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PULLOUT MODEL FOR STEEL FIBER REINFORCED CONCRETE

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1. INTRODUCTION

The failure of steel fiber reinforced concrete (SFRC) is generally attributed to the failure of the bond between fibers and matrix. Pullout test of fibers from SFRC is widely recognized as one of the basic tests to obtain information about the deformational behavior and failure mechanism of a given fiber-reinforced composite material. This study presents a pullout model for SFRC in uniaxial tension. The behavior of fiber and concrete of each unit is modeled and the material parameters are determined from experimental data. Through the simulation for test data, the appropriateness of the present model is examined.

2. MODELING OF FIBERS IN CONCRETE

Fibers inside concrete are modeled by using a shear lag model based on the stress criterion [1]. The pullout model of one fiber is shown in Fig. 1(a). A single fiber of a length of L is embedded in a matrix which is modeled as a shear lag with shear stiffness k on a rigid support. The fiber is assumed to have a constant cross-sectional area A and a constant Young's modulus E_f. The axial displacement is denoted by U and is assumed to be constant over the fiber cross section. The displacement at the fiber end U^* is

$$U^* = U(L) = \frac{P^* - q^*a}{E_f A\omega}\cosh\left[\omega(L-a)\right] + \frac{P^* - \frac{1}{2}q^*a}{E_f A}a \quad (1)$$

Then, the pullout force at the fiber end P^* can be expressed as

$$P^* = \frac{U^*E_fA\omega + q^*a\left[\cosh\left[\omega(L-a)\right] + \frac{1}{2}a\omega\right]}{\cosh\left[\omega(L-a)\right] + a\omega} \quad (2)$$

with parameter ω defined by $\omega = \sqrt{\frac{k}{E_fA}}$.

The stress criterion for debonding is based on the assumption that debonding takes place only when the maximum shear stress at the interface reaches a critical value, that is, debonding starts once the force per unit length q reaches the bond strength q_y. It is assumed that q_y is constant and the residual strength by friction q^* is expressed in terms of the bond strength q_y as follows.

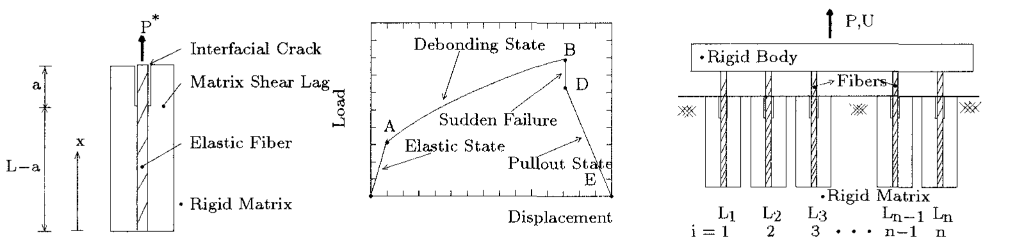
$$q^* = Dq_y \qquad (0 \le D \le 1) \quad (3)$$

From the condition for debonding, the pullout force at $x = L$ can be written as

$$P^* = q^*a + \frac{q_y}{\omega}\tanh\left[\omega(L-a)\right] \quad (4)$$

3. DISPLACEMENT INCREMENTAL TECHNIQUE

The load-displacement relationship for one fiber is shown in Fig. 1(b). From the origin O to point A, the fiber has an elastic relationship, which is referred to as *elastic state*. After reaching point A, debonding process starts and continues up to the maximum sustainable load level at point B, which is referred to as

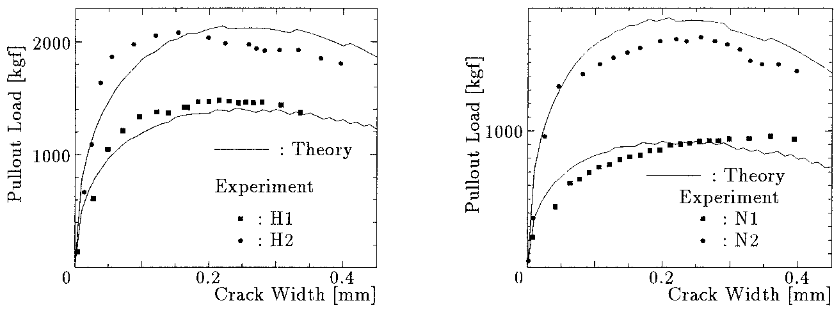


(a) Pullout Model (b) Load Versus Displacement (c) SFRC under Uniaxial Tension

Fig. 1 Fiber Model

Table 1 Optimum Values of Material Parameters

Test Data	Mortar Strength (kgf/cm^2)	Volume Fraction (%)	q_y (kgf)	k (kgf/cm^2)	n	D
H1	High	1	20	2.0x10^5	65	0.31
H2	624.1	2	20	2.0x10^5	100	0.31
N1	Normal	1	16.9	1.8x10^5	50	0.31
N2	328.4	2	16.9	1.8x10^5	100	0.31



(a) High Strength Mortar (b) Normal Strength Mortar

Fig. 2 Comparison with Experimental Result

debonding state. The debonding length a in this state can be obtained by taking the root of $\Psi(a) = 0$, where $\Psi(a)$ is obtained from Eqs. 2 and 4 by eliminating P^*. Either in a displacement-controlled test or load-controlled test, just after reaching point B, a catastrophic failure occurs and the sustainable load drops to a level at point D. After catastrophic failure, a successive pullout process continues until the fiber is totally pulled out. This state (D–E) is referred to as *pullout state.* Assuming that after catastrophic failure the remaining embedded part of fiber provides frictional resistance, the following relationship holds.

$$P^* = q^*(L - a) \quad \cdots\cdots (5)$$

4. VERIFICATION WITH EXPERIMENTAL RESULTS

A set of SFRC pullout test has been done to obtain information about load-displacement curves, as well as load-crack width curves [2]. The testing program was divided into two groups: high-strength and normal-strength mortar. Each group of experiment consists of 3 series of pullout tests, each with a different volume fraction of fiber: 0%, 1% and 2%. By comparing the sustained load between the SFRC (with volume fraction 1% and 2% of fiber) and the plain mortar(volume fraction of 0%), the load that is sustained by fibers in SFRC with percentages of fiber 1% and 2% can be obtained, respectively.

To simulate the experimental results, the following parameters are used: $E_f = 2.1\text{x}10^6\text{kgf/cm}^2$ and $A = 2.38\text{x}10^{-3}\text{cm}^2$. Fibers are assumed uniformly distributed and there are n effective fibers sustaining load across a crack surface (see Fig. 1(c)). The statistical distribution of fiber embedded length is varied from L_{min}=5mm to L_{max}=12.5mm. The optimum values of other material parameters are listed in Table 1 and the pullout load and displacement curves are shown in Fig. 2.

5. CONCLUSION

A shear lag pullout model based on the stress criterion is proposed for SFRC. By comparing with the experimental results, it is confirmed that the present model is suitable to express the pullout mechanical behavior of SFRC, giving the information of internal failure such as debonding length.

REFERENCES

1) Shah, S.P., Li, Z. and Stang, H. : *J. of Engineering Mechanics*, Vol. 116, No. 10, pp.2136–2150, 1990.
2) Shoji, H., Tsubaki, T. and Sumitro, S. : *Proc. of the JCI*, Vol 18, 1996.