Pseudo Strain Hardening Model of Ultra High Strength Concrete under Axial Tensile Loading

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ABSTRACT

According to the analysis of tension failure mechanism of UHSC specimen, one modified model based on ACK model by the introduction of partial debonding energy of non-first cracks and by the application of steel fiber number on unit area is presented in this paper. It can be used to explain the evolution mechanism of multiple cracking and pseudo strain hardening of UHSC. From the numerical results, to increase steel fiber length and to reduce steel fiber diameter in some region all can reduce the fiber volume fraction with the same multiple cracks for economic design of UHSC.

1. Introduction

Structural applications of FRC are currently under rapid development. Ultra high strength concrete (UHSC) with ductility matching that of metals will be commercially exploited in various applications. However, large amounts of steel fibers imply high cost. It is significant to carry out economic design of UHSC with relative low steel fiber volume fraction ensuring tensile strain hardening and multiple cracking. A first attempt to define the conditions leading to multiple cracking of normal fiber reinforced concrete (FRC) was suggested by Naaman in 1987[1], by setting that the maximum post-cracking stress in the composite under tension must be larger than the stress at first cracking. The condition to achieve multiple cracking of FRC was also derived using fracture mechanics concepts as developed by Li and Wu, 1992[2], etc.. Tjiptobroto and Hansen, developed a fracture mechanics based model to predict the strain at end of multiple cracking, and the critical volume fraction of fibers to guarantee the evolution of two cracks [3,4]. Assuming that the first crack will eventually be the failure crack, they assumed the energy required to form new microcracks is the summation of the matrix fracture energy, fiber strain energy, and matrix strain energy. In the assumption applied in their model derivation, no contribution from debonding energy is included in the model. However, for UHSC system with a significant increase in the composite elastic strain, the fiber-matrix interface will be subjected to a relatively high interface stress particularly for high modulus fibers. In fact, there exists initial partial debonding and post cracking partial debonding along all the cracks in UHSC except thefirst crack which will be completely debonded and be the final strain localize crack.

An analytical approach, based on the energy equilibrium associated with multiple cracking processes, was used to describe the occurrence of multiple microcracks of UHSC.

2. Modified model of strain hardening mechanism in UHSC

2.1 Energy changes analysis during multiple cracking in UHSC

Naaman and Shah [5] have proposed that an inelastic strain region exists in high-performance

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FRC. This region, denoted as Region II in Fig.2, is a result of multiple microcrackings and occurs between the end of linear elastic range and the peak load.

The differences between the proposed modified model and the model proposed by reference [3]are the introduction of partial debonding energy, the neglect of fiber strain energy and matrix strain energy at the end of Point 1 because of short fiber of UHSC,and in the evaluation of those energy terms. In the model derivation, it was assumed that at point 1 the partial debonding between fiber and matrix is present at the interface, while at point 2 it is assumed that the interfacial stress is frictional and uniform throughout the fiber embedment length. The assumption of partial debonding at first cracking is reasonable for high elastic modulus of steel fiber [6].

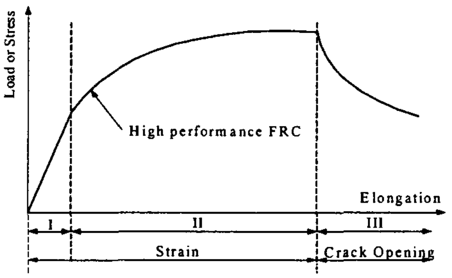

Fig. 2 Typical tensile load-elongation response for high performance FRC

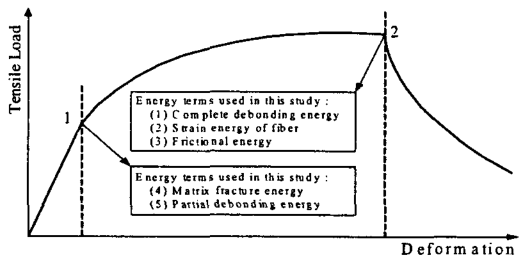

Fig. 3 Different energy terms considered in the modified model derivation

2.2 Energy terms E_{1-2} and E_{i0}

As shown in Fig.3, Point 1 corresponds to the occurrence of the first crack (microcrack). Between Point 1 and 2, this microcrack starts to open up, and at the same time other microcracks are formed in the composite. The energy required to open the first microcrack from Point 1 and Point 2, which is the end of Region II, denoted by E_{1-2}, is the sum of the complete debonding energy, fiber strain energy, and frictional energy (shown in Fig.3), and is given by Eq. (1)

$$E_{1-2} = \Delta E_{f-mc} + \Delta E_{fr} + E_{db} \tag{1}$$

In which

$$\Delta E_{f-mc} = 7L_f V_{ef} \tau_{fm}^2 L_f^2 / \left[6E_f(L_f+1)\pi D_f^4\right], \quad E_{db} = L_f G_{II} V_f / \left[(L_f+1)D_f\right],$$

$$E_{fr-total} = V_f \tau_{fm}^2 L_f^3 / \left[6(L_f+1)E_f D_f^2\right], \text{ and } E_{pdb} = L_{pdb} E_{db} / L_f$$

The partial debonding length after cracking,L_{pdb} , can be calculated using the following expression for interfacial stress developed based on the shear-lag theory [6].

The energy required to form new microcracks, denoted by $E_{20}, E_{30}, E_{40}, \cdots, E_{n0}$ is the sum of the matrix fracture energy and partial debonding energy, and is given by Eq. (2)

$$E_{20} \approx E_{30} \approx E_{n0} \approx G_m V_m + E_{pdb} \tag{2}$$

Where, G_m is the matrix fracture energy, and V_m is the matrix volume fraction.

2.3 Proposed modified mechanism

If $E_{20} < E_{1-2}$, crack II is formed with partial debonding and crack I is partially debonded too. If $E_{20} + E_{30} < E_{1-2}$, crack III is formed with partial debonding, and crack II go on with partial debonding, and crack I go on with partial debonding too. On the analogy of this, when $\left\{\sum_{i=2}^{n} E_{i0} \le E_{1-2}\right\} \cap \left\{\sum_{i=2}^{n+1} E_{i0} \ge E_{1-2}\right\} = \phi$ is satisfied, crack nth is formed with partial debonding, and crack (n-1)th go on with partial debonding, and so on, crack II go on with partial debonding, crack I is completely debonded and enters into pulling out stage, i.e. strain soft Region III. This time is corresponding to Point 2 as shown in Fig.3.

3. Numerical calculation and comparison analysis

The parameters of UHSCare fracture energy G_m 120N/m, frictional stress τ_{fm} 10MPa ,interfacial fracture energy G_{II} 120N/m, elastic modulus of matrix E_m 49100MPa, and elastic modulus of fiber E_f 200000MPa, respectively. Numerical results are shown in Fig. 5~Fig. 7. As can be seen that the opening energy of the first crack influences the evolution result of multiple cracking, i.e. E_{1-2} is one decisive part. Fig. 6 shows the distribution of the opening energy E_{1-2} of the first crack with the diameter and the length of steel fiber.

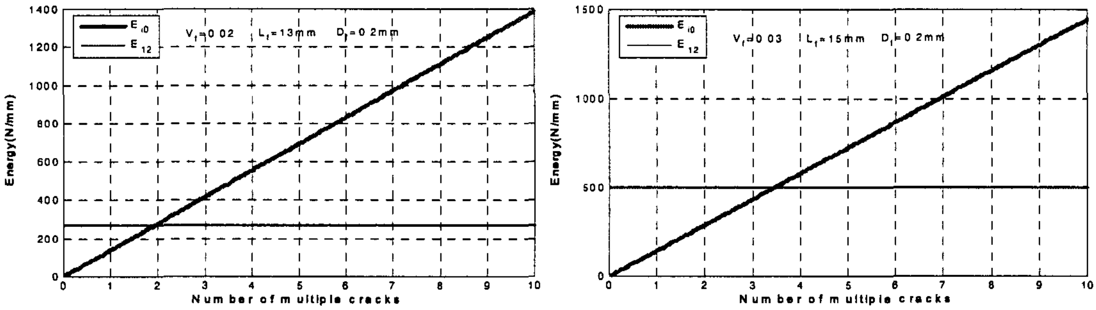

Fig.5 Variation of energy E_{1-2} and $\sum E_{i0}$ vs number of cracks

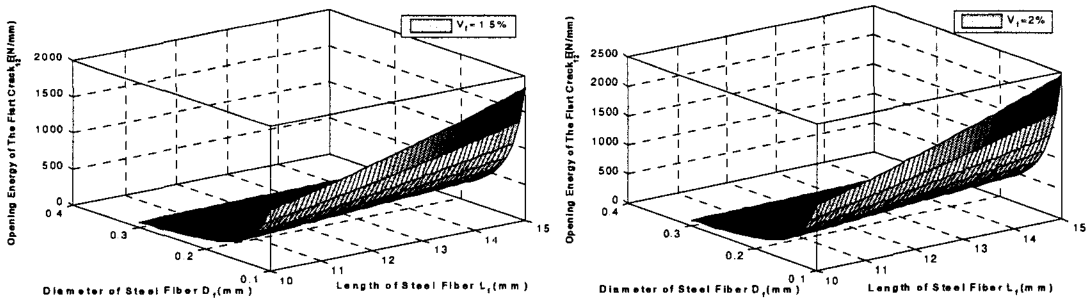

Fig. 6 Variation of opening energy E_{1-2} vs fiber diameter and length

The variation of energy with fiber volume fraction at different crack number, fiber length and fiber diameter is shown in Fig. 7.

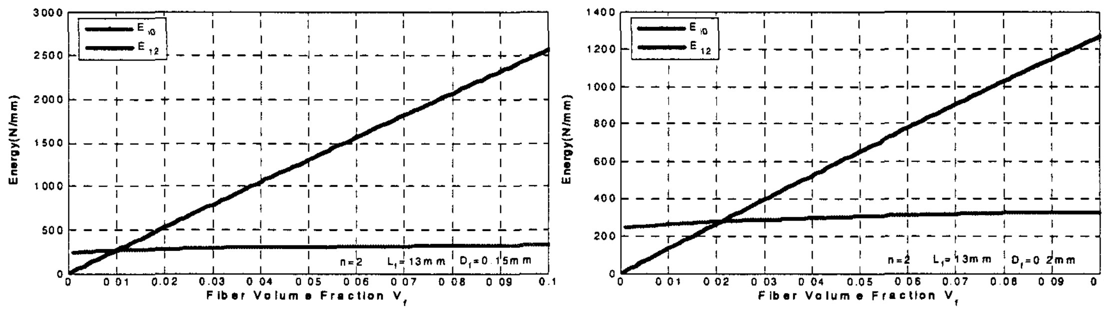

Fig. 7 Variation of energy E_{1-2} and $\sum E_{i0}$ vs fiber volume fraction

From the comparison of the parameters variation, to increase steel fiber length and to reduce steel fiber diameter all can reduce the fiber volume fraction with the same multiple cracks.If fiber length and diameter are kept in constant, only to increase fiber volume fraction can increase multiple cracking evolution.

4. Conclusions

(1) The modified model based on ACK model and reference [6] by the introduction of partial debonding energy of non-first cracks and by the application of steel fiber number on unit area from reference [7] are reasonable revision for the evolution mechanism of multiple cracking and pseudo strain hardening.

(2) From the modified model, all the important quantities like multiple cracking numbers n which representing pseudo strain hardening degree and appropriate fiber volume fraction based on certain steel fiber characteristics can be evaluated initially.

(3) To increase steel fiber length and to reduce steel fiber diameter in some region all can reduce the fiber volume fraction with the same multiple cracks for economic design of UHSC.

(4) With the constant fiber length and diameter, appropriate increasing of fiber volume fraction can increase multiple cracking evolution with considerable increasing of opening energy E_{1-2} of the first crack and the cumulative cracking energy $\sum E_{i0}$ of non-first cracks.

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6. References

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