrete interfaces. The proposed expression is as follows.

$$v_u = \rho f_y \mu$$

Where ν_u is the ultimate longitudinal shear stress at the interface;

ρ is the reinforcement ratio;

f_y is the yield strength of the reinforcement.

φ is the internal friction angle.

The tangent of the internal friction angle is also designated as coefficient of friction, represented by μ. This expression was proposed for smooth concrete surfaces, artificially roughened concrete surfaces, and concrete to steel interfaces.

The coefficient of friction was defined for several situations as:

μ = 1.7 for monolithic concrete (59.5°)

μ = 1.4 for artificially roughened joints (54.5°)

μ = 0.8-1.0 for ordinary construction joints (38.7°=45°)

The accepted design philosophy states that concrete tensile strengths should be neglected, all tensile forces are absorbed by steel reinforcement and shear forces are transmitted by friction. This design philosophy assumes that because of the relative slippage between old concrete and new concrete layers, the crack width at the interface increases, steel reinforcement leads to stretching, thus compressing the interface and shear forces are transmitted by friction.

Mattock and Hawkins (1972) presented a design expression to predict the ultimate longitudinal shear stress. This design expression was developed for the lower bound of the experimental tests used for calibration represented as

$$v_u = 1.38 + 0.8\left(\rho f_y + \sigma_n\right) \text{ (MPa)}$$

Where ν_u is the ultimate longitudinal shear stress at the interface;

ρ is the reinforcement ratio;

f_y is the yield strength of the reinforcement;

σ_n is the normal stress at the interface.

The first term is associated with obvious cohesiveness of the interface and the dowel action of the reinforcement, and the second term is associated with clamping stresses. The ultimate longitudinal stress is limited to a minimum value of 0.3 fc and 10.34 MPa (1500 pounds per square inch). The clamping force must be above 1.38 MPa (200 psi. Inch). The coefficient of friction was 0.8.

Loov (1978) was the first researcher to explicitly include the concrete strength by proposing the following non dimensional expression:

$$\frac{v_u}{f_c} = k\sqrt{\frac{\rho f_y + \sigma_n}{f_c}}$$

Where ν_u is the ultimate longitudinal shear stress at the interface;

f_c is the concrete compressive strength;

k is constant, for initially uncracked interfaces, Loov suggested the value of 0.5 for k.

ρ is reinforcement ratio;

f_y is the yield strength of the reinforcement;

σ_n is the normal stress at the interface;

For a concrete with compressive strength equal to 30.89 MPa (4480 psi) this expression is equal to the one proposed by Birkeland (1968). This design expression can be used with any consistent system of units. (SI or imperial).

In order to consider the concrete strength Walraven, Frenay and Pruijssers (1987) developed a large experimental study with 88 push off specimens and proposed a non-linear function to predict the shear strength of initially cracked interfaces and based on Walraven (1981) spherical model. The design expression including the reinforcement ratio, the yield strength of the reinforcement, and the concrete compressive strength is as follows:

$$v_u = C_1(\rho f_y)^{C_2}$$
$$C_1 = 0.822 f_c^{0.406}$$
$$C_2 = 0.159 f_c^{0.303}$$

Where ν_u is the ultimate longitudinal shear stress at the interface.

ρ is the reinforcement ratio.

f_y is the yield strength of the reinforcement

f_c is the concrete compressive strength of 150 mm cubic specimens.

The design expression is based on a model proposed by Walraven, where the concrete is represented by the binding paste and aggregates (assumed as spheres) and where the interface between both is considered as the weakest zone and therefore cracks will develop along this binder.

Randl (1997) made one of the most significant contributions to improving the accuracy of design expressions for estimating the ultimate stress of the longitudinal shear during transitions between concrete and concrete. Randl presented a design expression that explicitly includes the contribution of cohesion, friction and dowel action.

The first term cohesion is related to the contribution of the interlocking between aggregates. The second term friction is related to the contribution due to the longitudinal relative slip between concrete parts and is influenced by the surface roughness and the normal stress at the shear interface; and the third term dowel action is related to the contribution of the flexural resistance of the shear reinforcement crossing the interface. The proposed design expression is given as follows.

$$v_u = \underset{\text{Cohesion}}{C f_c^{1/3}} + \underset{\text{Friction}}{\mu\left[\sigma_n + \rho k f_y\right]} + \underset{\text{Dowel Action}}{\alpha\rho\sqrt{f_y f_c}} \leq \beta v f_c$$

Where ν_u is the ultimate longitudinal shear at the interface

μ is the coefficient of friction

σ_n is the normal stress at the interface due to external loading and tension in shear reinforcement

α is coefficient to take into account for the flexural resistance of reinforcement (dowel action)

ρ is the reinforcement ratio

f_c is the concrete compressive strength

f_y is the yield strength of the reinforcement.

C is the coefficient of cohesion.

k is coefficient of efficiency for a tensile force that can be transmitted to the shear reinforcement.

β is the coefficient allowing for angle of concrete diagonal strut

ν is the reduction factor for strength of concrete diagonal strut

Surface preparation	Surface roughness	Coefficient of cohesion	Coefficient of friction		k	α	β
	R	c	μ				
	(mm)	-	($f_{ck} \geq 20MPa$)	($f_{ck} \geq 35MPa$)	-	-	-
High-pressure water-blasting	≥ 3.0	0.4	0.8	1.0	0.5	0.9	0.4
Sand-blasting	≥ 0.5	0.0	0.7	0.7	0.5	1.1	0.3
Smooth	-	0.0	0.5	0.5	0.0	1.5	0.2

Table 1 Values of the design parameters for Randl (1997) Model.

III. CONCLUSIONS

An analysis of the design expressions derived from published studies shows that the behaviour of concrete to concrete surfaces subject to longitudinal tangential stresses can be predicted using the "theory of shear friction." The mechanism for transferring the load of shear forces between two concrete layers, according to the theory of shear friction, consists of: a) cohesion, due to mechanical adhesion between particles; b) friction, due to the existence of compressive stresses at the interface and to the relative the displacement between the concrete parts and c) the action of the dowel, due to the deformation of the rebars crossing the surface.

The literature review revealed several design expressions that have been proposed from 1960 to the present. Of these, five milestones in friction shear theory are highlighted. The scope of all design expressions is very large: from monolithic concrete elements to composite concrete elements with intentionally (rough surfaces) and not intentionally rough surfaces (smooth surfaces). Improvements are needed to increase the accuracy of design expressions and reduce the difference between them.

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