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Cracking of Concrete Members in Direct Tension

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This report is concerned with cracking in reinforced concrete caused primarily by direct tension rather than bending. Causes of direct tension cracking are reviewed, and equations for predicting crack spacing and crack width are presented. As cracking progresses with increasing load, axial stiffness decreases. Methods for estimating post-cracking axial stiffness are discussed. The report concludes with a review of methods for controlling cracking caused by direct tension.

Keywords: cracking (fracturing); crack width and spacing; loads (forces); reinforced concrete; restraints; stiffness; strains; stresses, tensile stress; tension; volume change.

CONTENTS

The 1992 revisions became effective Mar. 1, 1992. The revisions consisted of removing year designations of the recommended references of standards-producing organizations so that they refer to current editions.

CHAPTER 1-INTRODUCTION

Because concrete is relatively weak and brittle in tension, cracking is expected when significant tensile stress is induced in a member. Mild reinforcement and/or prestressing steel can be used to provide the necessary tensile strength of a tension member. However, a number of factors must be considered in both design and construction to insure proper control of cracking that may occur.

A separate report by ACI Committee 224 (ACI 224R) covers control of cracking in concrete members in general, but contains only a brief reference to tension cracking. This report deals specifically with cracking in members subjected to direct tension.

Chapter 2 reviews the primary causes of direct tension cracking, applied loads, and restraint of volume change. Chapter 3 discusses crack mechanisms in tension members and presents methods for predicting crack spacing and width. The effect of cracking on axial stiffness is discussed in Chapter 4. As cracks develop, a progressive reduction in axial stiffness takes place. Methods for estimating the reduced stiffness in the post-cracking range are presented for both one-dimensional members and more complex systems. Chapter 5 reviews measures that should be taken in both design and construction to control cracking in direct tension members.

CHAPTER 2-CAUSES OF CRACKING

2.1-Introduction

Concrete members and structures that transmit loads primarily by direct tension rather than bending include bins and silos, tanks, shells, ties of arches, roof and bridge trusses, and braced frames and towers. Members such as floor and roof slabs, walls, and tunnel linings may also be subjected to direct tension as a result of the restraint of volume change. In many instances, cracking may be attributed to a combination of stresses due to applied load and restraint of volume change. In the following sections, the effects of applied loads and restraint of volume change are discussed in relation to the formation of direct tension cracks.

2.2-Applied loads

Axial forces caused by applied loads can usually be obtained by standard analysis procedures, particularly if the structure is statically determinate. If the structure is statically indeterminate, the member forces are affected by changes in stiffness due to cracking. Methods for estimating the effect of cracking on axial stiffness are presented in Chapter 4.

Cracking occurs when the concrete tensile stress in a member reaches the tensile strength. The load carried by the concrete before cracking is transferred to the reinforcement crossing the crack. For a symmetrical member, the force in the member at cracking is

$$P = (1 - \rho + n\rho) A_g f_t' \qquad (2.1)$$

in which

A_g = gross area
= steel area
f_t' = tensile strength of concrete
n = the ratio of modulus of elasticity of the steel to that of concrete
p = reinforcing ratio = A_s/A_g

After cracking, if the applied force remains unchanged, the steel stress at a crack is

$$f_s = \frac{P}{A_s} = \left(\frac{1}{\rho} - 1 + n\right) f_t \qquad (2.2)$$

For n = 10, f_t' = 500 psi (3.45 MPa). Table 2.1 gives the steel stress after cracking for a range of steel ratios ρ, assuming that the yield strength of the steel f_y has not been exceeded.

Table 2.1-Steel stress after cracking for various steel ratios

ρ	$\frac{1}{\rho} - 1 + n$	f_s,* ksi (MPa)
0.005	209	105 (724)
0.010	109	55 (379)
0.030	42	21 (145)
0.050	29	15 (103)

*Assumes $f_s < f_y$

Table 3.1-Variability of concrete tensile strength: Typical results[5]

Type of test	Mean strength, psi (MPa)	Standard deviation within batches, psi (MPa)	Coefficient of variation, percent
Splitting test	405 (2.8)	20 (0.14)	5
Direct tensile test	275 (1.9)	19 (0.13)	7
Modulus of rupture	605 (4.2)	36 (0.25)	6
Compression cube test	5980 (42)	207 (1.45)	$3\frac{1}{2}$

Table 3.2-Relation between compressive strength and tensile strengths of concrete[6]

Compressive strength of cylinders, psi (MPa)	Strength ratio		
	Modulus of rupture* to compressive strength	Direct tensile strength to compressive strength	Direct tensile strength to modulus of rupture*
1000 (6.9)	0.23	0.11	0.48
2000 (13.8)	0.19	0.10	0.53
3000 (20.7)	0.16	0.09	0.57
4000 (27.6)	0.15	0.09	0.59
5000 (34.5)	0.14	0.08	0.59
6000 (41.4)	0.13	0.08	0.60
7000 (48.2)	0.12	0.07	0.61
8000 (55.1)	0.12	0.07	0.62
9000 (62.0)	0.11	0.07	0.63

*Determined under third-point loading.

For low steel ratios, depending on the grade of steel, yielding occurs immediately after cracking if the force in the member remains the same. The force in the cracked member at steel yield is $A_s f_y$.

2.3-Restraint

When volume change due to drying shrinkage, thermal contraction, or another cause is restrained, tensile stresses develop and often lead to cracking. The restraint may be provided by stiff supports or reinforcing bars. Restraint may also be provided by other parts of the member when volume change takes place at different rates within a member. For example, tensile stresses occur when drying takes place more rapidly at the exterior than in the interior of a member. A detailed discussion of cracking related to drying shrinkage and temperature effects is given in ACI 224R for concrete structures in general.

Axial forces due to restraint may occur not only in tension members but also in flexural members such as floor and roof slabs. Unanticipated cracking due to axial restraint may lead to undesirable structural behavior such as excessive deflection of floor slabs[1] and reduction in buckling capacity of shell structures.[2] Both are direct results of the reduced flexural stiffness caused by restraint cracking. In addition, the formation of cracks due to restraint can lead to leaking and unsightly conditions when water can penetrate the cracks, as in parking structures.

Cracking due to restraint causes a reduction in axial stiffness, which in turn leads to a reduction (or relaxation) of the restraint force in the member. Therefore, the high level stresses indicated in Table 2.1 for small steel ratios may not deve

restraint. This point is demonstrated in Tam and Scanlon's numerical analysis of time-dependent restraint force due to drying shrinkage.[3]

CHAPTER 3-CRACK BEHAVIOR AND PREDICTION EQUATIONS

3.1-Introduction

This chapter reviews the basic behavior of reinforced concrete elements subjected to direct tension. Methods for determining tensile strength of plain concrete are discussed and the effect of reinforcement on development of cracks and crack geometry is examined.

3.2-Tensile strength

Methods to determine tensile strength of plain concrete can be classified into one of the following categories: 1) direct tension, 2) flexural tension, and 3) indirect tension[4]. Because of difficulties associated with applying a pure tensile force to a plain concrete specimen, there are no standard tests for direct tension. Following ASTM C 292 and C 78 the modulus of rupture, a measure of tensile strength, can be obtained by testing a plain concrete beam in flexure. An indirect measure of direct tensile strength is obtained from the splitting test (described in ASTM C 496). As indicated in Reference 4, tensile strength measured from the flexure test is usually 40 to 80 percent higher than that measured from the splitting test.

Representative values of tensile strength obtained from tests and measures of variability are shown in Tables 3.1 and 3.2.

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