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Compressive membrane action in RC one-way slabs

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ABSTRACT

The static boundary conditions of reinforced concrete members often prevent longitudinal expansion by way of friction, restraints, etc. This restraint to the longitudinal expansion of reinforced concrete members induces membrane stresses which can cause compressive membrane action (CMA), resulting in an increase in the structural capacities. In the literature CMA is often referred to as arching action. In this paper, the results of NLFE analyses of one-way reinforced concrete slabs with respect to arching action and composite action in bending due to the membrane stress state are investigated, interpreted, and compared with the thrust line. Using equilibrium conditions, algebraic relationships for the structural behaviour can be derived and compared with the analytical results. Furthermore, the influence of CMA on various parameters, in particular steel stress σ_{sx}, mid-slab deflection w, and slenderness h/l, is illustrated.

1. Introduction

Compressive membrane action (CMA) occurs in reinforced concrete members if lateral expansion (dilatancy) is restrained; see Fig. 1. Longitudinal expansion of reinforced concrete members can be prevented either by applying external normal or constraint forces [1], or by providing specific support conditions. CMA generally leads to an increase in the structural capacity of structural members. Ritz [2] developed truss models for prestressed slab strips and square slabs in order to discuss the influence of membrane stress states on the structural behaviour of these members. Extensive literature reviews on CMA can be found in Ritz [2], Belletti et al. [3], and Einpaul et al. [1]. The influence of a tensile membrane stress state on the load–deformation behaviour of reinforced concrete structural elements was investigated experimentally by Galmarini et al. [4], Locher et al. [5], and Gouverneur et al. [6], amongst others. Theoretical considerations with respect to the tensile membrane stress state can be found in Galmarini [7], Belleti et al.[3,8], and Cantone et al. [9], amongst others.

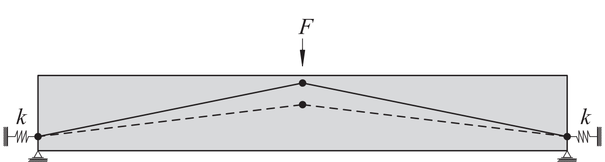

Fig. 1. Compressive membrane action (CMA) in laterally restrained slabs.

While it makes sense to neglect membrane action in the design of structural members, the structural capacities determined in the course of a structural assessment can be increased by considering this effect. Doing so can result in increased shear and punching shear capacities [1] and decreased steel stress amplitudes due to fatigue loading [10]. In this paper, the structural effect of membrane action in one-way reinforced concrete (RC) slabs is discussed. Using equilibrium conditions, algebraic relationships for arching action and composite action in bending can be derived and evaluated under consideration of the results of nonlinear finite element (FE) methods. This approach allows the correlation between the pressure line and the thrust line to be demonstrated. The nonlinear analyses were executed in ANSYS Mechanical APDL [11]. The constitutive law for reinforced concrete used in the NLFE analysis is based on the cracked membrane model [12] and was implemented as an ANSYS Usermat by Thoma et al. [13–15].

2. Compressive membrane action

The load transfer in a randomly loaded structure can be visualised as a funicular polygon [16]. In the case of compressive forces this is referred to as the thrust line; see Fig. 2(a). Decompression of the cross section or the thrust line extending beyond the cross section kern width results in internal compressive forces D_c of the pressure line. Moment equilibrium demands the corresponding tensile forces Z_s; see Fig. 2(b).

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Notation

a_{sx},a'_{sx}	reinforcement area bottom, top
b	plate width
c,c'	distance between edge of the concrete and centre of gravity of the reinforcement at the bottom, top
D_c	compressive force in the concrete
EA_c	longitudinal stiffness of the concrete cross section
E_s	Young's modulus of concrete
e	distance to centre of gravity of the reinforcement
e_c	width of the cross-section kern – corresponds to the middle third for a rectangular section
F	point load
f	spring stiffness factor
f_{ct}	tensile strength of concrete
f_{ctb}	flexural tensile strength of concrete
f_{sy}	yield strain of the reinforcement
f_{su}	ultimate strain of the reinforcement
f_{cc}	cylinder compressive strength of concrete
h	plate height
k	spring stiffness
k_{ctb}	flexural tensile strength factor
l	plate length
m_x	bending moment
n_x	normal force
n_{pl}	plastic normal force
q	line load
t	time
v_y	shear force
z	inner lever
z_x	distance to centre of gravity of compressive force
Z_s	tensile force of reinforcement
ε_c,ε_s	concrete strain, reinforcement strain
ε_{cu},ε_{su}	ultimate strain of concrete, reinforcement
ε_1	principal strain
σ_{sx}	steel stress at the crack
σ_c	concrete stress
θ_c	inclination of the compressive force D_c
θ_0,θ_1	bond shear stress factor
τ_{b0},τ_{b0}	bond shear stress
δ	slip
φ	creep factor
$\varnothing_s$,$\varnothing'_s$	reinforcement diameter bottom, top

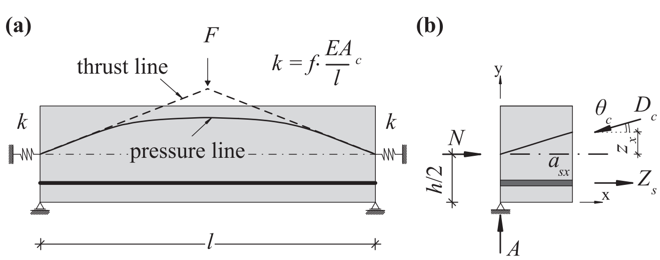

Fig. 2. (a) Thrust and pressure lines in a single-span slab strip; (b) free-body diagram.

Using the free-body diagram in Fig. 3, the two equilibrium conditions (Eqs. (1) and (2)) can be derived.

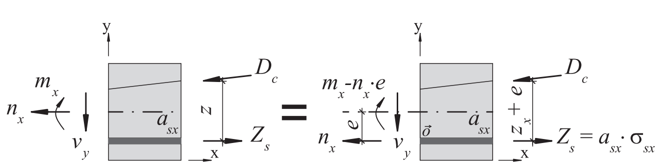

Fig. 3. Free-body diagram – internal forces.

$$\sum H = n_x \rightarrow n_x = a_{sx}\cdot\sigma_{sx} - D_c\cdot\cos(\theta_c) \tag{1}$$

$$\sum M_{\vec{o}} = m_x \rightarrow m_x - n_x\cdot e = D_c\cdot\cos(\theta_c)\cdot(z_x + e) \tag{2}$$

Using Eqs. (1) and (2) the relationship for the pressure line

$$z_x + e = \frac{m_x - n_x\cdot e}{a_{sx}\cdot\sigma_{sx} - n_x} \tag{3}$$

can be determined, where $e = const$. Setting σ_{sx} to 0 in Eq. (3) yields the analytical solution for the thrust line:

$$z_x = -\frac{m_x}{n_x} \tag{4}$$

If Eq. (1) is taken into account in solving the equilibrium condition (Eq. (2)), and $\partial/\partial x(m_x)$ is calculated, the following result is obtained:

$$v_y = \frac{\partial}{\partial x}m_x \tag{5}$$

$$= \underbrace{(z_x + e)a_{sx}\frac{\partial}{\partial x}\sigma_{sx}}_{\text{①}} + \underbrace{(a_{sx}\sigma_{sx} - n_x)\frac{\partial}{\partial x}z_x}_{\text{②}}\ldots$$
$$\ldots -\underbrace{z_x\frac{\partial}{\partial x}n_x}_{\text{③}}, \tag{6}$$

where $e = const$. The first and second terms of Eq. (6) correspond to the portions of the shear force due to bending ① and arching action ②, respectively. According to Marti [17,18], the first term in Eq. (6) can also be interpreted as the change in force in the reinforcement per unit length and hence be correlated to the required bond stresses. The third term corresponds to the portion of the shear force due to membrane action ③. Furthermore, Eq. (7) follows from Eq. (6) or from taking the partial derivative of Eq. (3).

$$\frac{\partial}{\partial x}z_x = \frac{1}{a_{sx}\cdot\sigma_{sx} - n_x}\cdot\ldots$$
$$\left(v_y - a_{sx}\cdot(z_x + e)\cdot\frac{\partial}{\partial x}\sigma_{sx} + z_x\frac{\partial}{\partial x}n_x\right) \tag{7}$$

If the internal forces m_x,n_x, and v_y and the steel stresses σ_{sx} are known (for example from a nonlinear FE analysis), the derivatives $\partial/\partial x(\sigma_{sx})$ and $\partial/\partial x(n_x)$ can be determined numerically in a first step. By taking into account Eq. (7) it becomes possible to evaluate the equation of the pressure line (Eq. (3)) and the individual terms (①- ③) of the equation for the shear force (Eq. (6)). Interpretation of the three terms of Eq. (6) then allows a detailed analysis of the flow of forces and determination of the extent to which the load is transferred via bending, arching action, or membrane action. The flow of forces changes if shear reinforcement is present and can be described with stress field models (e.g., [19]).

For the special case of a constant normal force, Eqs. (6) and (7) simplify to:

$$v_y = \underbrace{(z_x + e)a_{sx}\frac{\partial}{\partial x}\sigma_{sx}}_{\text{①}} + \underbrace{(a_{sx}\sigma_{sx} - n_x)\frac{\partial}{\partial x}z_x}_{\text{②}}, \tag{8}$$

where

$$\frac{\partial}{\partial x}z_x = \frac{1}{a_{sx}\sigma_{sx} - n_x}\left(v_y - a_{sx}(z_x + e)\frac{\partial}{\partial x}\sigma_{sx}\right). \tag{9}$$

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