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Simulating Distributed Reinforcement Effects in Concrete Analysis

by

A. H. Marchertas
Reactor Analysis and Safety Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439, U.S.A.

Abstract

The effect of the bond slip is brought into the TEMP-STRESS finite element code by relaxing the equal strain condition between concrete and reinforcement. This is done for the elements adjacent to the element which is cracked. A parabolic differential strain variation is assumed along the reinforcement from the crack, which is taken to be at the centroid of the cracked element, to the point where perfect bonding exists. This strain relationship is used to increase the strain of the reinforcement in the as yet uncracked elements located adjacent to a crack. By the same token the corresponding concrete strain is decreased. This estimate is made assuming preservation of strain energy in the element.

The effectiveness of the model is shown by examples. Comparison of analytical results is made with structural test data. The influence of the bonding model on cracking is portrayed pictorially.

1. Introduction

Analytical modeling of reinforced concrete in the presence of cracking has seen rapid development since the sixties. This development was made easier to a great extent by the finite element technique as well as the ever-increasing availability of fast computers. The development in analytical methods of reinforced concrete structures has evolved along two paths -- one called the micro approach and the other the macro approach.

The intent of the micro approach is to simulate in detail the individual reinforcement and the respective transmittal of loading to the concrete. This is accomplished by means of separate elements. Cracking is usually represented in a discrete way. This type of modeling provides details on the interaction of individual reinforcing members with the immediate neighborhood of the concrete. Very respectable results for this model have been obtained and are summarized in [1]. A well planned effort of experiments and analytical modeling in the Netherlands has resulted in remarkable success simulating the cracking in plane structures [2]. It must be realized that simulating the interaction of reinforcement and concrete in detail puts excessive demands on reference input data and the number of modeling elements required. It is also clear that the micro model can be economically utilized only for the analysis of structures of limited sizes, possibly components of a structure. It is an important tool in the research of reinforced concrete structures.

A The macro model endeavors to simulate the global response of the concrete structure. To this end it includes simplifications of as many features of reinforced concrete behavior as possible for the sake of efficiency. Thus, the individual members of reinforcement are smeared out or averaged throughout respective areas of the concrete. The assumption normally made is that perfect bonding exists between reinforcement and concrete. Also, cracking is usually assumed to occur within the concrete elements. This macro approach does not predict the cracking pattern of the failed structure very well. However, a minimum amount of input data is required and the global response of the structures is predicted with remarkably good accuracy as summarized in [1].

For evaluation purposes of nuclear reactor concrete containment structures both approaches are important. To date our attention has concentrated on the global response of the containment structure. Hence, emphasis was placed on the development of the macro-type model. The formulation incorporated in the TEMP-STRESS [3] code is described in the following sections.

2. Distributed Reinforcement

The reinforcement in a quadrilateral element is assumed to be positioned at an angle ψ with respect to the x-axis of Fig. 1. The strain of the reinforcing rod is related to the cortesian strain as follows:

$$\varepsilon_\psi = \{b(\psi)\}^T \begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix}, \quad \text{and} \quad \{b(\psi)\} = \begin{bmatrix}\sin^2\psi\\ \cos^2\psi\\ \sin\psi\cos\psi\end{bmatrix}, \qquad (1)$$

where ε_ψ is the strain experienced by the reinforcing rod and ε_x, ε_y, γ_{xy} are the engineering strains in Cartesian coordinates. For the strain ε_ψ, a uniaxial stress strain analysis yields a corresponding stress σ_ψ in the reinforcing bar. By transformation, the Cartesian components of stress become

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_{xy}\end{bmatrix} = A_\psi\, \sigma_\psi\, \{b(\psi)\}\ , \qquad (2)$$

where A_ψ is the ratio of the cross-sectional area of the reinforcement to the total cross-sectional area of the element. These stress components provide the contribution of the reinforcing member to the stress field of the concrete element.

Provisions are also made to allow another reinforcing rod to be positioned at an angle ψ + 90° with respect to the x-axis. The contribution of this reinforcing rod to the stress of the element is calculated in the same way. Reinforcement in the circumferential direction is also provided for in the axisymmetric case .

3. Simulation of Bonding

In previous simulations of reinforcement within a concrete element it was assumed that concrete and reinforcement act together in responding to an applied load. In fact, the analytical model assumed that the concrete and reinforcement were subject to the same strain. While this is a good approximation for an uncracked structure, it is not the case in the presence of cracks; local strain discrepancies would be expected at the crack locations. Slippage of reinforcement with respect to concrete would violate the equal strain assumption close to the cracks and parallel to the reinforcement.

It is observed that at the crack and along its axis the reinforcement is strained to its maximum, while at some distance away from the crack, the reinforcement again acts together with the concrete and the effect of the crack is negligible. This is illustrated in Fig. 2 for a reinforced concrete test specimen where a tensile force is applied to the bar embedded in the block. The first cracks to form in the specimen are a considerable distance from the end face. According to Broms [4], primary cracks in the test specimen occur roughly at a distance of about twice the cover distance (t). Cover distance is defined as the distance from the center of the bar to the closest concrete surface. Continued loading may cause secondary cracks to form between the primary cracks.

It is proposed to apply the cracking information of the reinforced bar to the analytical model of a finite element code. The cover distance (t) must then be defined in the context of the continuum elements. For the present analytical model we express the cover distance as half of the square root of the product of the equivalent element diameter in the x-y plane and the width of the cracked element. Mathematically, this is equivalent to

$$t = \frac{1}{2}\sqrt{w\sqrt{4A/\pi}}\ , \tag{3}$$

where A is the plane area of the computational grid and w is the width of the structural member. It is further assumed that the reinforcement strain has a parabolic distribution as shown in Fig. 3. Thus, the estimate of strain in the concrete element adjacent to an existing crack may be expressed as

$$\varepsilon_c = \varepsilon_d - \Delta\varepsilon_c\ , \quad \text{and} \quad \Delta\varepsilon_c = \Delta\varepsilon_{max}\left(1 - \frac{\xi}{d}\right)^2 , \tag{4}$$

where ε_d is the strain of the adjacent element, ξ is the distance from the centroid of the cracked element, $\Delta\varepsilon_{max}$ is the maximum strain difference between concrete and reinforcement (assumed to be located at the centroid of the cracked element).

If ε_c represents the concrete strain of the element next to the cracked element, then a corresponding adjustment must also be made on the reinforcement strain. This adjustment is made on the assumption that the internal energy of the particular element is preserved. Assuming that the behavior of reinforcement is elastic (Young's modulus E_s), the strain in the reinforcement becomes

$$\varepsilon_s = \varepsilon_d + \Delta\varepsilon_c\sqrt{(E_cA_c)/E_sA_s}\ , \quad \text{and} \quad E_c = (\sigma_c^n - \sigma_c^{n-1})/(\varepsilon_d^n - \varepsilon_d^{n-1})\ , \tag{6}$$

where the superscript n refers to the time step; A_c and A_s are the percentages of cross-sectional area of concrete and steel, respectively.

It is important to note that the adjustment of strain due to the slip of concrete and reinforcement is made in the elements surrounding the existing crack. This adjustment involves one unknown, d, which must be calibrated with experimental data.

4A Illustration of Results

As an illustration of the effectiveness of the formulations described here, we refer to the classic cracking test results of beams described by Cervenka and Gerstle [5]. Shown in Fig. 4 are the dimensions, loading, and reinforcement. Because of symmetry, each half of the test specimen can be considered to be a shear wall panel subjected to a single transverse load. In this analysis, velocity strain quadilateral elements are used to model the concrete and reinforcement as a composite material. The properties used for concrete are: f'_c = 26.8 MPa, f'_t = 3.6 MPa, $E_c = 2.0 \times 10^4$ MPa; and for steel: σ_y = 353 MPa, $E_s = 1.9 \times 10^5$ MPa.

Very close correlation between experiment and analysis is obtained of the load deflection curves shown in Fig. 5. This, however, has been well predicted by previous analytical methods which use purely elastic concrete simulation with cracking [5]. What is more important here is the prediction of cracking. Figure 6 shows the cracking pattern for three levels of loading and two analytical simulations. The first simulation assumes that reinforcement and concrete are rigidly bound together, while the second shows the corresponding results with bonding slip taken into account ($d = 4$ is assumed). It is observed that the predicted crack spacing of the second analytical model corresponds to the spacing shown by the experimental data.

5. Concluding Remarks

A simple model is introduced to approximate the effects of bonding between reinforcement and concrete for a macro-type formulation. With this approach only one parameter (d) needs to be established to account for the bond slip effect. In the formulation presented here, a simple parabolic distribution, eq. (5), was assumed to represent the axial strain variation between the reinforcing rod and the surrounding concrete close to a crack. A functional relationship, which is able to include the effect of variable cover distance and other relevant parameters could be used just as well. It is also observed that experimental information for such an implementation of the bond-slip effect would be easy to obtain.

The prediction of discrete cracking by any structural code is very difficult indeed. The bond slip model of reinforcement and concrete simulates the spacing of cracks more realistically than was heretofore possible with a macro-type code. This approach should be a valuable addition to the modeling of distributed reinforcement in concrete codes.

Acknowledgements

The author extends his sincere appreciation to Dr. J. M. Kennedy for his help and support. This work is part of the Engineering Mechanics Program of the Reactor Analysis and Safety Division, Argonne National Laboratory and is supported by the U.S. Department of Energy.

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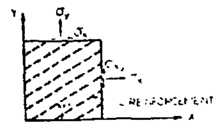


Fig. 1

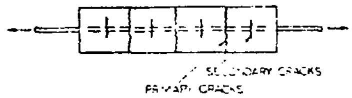


Fig. 2

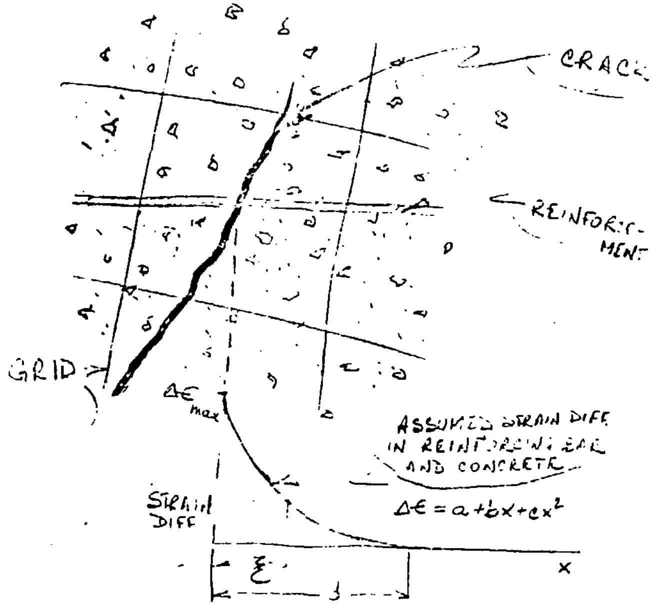


Fig. 3

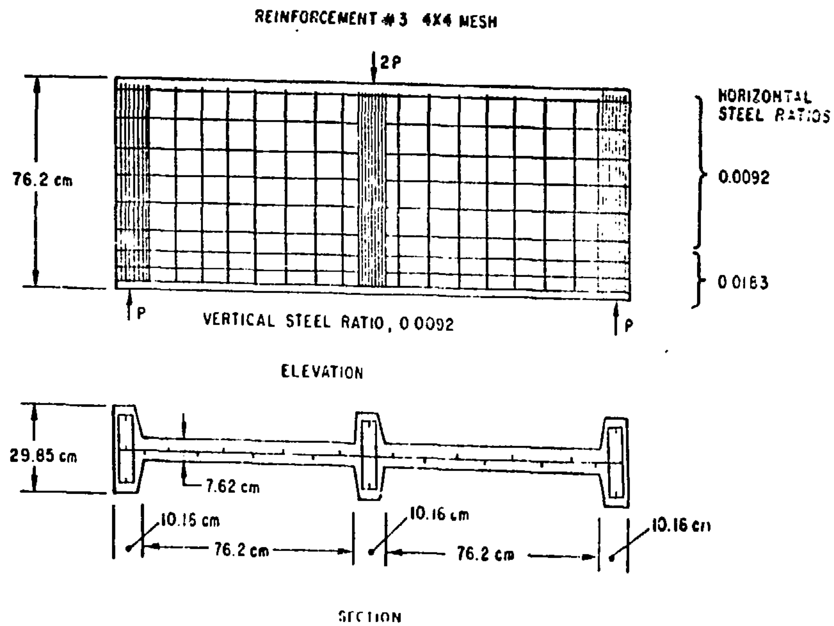


Fig. 4

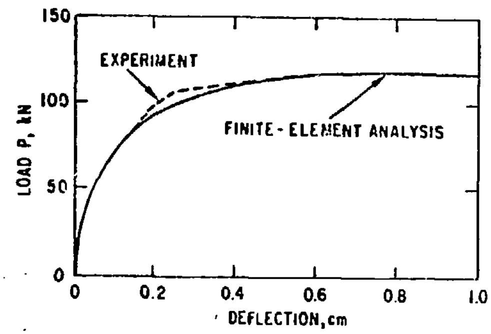
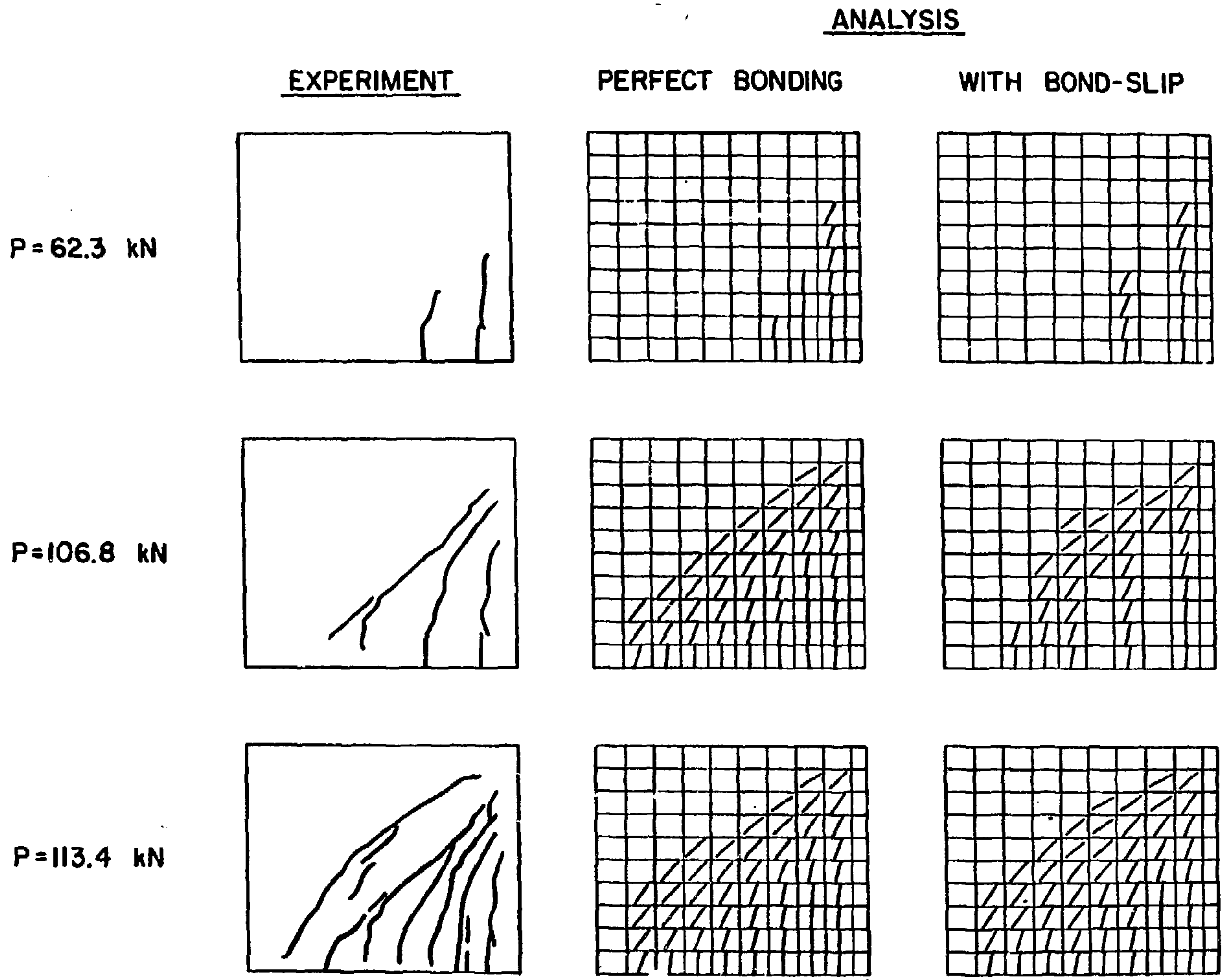


Fig. 5



ANALYSIS
EXPERIMENT
PERFECT BONDING
WITH BOND-SLIP
P = 62.3 kN
P=106.8 kN
P=113.4 kN

FIGURE CAPTIONS

1. Representation of Smeared Reinforcement
2. The Formation of Cracks in a Reinforced Concrete Specimen
3. Assumed Strain Difference Between Reinforcement and Concrete
4. Dimension, Reinforcement, and Loading of Test Panel [5]
5. Central Deflection of Test Panel
6. Cracking Simulations at Different Loads