

論文 Strain Gradient Effect on Tension Stiffening of Reinforced Concrete

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ABSTRACT: The aim of the present study is to discuss the strain gradient effect on tension stiffening of reinforced concrete members under flexure and/or axial loads. The analytical model is derived from the micro-bond characteristics. The local steel strain and stress are computed from which the average moment-curvature relationship is derived. The average crack spacing is simply computed by a stress-based cracking criterion. A comparison with experimental observations was carried out to verify the effectiveness of analysis. The analysis fairly agrees with the experimental results.

KEY WORDS: bond-slip-strain, tension stiffening, crack spacing, strain gradient, flexure.

1. INTRODUCTION

It has been widely known that crack spacing in reinforced concrete members subjected to axial tension is different from those members under bending moments (CEB-FIP [1]). Since the crack spacing is an important factor that affects the stiffening behavior of cracked concrete (Salem and Maekawa, [7], [8]), it is considered that the strain gradient across the cross section of RC members plays a significant role on the tension stiffening. In this study, this role is studied. Crack spacing is predicted by a simple stress-based criterion (Salem and Maekawa, [7], [8]). In this method, the local stress of concrete is checked and cracking is introduced whenever the local stress reaches the cracking strength of concrete.

Fig. 1 illustrates a schematic drawing to explain the role of strain gradient on members cracking. In this figure, two members are shown, one is under axial tension while the other is under pure flexure. It was assumed that the height of the tension member is half that of the flexure member. In other words, the concrete portion that resists tensile stresses, at the middle non-cracked section of the flexure member, has the same area as that of the tension member. However, since the concrete stresses at the middle section of the flexure member is linearly distributed in consistence with the linear strain distribution at that section, the maximum stress will be double that of the tension member under the same loading level. As a result, more cracks are most likely to talk place in the flexure members.

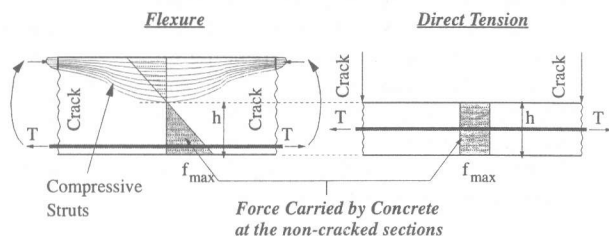


Fig. 1 Cracking Response in Axial Tension and Flexure Members

2. MODELING ASSUMPTIONS

- (1) There is no real physical slip between concrete and reinforcement at the location of reinforcement (Okamura and Maekawa, [4]). In other words, the crack width at the steel location is zero and the concrete has the same elongation of reinforcement at that location. Following this fact, the bond-slip-strain model of Shima et al [3] is used.

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- (2) Strain distribution along the non-cracked section is linear following Bernoulli's assumption. This implies that the assumption is restricted to the shallow members, as it is not realistic for deep beams or shear walls.
- (3) The bond properties between steel and concrete in flexure members are the same as tension members. Due to strain gradient, there might be some difference but not significant. However, this is out of target of the present study.
- (4) Cracking of concrete takes place whenever the local concrete stress reaches the tensile strength. In this model, the average crack spacing (Salem and Maekawa, [7], [8]) is applied.
- (5) The location of the neutral axis is linearly changing between the crack location and the middle non-cracked section (see Fig. 2). In this region concrete is still non-cracked but the tensile resistance is not fully utilized due to its dependence on the amount of stress transferred by bond with the steel bar.
- (6) For large-scale members the concept of effective RC zones developed by An et al [9] is adopted. In this case, only the RC zone is considered to resist the tensile load and is responsible for cracking if its resistance is lower than the tensile load as illustrated in Fig. 3.
- (7) For the concrete under compression, the elasto-plastic and fracture model developed by Maekawa and Okamura [2] is adopted.

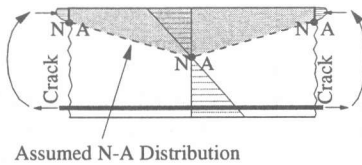


Fig. 2 Assumed Neutral Axis Distribution between Cracked and Non-cracked Sections

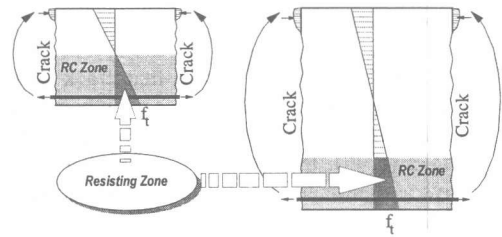


Fig. 3 Effective Reinforced Concrete Zone Concept

3. ANALYSIS

3.1 COUPLED FLEXURE AND AXIAL LOADS

In case of flexure coupled with axial loads, the neutral axis at the non-cracked section is shifted up or down depending on the types of axial load, tension and compression. The shifted distance is determined from the ratio of the axial load to the bending moment. From Fig. 4, it can be shown that the shifted distance is,

$$x = \left(\frac{N}{M} \right) \left(\frac{h^2}{12} \right) \quad (1)$$

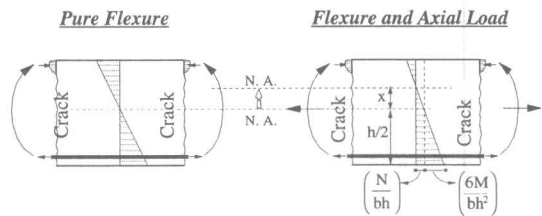


Fig. 4 Neutral Axis Shift for Coupled Axial and Flexure Loading

where, N is the axial load, M is the bending moment and h is the height of the cross section.

3.2 COMPUTATIONS SCHEME

The analytical scheme is similar to the analysis under axial tension by Salem and Maekawa [7], [8]. Analysis scheme is shown in Fig. 5. In the scheme, the local bond stresses along steel bar are computed by solving the nonlinear governing bond equations satisfying both the slip compatibility and the boundary conditions of zero slip and zero bond stresses at the midway between two adjacent cracks. The bond-slip-strain model developed by Shima et al [3] is adopted. Deterioration of bond stresses that occurs due to crushing and spalling of concrete close to crack surface are taken into account by the implementation of the bond deterioration model of Qureshi and Maekawa [6].