보통강도 및 고강도 콘크리트의 전단전달

Shear Transfer in Normal and High Strength Concrete

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ABSTRACT

Cracks in concrete can submit shear forces by virtue of the roughness of their interfaces. With regard to this roughness, the crack faces play an important role. By transmitting normal and shear stress across their faces, shear cracks contribute to shear resistance. This process is called shear transfer or more generally, shear friction.

Both experimental and analytical program to investigate shear transfer mechanism in normal and high strength concrete were included in this study. The parameters investigated in push-off test included the concrete strength, the presence and amounts of steel stirrups, and aggregate size. Solution procedure based on the truss model was developed to analyze the shear transfer behavior. In general, it can be seen that the analytical results agree well with results of shear transfer test.

1. Introduction

The shear transfer mechanism in concrete structure has been the object of experimental as well as analytical studies. In general, two distinct shear transfer behaviors can be identified according to the initial state of the plane which may be initially cracked or uncracked. The behavior in the initially cracked plane is governed largely by the shear-slip characteristics of cracked plane. For this case where shear is being transferred across a cracked plane, the behavior will be dominated by crack interlock and dowel action. Final failure occurs along the pre-existing crack, due to sliding.

In this study, push-off tests on initially uncracked specimens and analyses based on truss model are conducted to investigate shear transfer mechanism in concrete elements. For the initially uncracked plane reinforced with stirrups, the shear behavior is quite different. Shear is being transferred through a truss-like action produced by the combination of the compressive force in the concrete struts and the tensile force that the steel reinforcement crossing the shear plane develops. Experimental and analytical programs for shear transfer are undertaken to investigate the effect of the concrete compressive strength, the presence of steel stirrups as shear reinforcement, the amount of steel stirrups, and the maximum aggregate size. In the analytical program, solution procedure based on the truss model is developed

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2. Shear Transfer Analysis Model by Truss Action Theory

A concrete element is reinforced with longitudinal bars in the l-direction and with transverse bars in the t-direction. It is subjected at its edges to the in-plane normal stresses f_l and f_t, as well as the shear stresses τ_{lt}. After diagonal cracking, a series of diagonal compression struts is formed, resulting in a truss-like action. It is assumed that the element takes only compressive stress f_d in the direction of the compression struts, and tension stress f_r in the r-direction transverse to the compression struts. The shear stress τ_{dr} is assumed zero. The angle between the $l-t$ and $d-r$ coordinate systems is designated as α.

Equilibrium

The stresses f_l, , f_t and τ_{lt} in the reinforced concrete element are resisted by the concrete and steel reinforcement. The stresses contributed by concrete are designated as f_{lc}, f_{tc}, and τ_{ltc}. The concrete stresses in the two coordinate systems($l-t$ and $d-r$) are transformed according to the usual stress transformation equations using Mohr's stress circle. By super-imposing the contributions of the concrete and steel stresses, the following equilibrium equations can be obtained.

$$f_l = f_d \cos^2\alpha + f_r \sin^2\alpha + \rho_l \sigma_{ls} \quad (1)$$

$$f_t = f_d \sin^2\alpha + f_r \cos^2\alpha + \rho_t \sigma_{ts} \quad (2)$$

$$\tau_{lt} = (f_d - f_r) \sin\alpha \cos\alpha \quad (3)$$

Compatibility

Assuming that the strains are distributed uniformly in the element, they can be transformed according to the following equations expressed using the Mohr's strain circle

$$\varepsilon_l = \varepsilon_d \cos^2\alpha + \varepsilon_r \sin^2\alpha \quad (4)$$

$$\varepsilon_t = \varepsilon_d \sin^2\alpha + \varepsilon_r \cos^2\alpha \quad (5)$$

$$\gamma_{lt} = 2(\varepsilon_d - \varepsilon_r) \sin\alpha \cos\alpha \quad (6)$$

where ε_l and ε_t are normal strains in the $l-t$ coordinate system; ε_d and ε_r are normal strains in the $d-r$ coordinate system; γ_{lt} is shear strain in $l-t$ coordinate system.

Constitutive Laws of Concrete in Tension

In general, a typical tensile stress-strain curve of concrete consists of two distinct branches. Before cracking the stress-strain relationship is essentially linear. Both the steel and the concrete behave elastically and carry the tensile load in proportion to their respective stiffness. Experimental data can be represented by the following stress-strain relationships for ascending and descending branch.[Vecchio and Collins, 1982, 1993]

$$\text{for } \varepsilon_c \le \varepsilon_{cr}, \quad f_c = E_c \varepsilon_c \quad (7)$$

$$\text{for } \varepsilon_c > \varepsilon_{cr}, \quad f_c = \frac{\alpha_1 \alpha_2 f_{cr}}{1 + \sqrt{500 \varepsilon_c}} \quad (8)$$

Constitutive Laws of Concrete in Compression

From the results of various test specimens, it became evident that the response of cracked concrete in compression was substantially different from that of plain uniaxially compressed concrete. The presence of large transverse tensile strains resulted in substantial reductions in the strength and stiffness of the concrete in compression. Hence, experimental and theoretical investigations have been undertaken to address this apparent compression softening effect.

The web of reinforced concrete beams under shear is in a state of biaxial tension-compression. The presence of simultaneous transverse tensile strain leads to a deterioration of the compressive strength of cracked concrete

Vecchio and Collins[1982] used Hognestad's parabola for the uniaxial compressive stress-strain curve of concrete. Both peak stress, f_c' and its associated strain, ε_o were multiplied by the softening parameter, β as follows.

$$\beta = \frac{1}{0.85 + 0.27\varepsilon_1/\varepsilon_2} \tag{9}$$

From the results of panel test, Vecchio and Collins[1993] proposed another compressive stress-strain relationship for concrete by modify the softening parameter.

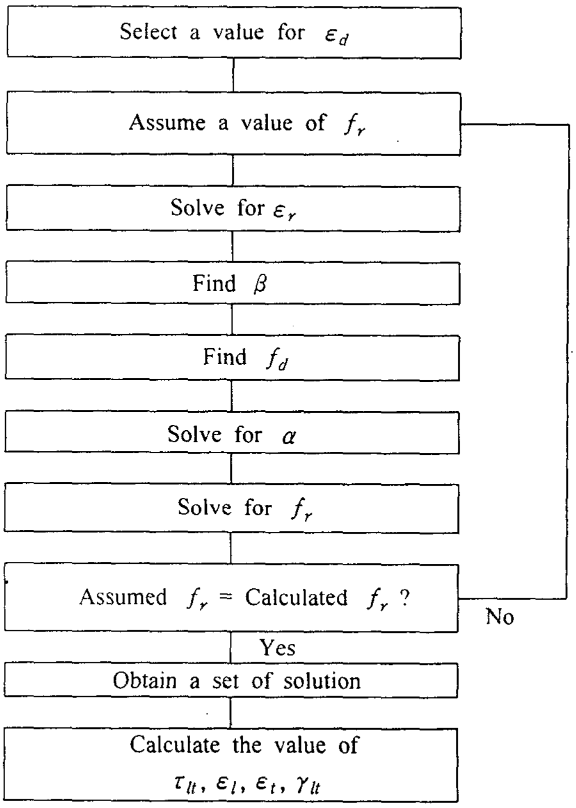


Fig. 1 Procedure to Solve Simultaneous Equations

$$\beta = \frac{1}{0.80 + 0.34\varepsilon_1/\varepsilon_o} \tag{10}$$

In this study, Eq. (9) and (10) are denominated Vecchio and Collins Model A and Model B, respectively. Belarbi and Hsu[1995] observed two softening effect and proposed the following softening parameter.

$$\beta = \frac{0.9}{\sqrt{1 + K_\sigma \varepsilon_1}} \tag{11}$$

Another softening coefficient was proposed by Prisco and Gambarova. [1995] To account for the effects of transverse reinforcement in tension, the concrete strength is reduced in one of two possible ways

$$f_c = 0.75 f_c', \text{ or}$$

$$f_c = \frac{0.90 f_c'}{\sqrt{1 + 600\varepsilon_1}} \tag{12}$$

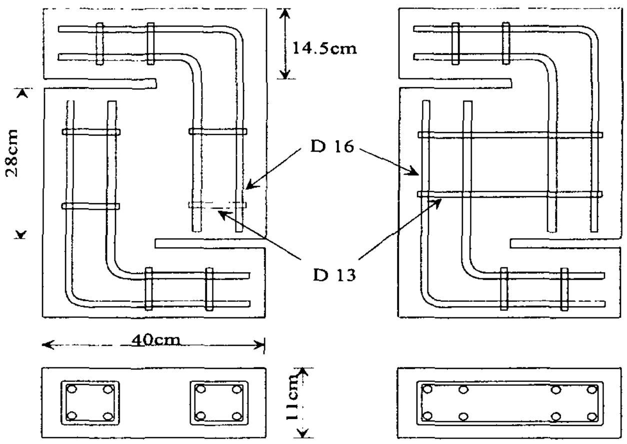
The softening models described in this section were incorporated to constitutive law of concrete in compression.

Analysis Procedure

By combining the equations given by equilibrium, compatibility, and constitutive laws, a system of the preceding equations involving unknowns can be defined. The method of solution used for this system of equations was the one proposed by Hsu et al.[1987] The iterative procedure to solve the simultaneous equations is as shown in Fig. 1.

3. Manufacturing of Push-off Specimens and Instrumentation

For the shear transfer tests, push-off specimens, shown in Fig. 2, were used. These push-off specimens had overall dimensions of $400\times600\times11$ cm. In the manufacturing of the push-off specimens, the first step was to prepare the steel bar reinforcement. The vertical L-shaped D 16 deformed bars were tied together using hoops made out of D 13 deformed bars. For the specimens without steel stirrup crossing the shear plane, the vertical reinforcements were assembled using small hoops.



(a) Without Stirrup (b) With Stirrups

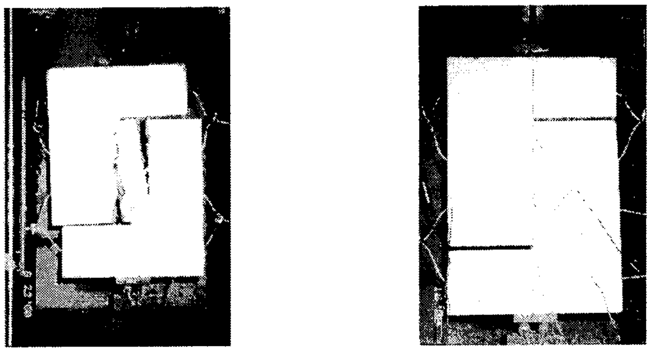
Fig. 2 Geometry of Specimens and Reinforcement Distribution

For the purpose of monitoring the strain in the steel stirrups crossing the shear plane, two strain gages were placed on the steel bars. After curing of push-off test specimens, surface strain gages and LVDTs(Linear Variable Displacement Transformers) were glued and attached right before testing. The measurements of concrete strain using DEMEC gages were also carried out. The DEMEC gages were used for measurement of the average strains on the surface of the concrete.

4. Experimental and Analytical Results

Two distinct failure modes were encountered in the push-off tests depending on the presence or absence of steel stirrups. For specimens without shear reinforcement, failure occurred abruptly along the shear plane right after formation of several inclined cracks as shown in Fig. 3. The failure mode of the push-off test specimens without steel stirrup reinforcement was very brittle, with no warning before collapse. These specimens lost their integrity, breaking into several pieces. They didn't show any softening behavior after the maximum shear stress was reached.

In the case of specimens reinforced with stirrups, crack formed inclined to the shear plane. These cracks extended to form well defined compressive struts in the concrete, which in combination with the tensile force being carried by the steel stirrups, created a truss action.



(a) Without Stirrup (b) With Stirrups

Fig. 3 Specimens after Failure

For the push-off test specimens manufactured using normal and high strength concrete with steel stirrup, that is C24A19S2, C40A19S2, and C60A19S2, the shear stress vs. shear strain curve is shown in Fig. 4. Shear stress - stirrup strain curve which is for specimens having 2 steel stirrup reinforcements crossing shear plane is shown in Fig. 5. The steel strain of push-off test specimen involving high strength concrete, that is C60A19S2, increased up to failure. After the maximum shear stress was reached in the C60A19S2 specimen, there was a sudden drop in load.

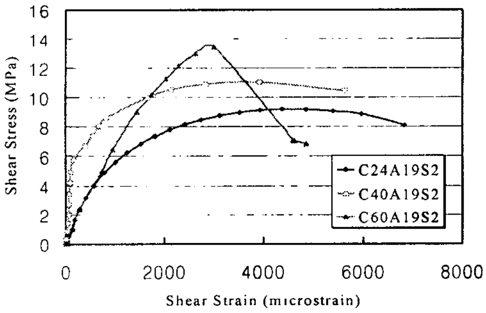


Fig. 4 Shear Stress vs. Shear Strain

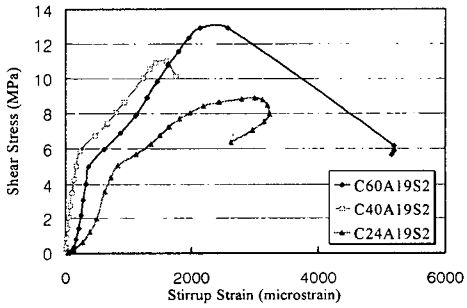
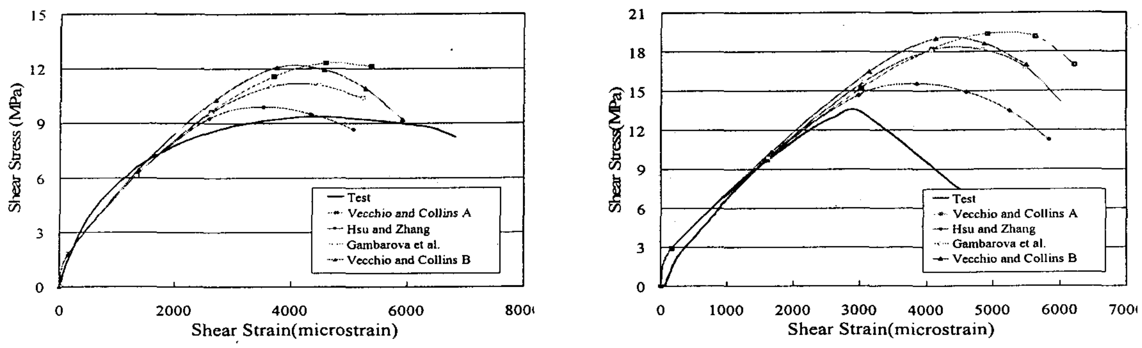


Fig. 5 Shear Stress vs. Stirrup Strain

In order to compare the test results with model prediction, the shear stress vs. shear strain curves for normal and high strength concrete push-off specimens with steel stirrups are plotted in Fig. 6. Various softening parameters were incorporated in the constitutive law of concrete in compression. For various specimens, the predicted values by analytical model in which Hsu and Zhang's softening parameter incorporated agree well with test results. The models in which other softening parameters including Vecchio et al.'s and Gambarova et al's incorporated over-estimated the maximum shear stress.



(a) Normal Strength Concrete (b) High Strength Concrete

Fig. 6 Effect of Softening Parameters on Shear Behavior

5. Conclusions

both experimental and analytical program to investigate shear transfer mechanism in concrete members were included in this study. In the experimental program, initially uncracked push-off specimens were tested for the investigation of shear transfer. The parameters investigated included the concrete strength, the presence and amounts of steel stirrups, and the aggregate size.

In the normal strength concrete specimens with steel stirrups, ultimate failure occurred when the compression struts crushed in concrete. In the high strength concrete specimens, on the other hand, ultimate failure occurred when the steel stirrups developed their yield strength. The push off specimens with smaller aggregate developed higher shear strength and showed more ductile failure modes. In the analytical program, solution procedure based on the truss model was developed. In general, it can be seen that the analytical results agree well with push-off test results.

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