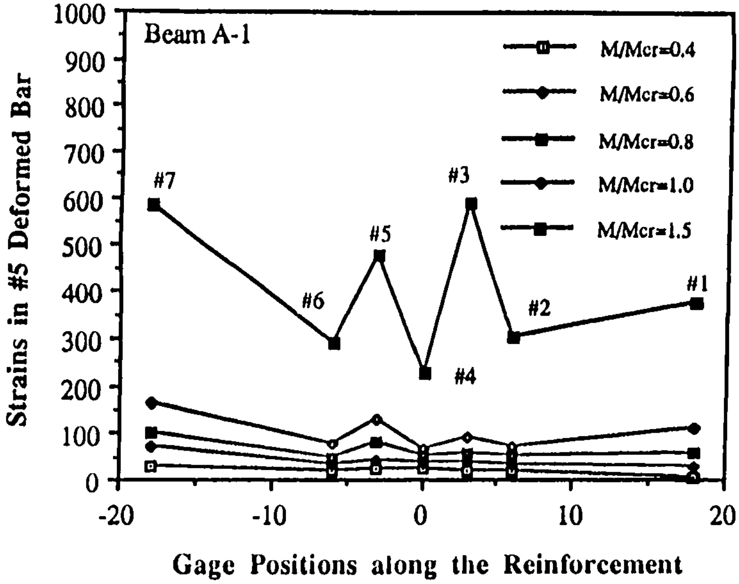

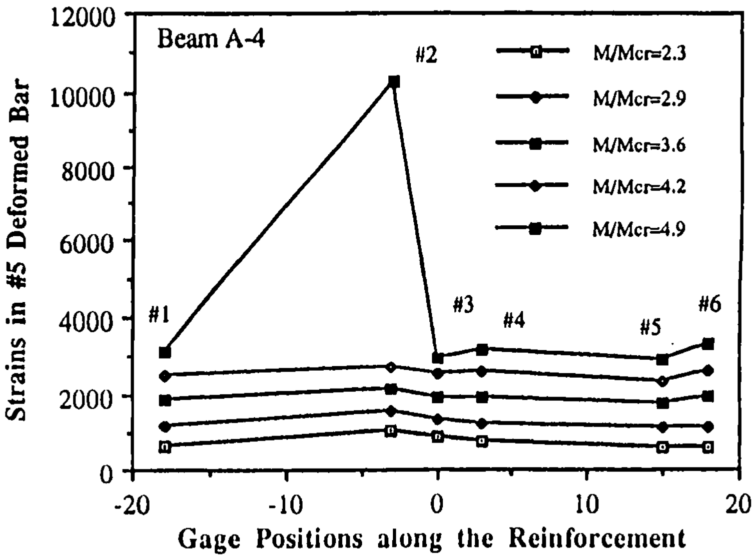

Fig. 2—Strain variations along the main tension reinforcement at load levels close to the cracking capacity of the section: a) control regularly reinforced beam A-1; b) prism reinforced beam A-4

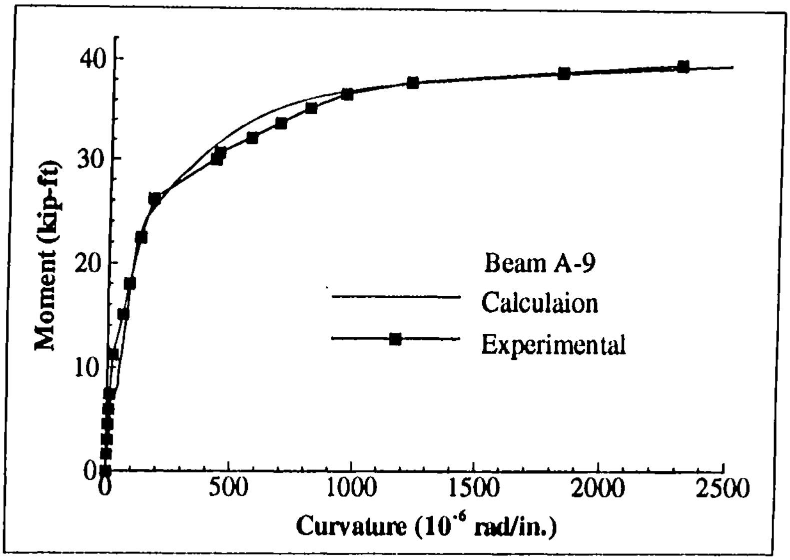

Fig. 3—Theoretical and experimental moment-curvature relationship in typical beam A-9

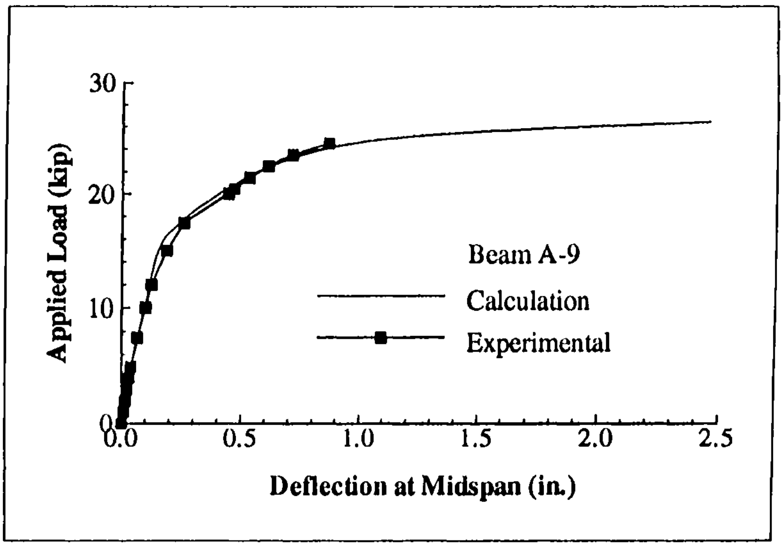

Fig. 4—Theoretical and experimental load-deflection relationship in typical beam A-9

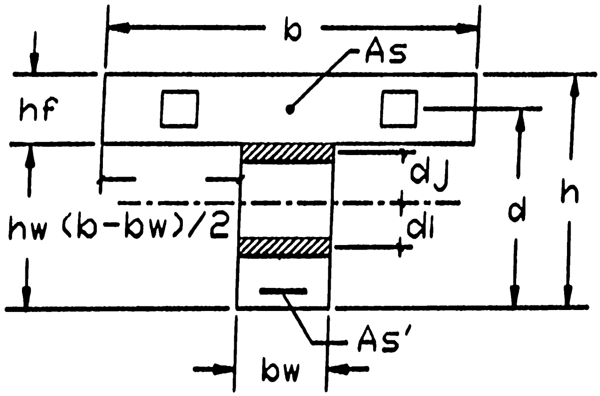

Fig. 5—Cross-section used in parametric study

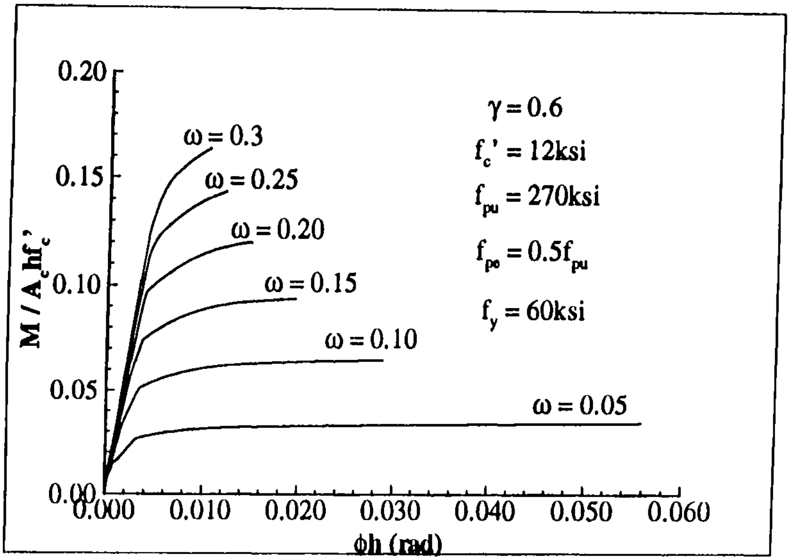

Fig. 6a—Typical effect of reinforcing index ω on M-ϕ curves

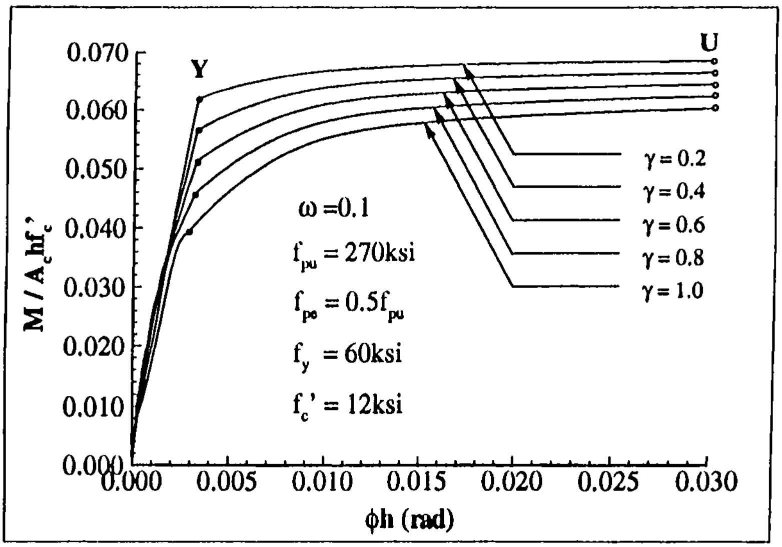

Fig. 6b—Typical effect of reinforcing index γ on M-ϕ curves

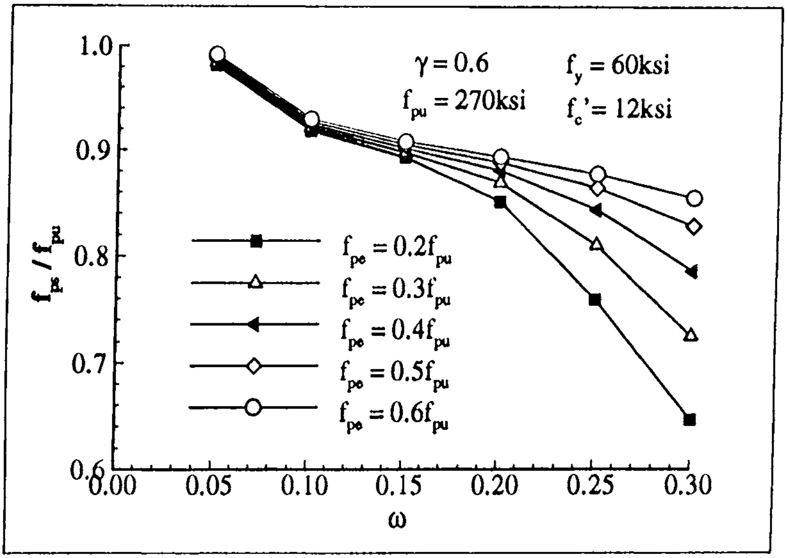

Fig. 7—Typical effect of reinforcing index on stresses in strands at ultimate

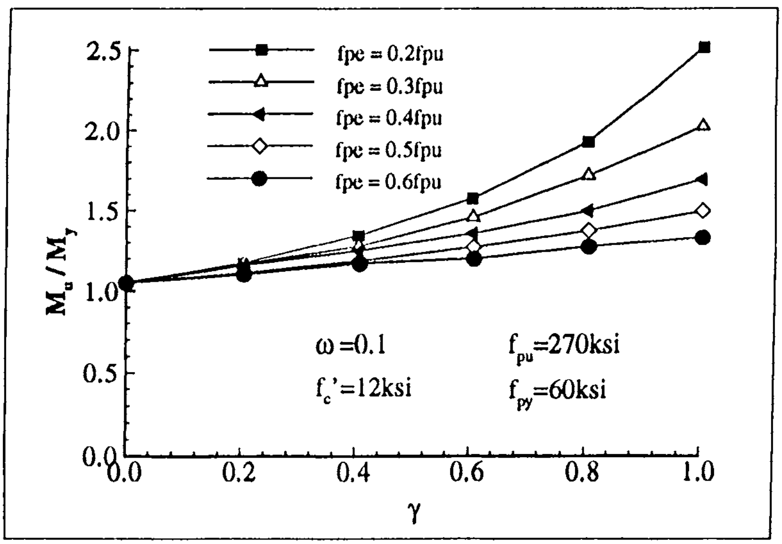

Fig. 8a—Typical effect of reinforcing index γ on sectional reserve strength: M_u/M_y versus γ

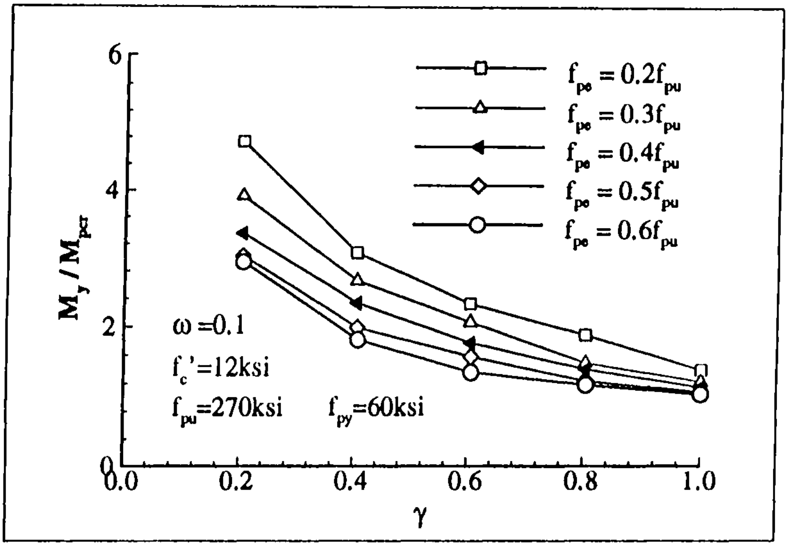

Fig. 8b—Typical effect of reinforcing index γ on sectional reserve strength: M_y/M_{pcr} versus γ

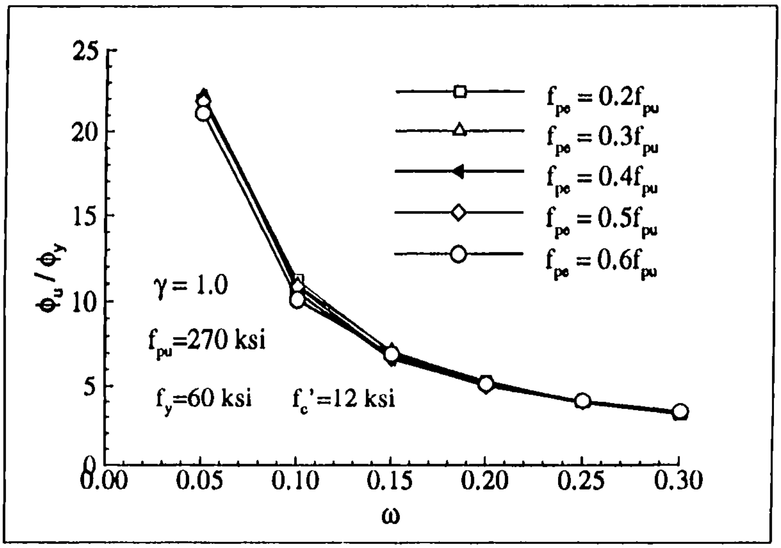

Fig. 9a—Typical effect of reinforcing index on sectional ductility with different effective prestress f_{pe}

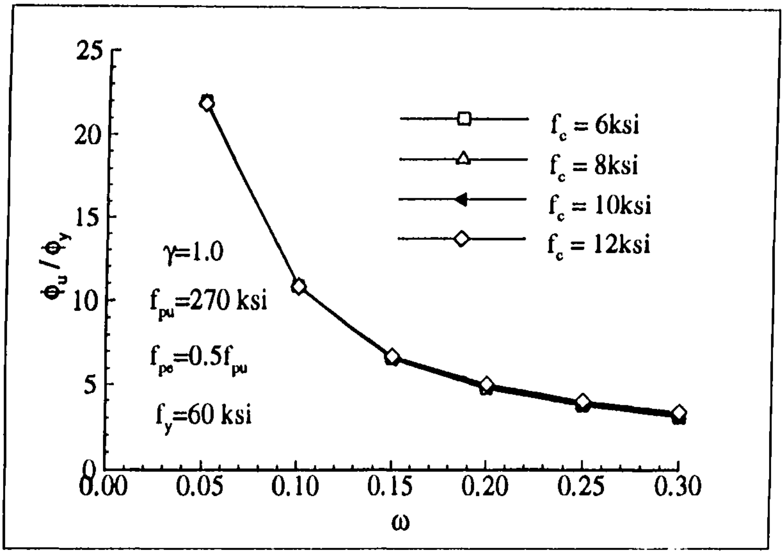

Fig. 9b—Typical effect of reinforcing index on sectional ductility with different concrete compressive strengths f_c'

Effect of Openings on Deflections and Strength of Reinforced Concrete Slabs

by M. A. Bhatti, B. Lin,
and J. P. Idelin Molinas Vega

Synopsis: The usual design practice for analysis of reinforced concrete slabs with openings is to neglect holes if their area is less than 10-12% of the total slab area. This practice is based in part on studies conducted in early sixties regarding the effects of holes on the elastic behavior of plates. A literature survey revealed no specific studies regarding the effects of holes on deflection and strength of reinforced concrete slabs with openings. This paper presents a numerical study of the effects of openings of different sizes on the behavior of reinforced concrete slabs. A nonlinear finite element model for reinforced concrete slabs is developed using three dimensional *brick* elements taking into account cracking and crushing of concrete, and plasticity of both reinforcement and concrete. Distributed and concentrated loads are applied to slabs until collapse. Results show that when slabs are subjected to uniformly distributed loads, the openings do not have much effect on their strength and serviceability. The openings should be considered, however, when designing slabs subjected to concentrated loading where the opening ratios are larger than 2.5% .

Keywords: Cracking (fracturing); deflection; finite element analysis; loads (forces); nonlinear analysis; openings; reinforced concrete; slabs; strength

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RESEARCH SIGNIFICANCE

It is usual practice in the design of concrete slabs that openings of up to 12% of the total area of the slab are considered negligible and such slabs are designed as if holes do not exist. However the basis for this *rule of thumb* is not very clear as relatively few analyses of slabs with openings have been published in literature. Several studies regarding the effect of openings on the elastic behavior of plates were conducted by means of numerical methods at the University of Illinois [1, 2]. So far, no specific analysis of the effect of openings in reinforced concrete slabs is known to the authors. This paper presents numerical analysis of the effect of openings on the behavior of reinforced concrete slabs.

FINITE ELEMENT MODEL FOR REINFORCED CONCRETE SLABS

For purposes of this analysis, a singly reinforced concrete slab is divided into three layers: concrete cover layer, steel reinforcement layer, and main concrete layer. With a given steel reinforcement ratio, ρ, an equivalent thickness for the steel layer is defined. Each layer is then represented by three-dimensional solid eight-node finite elements, as shown in Figure 1. This approach offers the greatest flexibility in defining nonlinear material properties.

The general purpose finite element program ANSYS 5.0 [3] is used to model different slabs analyzed in this paper. The element SOLID45 is employed to model steel reinforcement. Elastic-perfectly plastic stress-strain behavior is assumed for this element.

The element SOLID65 is chosen to model concrete. The concrete material properties are assumed to be isotropic and the cracking and crushing of concrete is considered. The criterion for failure of concrete due to multiaxial stress state is expressed in the form

$$\frac{F}{f_c'} - S \geq 0 \qquad (1)$$

where

F is a function of the principal stresses
S represents failure surface
f_c' is the uniaxial crushing strength of concrete.

The element employs the failure criterion of Willam and Warnke [4]. Figure 2 shows the failure surface for a stress state that is nearly biaxial. Concrete cracking occurs when the failure criterion of equation (1) is satisfied and any of the principal stresses is tensile. Concrete crushing occurs if all principal stresses are compressive.

The failure surface is defined in terms of following five parameters, two of which are specified independently.

$f_{cb} = 1.2\ f_c'$ $\quad f_1 = 1.45\ f_c'$ $\quad f_2 = 1.725\ f_c'$

f_t' and f_c' are the ultimate tensile and compressive strengths of concrete respectively

The stress-strain matrix for concrete, before cracking or crushing, is defined as follows.

$$[D_c] = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} (1-\nu) & \nu & \nu & 0 & 0 & 0 \\ \nu & (1-\nu) & \nu & 0 & 0 & 0 \\ \nu & \nu & (1-\nu) & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{(1-2\nu)}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2} \end{bmatrix} \qquad (2)$$

where E = Young's modulus and ν = Poisson's ratio for concrete.

Once cracking occurs at an integration point, the stress-strain matrix of equation (3) is used for open cracks and that given by equation (4) is used for closed cracks.