CRACKING OF PRESTRESSED CONCRETE CONTAINMENTS
DUE TO INTERNAL PRESSURE

by

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SUMMARY

Twelve wall segments having prestressing tendons and surface reinforcement similar to that in prestressed concrete secondary containment structures were loaded in uniaxial or biaxial tension to 95% of the ultimate strength of the prestressing tendons. Crack spacings and widths were measured at various load intervals. The ratio of tensile forces applied in each direction was varied to simulate the stress conditions occurring at different locations of the dome and wall portions of the structure.

It was observed that some cracks penetrated completely through the wall segments while other cracks penetrated only to the depth of the surface reinforcement. The crack spacing was found to be dependent on the spacing of the transverse reinforcement and prestressing tendons. Certain cracks, generally located at tendons opened to become through-the-wall cracks. These cracks frequently split to form two surface cracks. By the time that strains corresponding to the yielding of the surface reinforcement were reached, all cracks observed in the tests had formed. At greater strains certain existing cracks became wider. Rules for determining the spacing and widths of both through-the-wall and surface cracks are given based on the steel spacing and section thickness. Concrete cover was not found to have a significant influence on crack spacing.

The procedures developed to determine crack spacing and widths were applied to a 1/14 scale test structure. Observed values agreed well with predicted values.
The reactors in a Canadian nuclear power plant of the Gentilly-2 type are enclosed in a circular prestressed concrete structure. In the event of certain malfunctions in which pressurized gases or steam are discharged, this concrete enclosure acts as a containment structure to prevent these products from escaping into the atmosphere. When the internal pressures exceed the sum of the prestress and the tensile strength of the concrete cracking will occur. The development of cracking (1,2), crack widths and leakage through cracks (3) were studied in this project. Both analytical and experimental studies were carried out. The experiments involved 1/4 scale models of segments representing pieces cut from the walls of a containment vessel (wall segment tests) reported in this paper and Ref. 4 and 5, and a test of a 1/14 size model of a containment building reported in Ref. 6 and 7.

Wall Segment Tests

To determine the response of prestressed concrete sections to tensile forces a total of twelve 1/4 scale wall segments designed and loaded to represent various locations in a containment structure were constructed and tested to failure. A typical segment was 31.5 in. square by 10.5 in. thick, reinforced in two directions and prestressed in one or two directions as shown in Fig. 1. Sections through a segment are shown in Fig. 1 of Ref. 3. Major variables were the ratio of prestressing in the two directions, variations in concrete cover and bar spacing, combined axial tension and moment, scale effects, and lap splices of reinforcement.

Loads were applied to the segments by pulling on the reinforcement and prestressing strands using specially designed loading yokes to ensure uniform strain over the section as shown in Ref. 5. "Circumferential" loads were applied using a 1,400,000 lb. capacity KTS testing machine and "meridional" loads were applied by four 200 kip capacity hydraulic rams reacting against a load frame.

Approximately 160 measurements were recorded at each load level and included such items as vertical load, horizontal load, forces transferred to tendons, forces transferred to reinforcement, reinforcement strains, concrete strains, elongation of specimen, crack widths, and slip of tendons. Loading was applied in increments and terminated at approximately 95% of the rupture strength of the tendons to avoid damage to loading apparatus and instrumentation.

Determination of Crack Spacing

A survey of existing procedures for predicting crack spacing and widths was made and reported in Ref. 8. The application of these techniques did not predict the crack spacing or width observed in the wall segments. This was not entirely unexpected since none of the previous investigators had considered biaxially loaded prestressed sections of such large thickness compared to the reinforcement and cover. This necessitated the development of a means of predicting the spacing and size of cracks from computed mean strains that was applicable to containment type structures.

It was observed in the segment tests that, when a load was applied, the specimens initially cracked at one location. With further loading, more cracks occurred reducing the crack spacing. These cracks were observed to coincide with reinforcing bar locations. After the formation of a sufficient number of cracks, further loading produced no new cracks but certain cracks opened to accommodate the increasing strains.
The average crack spacing in three segments is plotted as a function of average strain in Fig. 2. It is concluded that no new cracks form after a strain of 0.002 (the yield strain of the reinforcing bars) and that the crack spacing is essentially independent of the concrete cover.

A reinforcing bar has a modulus of elasticity 7 to 10 times that of the surrounding concrete. When a bar is embedded perpendicular to the direction of applied stress in a softer medium, as shown in Fig. 3, the tensile stresses at A and B increase and those at C and D decrease slightly. If, however, the bond is broken at A and B, the stresses at C and D increase significantly, approaching those found adjacent to a circular hole. This stress concentration will reduce the average tensile stress required to crack the concrete. As a result, if a crack is expected in a given region, it will likely occur at a transverse reinforcing bar. This is particularly true if the transverse bar spacing is similar to the expected crack spacing.

For reinforced concrete members subject to tension, the expected crack spacing is given by Beeby (8) as:

\[ s = 1.33c + 0.008d_b A/A_b \]  

where:
- \( c \) = concrete cover
- \( d_b \) = diameter of reinforcing bar
- \( A_b \) = area of reinforcing bar
- \( A \) = area of concrete concentric to the bar
- \( (2c + d_b) \cdot (\text{bar spacing}) \)

If the spacing of the reinforcing bars is between a half and one times the minimum expected crack spacing, the stress concentrations at the bars should be enough to cause cracking at each bar location. For bar spacings between one and two times the minimum expected spacings, the formation of cracks along the bars should make additional cracks between bars unlikely. Thus, surface cracks should be expected to follow transverse bars if these bars are spaced between half and two times the expected crack spacing. Such cracking was typical of that observed in the segments as shown in Fig. 4.

To determine how the cracks propagated through the wall a number of specimens were sawn in two. The cracks in Segment 1 in Fig. 5 are representative of the meridional cracks expected in the prototype. From an examination of all the segments it was concluded that roughly one-half of the cracks extended through the segments and in most cases these cracks divided near the surface to form two surface cracks. In all wall segments which had prestressing tendons parallel to the cracks, the through-the-wall cracks occurred at the prestressing tendons. In these cases, surface cracks which did not penetrate through the wall developed at strains greater than about 80% in the yield strain of the reinforcing bars.

From further observations of the segments, it was concluded that the effects on cracking of the transverse state of stress in segments loaded in biaxial tension were small and could be ignored in crack width calculations with relatively little error; the presence of bar splices did not significantly affect crack widths for average strains up to 0.002, although at high strains the existing cracks at the ends of the splice tended to open more; and, while the presence of a bending moment had a predictable effect on surface strains and hence
cracking, the presence of a moment about one axis had little effect on the widths of cracks perpendicular to that axis.

As a result of these observations, a series of rules were developed for use in computing the mean spacing of cracks in the wall segment specimens. It is expected that the same rules would apply to the prototype structure.

1. If the spacing of transverse bars is between 0.5 and 2 times the crack spacing computed from Eq. 1, cracks will form along each of the transverse bars by the end of the test. The cracking will be limited to these cracks.

2. The spacing of cracks at the surface of the specimen is independent of the radial distance from the longitudinal bars (bars perpendicular to the cracks) to the point on the surface where the cracks were observed.

3. In walls containing prestressing tendons parallel to the direction of cracking, through-the-wall cracks will occur at the same spacing as the tendons. Should the tendon spacing exceed twice the wall thickness an additional through-the-wall crack will occur midway between the tendons.

4. In the walls without prestressing tendons parallel to the direction of cracking, through-the-wall cracks will occur at every second reinforcing bar and not further apart than the wall thickness.

5. The number of through-the-wall cracks will stabilize by the time the strain reaches 0.002. At any given strain less than 0.002 the number of through-the-wall cracks can be given as:

\[ N = \frac{N_{twc} \left( E_{s2} - E_{s2,cr} \right)}{0.002 - E_{s2,cr}} \] (2)

where \( N \) is the number of through-the-wall cracks at the load in question; \( N_{twc} \) is the final number of through-the-wall cracks according to assumptions 3 or 4; \( E_{s2} \) is the strain in the reinforcing bars at the crack (see Eq. 6); \( E_{s2,cr} \) is the average strain at the onset of cracking (see Eq. 10).

6. At a spacing of 0.002, surface cracks form so that the final spacing agrees with rules 1 and 2.

Computed Mean Crack Width

When computing crack widths it is necessary to distinguish between through-the-wall cracks which result in paths of leakage and surface cracks which do not. In leakage calculations it is sufficient to consider only through-the-wall cracks while for comparison to cracking tests the widths of both types must be included. Although the crack widths follow a statistical distribution only computations for the representative or mean width are considered here since in a structure as large as a containment vessel the leakage can be expressed as a function of the average crack width.

The procedure outlined below may be used to determine crack widths and spacings for prestressed wall sections containing two layers of reinforcement near each face in percentages and spacings normally associated with the Gentilly-2 type of secondary containments. The procedure is based partly on a modification of a theory proposed by Leonhardt (5) and partly on the observations listed in the previous section.
The width of through-the-wall cracks is computed first since surface cracks that do not penetrate through the wall are assumed to occur to relieve tension built up in the concrete between the through-the-wall cracks and will generally not form until the reinforcing bars have yielded at the through-the-wall cracks. The expected spacings of these cracks were presented earlier.

The width of a through-the-wall crack computed at the tendon is given by Eq. 3. This width is assumed to be divided evenly between two cracks extending to the surface.

\[ w_{twc} = \varepsilon_{s2} t_o + \varepsilon_m t \]  

where:

- \( \varepsilon_{s2} \) = steel strain at the crack, Eq. 6
- \( t_o \) = unbonded length at a crack, Eq. 11
- \( \varepsilon_m \) = average strain measured over a length that includes several cracks, Eq. 8, or the mean strain from the analysis described in Ref. 1 or 5.
- \( t \) = bond transfer length, Eq. 4.

The bond transfer length, \( t_t \), was taken as:

\[ t_t = s - t_o \]  

At any load level subsequent to critical cracking but prior to yielding the reinforcing bars the steel stress and strain is given by:

\[ f_{s2} = \frac{P - F_{se}}{A_s + A_p} \]  

\[ \varepsilon_{s2} = \frac{f_{s2}}{E_s} \]  

where

- \( F_{se} \) = effective prestress force after losses
- \( A_s \) = area of reinforcing bars
- \( A_p \) = area of prestressing tendons
- \( E_s \) = modulus of elasticity of steel.

When the force \( P \) exceeds that required to yield the reinforcing bars the value of \( f_{s2} \) should be taken as \( f_{p2} \) where:

\[ f_{p2} = \frac{P - A_s f_{p2}}{A_p} \]  

and the value of \( \varepsilon_{s2} \) can then be obtained from the stress-strain curve for the tendon.

The mean strain \( \varepsilon_m \) is computed as:

\[ \varepsilon_m = \varepsilon_{s2} \left[ 1 - \left( \frac{f_{s2,cr}}{f_{s2}} \right)^2 \right] \]  

These terms can be evaluated as follows. The average stress and strain in the reinforce ment at the beginning or onset of cracking are defined as:

\[ f_{s2,cr} = \frac{P_{cr} - F_{se}}{A_s + A_p} \]
and

\[ \varepsilon_{s2,cr} = \frac{f_{s2,cr}}{f_s} \]  

(10)

where

\[ f_{s2,cr} = \text{the tensile force required to crack the section} \]

The length of "almost lost" bond, \( L_0 \), is obtained from the expression:

\[ L_0 = \frac{f_{s2,cr}}{6500} d_b \]  

(11)

where \( L_0 \) is in inches and 6500 has units of psi. For a tendon, \( d_b \) taken as the diameter of an equivalent bar having the same cross-sectional area as the wires in the tendon.

Widths of surface cracks are computed in a similar manner from the expression:

\[ \omega_s = \varepsilon_{s2} \frac{t_{os}}{f'_t} \]  

(12)

where \( \varepsilon_{s2} \) and \( \omega_s \) are the same as for through-the-wall crack computations.

The effective unbonded length at a surface crack, \( L_{os} \), may be computed from:

\[ L_{os} = \frac{f_{s,cr} d_b}{8500} \]  

(13)

where:

\[ f_{s,cr} = f'_t \frac{A_t}{A_b} \text{(psi)} \]

\[ f'_t \text{ = tensile strength of concrete} \]

The bond transfer length at surface cracks, \( L_{ts} \), is taken as:

\[ L_{ts} = (\text{bar spacing}) - L_{os} \]  

(14)

Comparison of Computed and Measured Crack Widths

While the widths of individual cracks and crack width distributions were determined for both the wall segments and the test structure (2,6), only the mean crack or representative crack width is required to predict overall behavior and leakage. An evaluation of the accuracy procedures presented in this paper for determining the spacing and magnitude of the mean crack can be made by comparing the sum of the computed crack widths in a given gage length, \( L \), which contains several cracks, with the sum of the measured crack widths in the same length.

Prior to yielding of the reinforcement the computed elongation is assumed equal to:

\[ E_w = N_{twc} \cdot W_{twc} \]  

(15)

where \( N_{twc} \) and \( W_{twc} \) are the number and mean width of the through-the-wall cracks in the assumed gage length. After yielding of the reinforcement the total elongation is:

\[ E_w = N_{twc} \cdot W_{twc} + N_{s} \cdot W_{s} \]  

(16)

where \( N_s \) and \( W_s \) are the number and mean widths of the surface cracks.

Comparisons with measured data were on the basis of the dimensionless ratio, \( E_w/L \). In the range of loading from a strain of 0.0005 to 0.002, this is, for the period that cracks are growing and extending, for segment specimens without splices or moments (segments 1 to 6 and 8), the mean ratio of measured to computed \( E_w/L \) was 1.07 with a coefficient of variation...
of 0.347. This coefficient of variation compares well to values obtained by Beeby (8) and others. 

Measured and computed values of $L_w/L$ for the test structure computed by the technique described above are shown as a function of internal pressure shown in Fig. 6. The agreement between measured and computed values is sufficiently good that the procedures developed for predicting crack spacing and width have adequate accuracy for use in predicting overall response.

Application of Cracking Analysis

The rules presented earlier for determining crack widths and spacing can be used to estimate cracking of a prototype containment. Using the strains computed at a given load using an analysis similar to the one described in Ref. 1, the surface is divided into zones of equal surface strain. The rules given earlier are used to determine the number, extent and width of the cracks in each zone. The resulting family of crack dimensions can then be used in conjunction with the technique described in Ref. 3 to estimate leakage.

References


Fig. 1 - Side View of Wall Segment Specimen
Fig. 2 - Effect of Cover, Bar Spacing and Strain on Crack Spacing
Fig. 3 - Bar Embedded in Concrete
Fig. 5 - Cracks inside Segment 1 at End of Test