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Cracking caused by early-age deformation of concrete – prediction and control

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Abstract

This paper deals with the control of cracking caused by restraint to early-age cooling and shrinkage of concrete. Such cracking is inevitable in many situations and a significant amount of reinforcement crossing each crack is required for crack control. Rational procedures are proposed for determining the degree of restraint in a variety of practical reinforced concrete members and the amount of reinforcement required for the control of early-age cracking. Procedures for calculating the width and spacing of cracks are also outlined.

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Keywords: Concrete; crack control; cracking; early-age deformation; heat of hydration; restraint; serviceability; shrinkage.

1. Introduction

In many situations, cracking in reinforced concrete structures is inevitable. Cracks occur wherever and whenever the tensile stress in the concrete reaches the tensile strength of the concrete. After the concrete sets and hardens, tensile stress at any location may be caused by many different factors, including early-age heat of hydration, applied loads, restrained shrinkage, temperature changes, settlement of supports and so on. Cracks caused by restraint to load-independent deformation, including deformations due early-age cooling, shrinkage or ambient temperature changes, are termed *intrinsic cracks*. After cracking, further shrinkage induced deformation causes significant increases in crack widths with time.

Many variables influence the width and spacing of intrinsic cracks, including the quantity, orientation and distribution of the reinforcement crossing the crack, the cover to the reinforcement, the bond characteristics of the reinforcement, the deformational properties of the concrete (including its creep and shrinkage characteristics), the environment and the size of the member. Considerable variations exist in the crack width from crack to crack and in the spacing between adjacent cracks, because of random variations in the properties of the in-situ concrete.

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Control of cracking in concrete structures is often achieved by limiting the stress in the bonded reinforcement at the cracked section to some appropriately low value and ensuring that the bonded reinforcement is suitably distributed within the tensile zone. Building codes usually specify the maximum bar spacing for bonded reinforcement and the maximum concrete cover. Deterministic procedures for calculating crack widths are often specified, with the intention to control cracking by limiting the calculated crack width to some appropriately low value. However, the influence of shrinkage on crack widths is often not adequately considered and, as a consequence, excessively wide cracks in reinforced concrete structures are a relatively common problem.

This paper deals with the control of intrinsic cracking caused by restraint to early-age cooling and shrinkage of concrete. Rational procedures are proposed for determining the effect of restraint and the development of tensile stresses in the concrete. Guidance is also provided for estimating the maximum width and spacing of cracks.

2. Early-age thermal and shrinkage induced stresses and strains

The heat of hydration in a concrete element in the first day or so after casting rises to a peak value and then dissipates. As the concrete element cools, restraint to the early-age contraction may cause cracking in the immature concrete. In many situations, early-age thermal cracking cannot be avoided, but it can be controlled by avoiding excessive heat of hydration, reducing restraint where possible and using an adequate quantity and distribution of reinforcement crossing the cracks.

Calculation of the tensile stresses that initiate cracking is complicated by the changing elastic modulus of the young concrete and the relaxation of stress resulting from tensile creep of the concrete. The free temperature strain due to a change in temperature is $\varepsilon_T = \alpha_c \Delta T$, where α_c is the coefficient of thermal expansion for concrete and ΔT is the temperature change (negative for a drop in temperature). While the concrete is cooling, autogenous shrinkage (and perhaps drying shrinkage) is also taking place, so that the stress-independent strain is the sum of the temperature and shrinkage induced strains $\varepsilon_{T+cs} = \alpha_c \Delta T + \varepsilon_{cs}$. The actual strain ε_{actual} measured at a point in the member is significantly different from ε_{T+cs} and the difference $\varepsilon_{.r} = (\varepsilon_{actual} - \varepsilon_{T+cs})$ is the stress-related strain resulting from restraint and consists of elastic and creep strains. This tensile restrained strain is often expressed as:

$$\varepsilon_r = -(\alpha_c \Delta T_{max} + \varepsilon_{cs}) R \tag{1}$$

where R is a restraint factor that depends on the thickness of the concrete element, the shape of the temperature differential across the member and the restraint provided by embedded reinforcement and by adjacent members and supports (i.e. the external boundary conditions). Determination of the restraint factor R is discussed subsequently. Bamforth [1] suggested that for the assessment of early-age cracking, the autogenous shrinkage at age 3 days should be considered.

Provided cracking has not occurred, the restrained strain in Eq. 1 can be expressed in terms of the tensile stress (σ_r) at the time under consideration. That is:

$$\varepsilon_r = \varepsilon_{elastic} + \varepsilon_{creep} = (\sigma_r / E_c) + \chi \varphi (\sigma_r / E_c) \tag{2}$$

where φ is the tensile creep coefficient associated with the heat of hydration time period and χ is an aging coefficient to account for the fact that σ_r is gradually applied to the concrete. Before cracking, the stress caused by restraint σ_r may therefore be determined by rearranging Eq. 2:

$$\sigma_r = \varepsilon_r E_{aaef} \tag{3}$$

where E_{aaef} is the age-adjusted effective modulus of the concrete given by:

$$E_{aaef} = E_c / (1 + \chi \varphi) \tag{4}$$

If cracking occurs, part of the average restrained strain (measured over a gauge length greater than the crack spacing) is