

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.

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CONTENTS

Chapter 1-Introduction, pg. 224.2-2

Chapter 2-Causes of cracking, pg. 224.2-2

- 2.1-Introduction
- 2.2-Applied loads
- 2.3-Restraint

Chapter 3-Crack behavior and prediction equations, pg. 224.2-3

- 3.1-Introduction
- 3.2-Tensile strength

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.

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3.3-Development of cracks

3.4-Crack spacing

3.5-Crack width

Chapter 4-Effect of cracking on axial stiffness, pg. 224.2R-6

4.1-Axial stiffness of one-dimensional members

4.2-Finite element applications

4.3-Summary

Chapter 5-Control of cracking caused by direct tension, pg. 224.2R-9

5.1-Introduction

5.2-Control of cracking caused by applied loads

5.3-Control of cracking caused by restraint of volume change

Notation, pg. 224.23-10

Conversion factors-S1 equivalents, pg. 224.2R-11

Chapter 6-References, pg. 224.2R-11

6.1-Recommended references

6.2-Cited references

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

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

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

ρ = reinforcing ratio = A_s/A_g

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

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

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 $f_s < f_y$.

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Table 3.1-Variability of concrete tensile strength: Typical results⁵

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)	3½

Table 3.2-Relation between compressive strength and tensile strengths of concrete⁶

Compressive strength of cylinders, psi (MPa)	Strength ratio		Direct tensile strength to modulus of rupture*
	Modulus of rupture* to compressive strength	Direct tensile strength to compressive strength	
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 slabs¹ 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 develop if the cracking is due to

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 tension⁴. 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.

ACI 209R suggests the following expressions to esti-

mate tensile strength as a function of compressive strength

$$\text{modulus of rupture: } f_r = g_r [w_c (f_c')]^{1/2} \quad (3.1)$$

$$\text{direct tensile strength: } f_t' = g_t [w_c (f_c')]^{1/2} \quad (3.2)$$

where

- w_c = unit weight of concrete (lb/ft³)
- f_c' = compressive strength of concrete (psi)
- g_r = 0.60 to 1.00 (0.012 to 0.021 for w_c in kg/m³ and f_c' in MPa)
- g_t = 0.33 (0.0069)

Both the flexure and splitting tests result in a sudden failure of the test specimen, indicating the brittle nature of plain concrete in tension. However, if the deformation of the specimen is controlled in a test, a significant descending branch of the tensile stress-strain diagram can be developed beyond the strain corresponding to maximum tensile stress. Evans and Marathe⁷ illustrated this behavior on specimens loaded in direct tension in a testing machine modified to control deformation. Fig. 3.1 shows tensile stress-strain curves that include unloading beyond the maximum tensile stress. More recent work by Petersson⁸ shows that the descending branch of the curve is controlled primarily by localized deformation across individual cracks, indicating that there are large differences between the average strain (Fig. 3.1) and local strains.

3.3-Development of cracks

When a reinforced concrete member is subjected to tension, two types of cracks eventually form (Fig. 3.2). One type is the visible crack that shows at the surface of the concrete, while the other type does not progress to the concrete surface. Broms⁹ called cracks of the first type primary cracks and those of the second type secondary cracks.

Each of the two types of cracks has a different geometry. The primary or external cracks are widest at the surface of the concrete and narrowest at the surface of reinforcing bars.¹⁰⁻¹² The difference in crack width between the concrete surface and the reinforcing bar is small at low tension levels (just after crack formation), and increases as the tension level increases; therefore, the crack width at the reinforcing bar increases more slowly than the width at the concrete surface with an increase in load. The deformations on the reinforcing bars tend to control the crack width by limiting the slip between the concrete and the steel.

The secondary, or internal, cracks increase in width with distance away from the reinforcement before narrowing and closing prior to reaching the concrete surface. More detail on internal crack formation is presented in Reference 13.

Because of the variability in tensile strength along the length of a tension member, cracks do not all form at the

same stress level. Clark and Spiers¹⁴ estimated that the first major crack forms at about 90 percent of the average concrete tensile strength and the last major crack at about 110 percent of the average tensile strength. Soma-yaji and Shah¹⁵ used a bilinear stress-strain diagram for concrete in tension to model the formation of cracks along the member at increasing load levels. They assumed that the tensile strength beyond first cracking was a function of the strain gradient in the concrete along the length of the bar.

Induced tensile stresses caused by restrained concrete shrinkage affect the amount of cracking that is visible at a given tensile force. This has been made apparent by tensile tests conducted to compare the performance of Type I cement and Type K shrinkage-compensating cement in concrete specimens.¹⁶ Specimens placed under the same conditions of environment and loading had markedly different cracking behavior.

When specimens made with Type I cement had fully developed external cracks, the specimens made with Type K cement exhibited fewer and narrower external cracks. The Type K specimens exhibited first cracking at a higher load than the Type I specimens, and in some tests no visible cracking was evident in Type K specimens.

The compressive stress induced in the concrete by the restrained expansion of the Type K cement was apparently responsible for increasing the loads both at first cracking and at which cracking was fully developed. Thus, efforts to compensate for concrete shrinkage also appear to help reduce cracking.

3.4-Crack spacing

As a result of the formation of cracks in a tension member, a new stress pattern develops between the cracks. The formation of additional primary cracks continues as the stress increases until the crack spacing is approximately twice the cover thickness as measured to the center of the reinforcing bar."

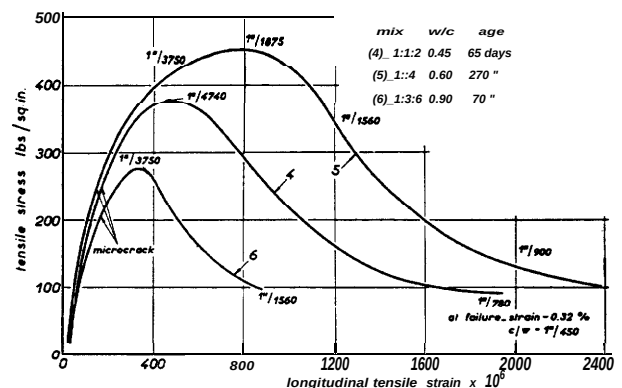


Fig. 3.1-Tensile stress-strain diagrams for concrete⁷ (includes unloading portion)