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OBSERVED CRACKS IN WALLS OF MIDLAND PLANT STRUCTURES

By

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INTRODUCTION

A series of previous reports have presented an evaluation of the structural significance of cracks observed in the Feedwater Isolation Valve Pits, Auxiliary Building Control Tower and Electrical Penetration Areas, Diesel Generator Building, and Service Water Pump Structure at Midland Nuclear Power Plant Units 1 and 2.(1-5)** Observed cracks in the structures were described and significance of the cracks relative to future load carrying capacity was discussed. A site plan for the Midland Plant which indicates buildings evaluated is shown in Fig. 1.

Cracks observed in the Feedwater Isolation Valve Pits, and the Auxiliary Building Control Tower and Electrical Penetration Areas were attributed primarily to restrained volume changes that occurred during curing and drying of concrete. Cracks observed in the Diesel Generator Building were attributed to restrained volume changes and to reported differential settlement between duct banks under the building and the north and south portions of the building. Cracks observed in the Service Water Pump Structure were attributed primarily to restrained

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**Numbers in parentheses refer to references listed at the end of this report.

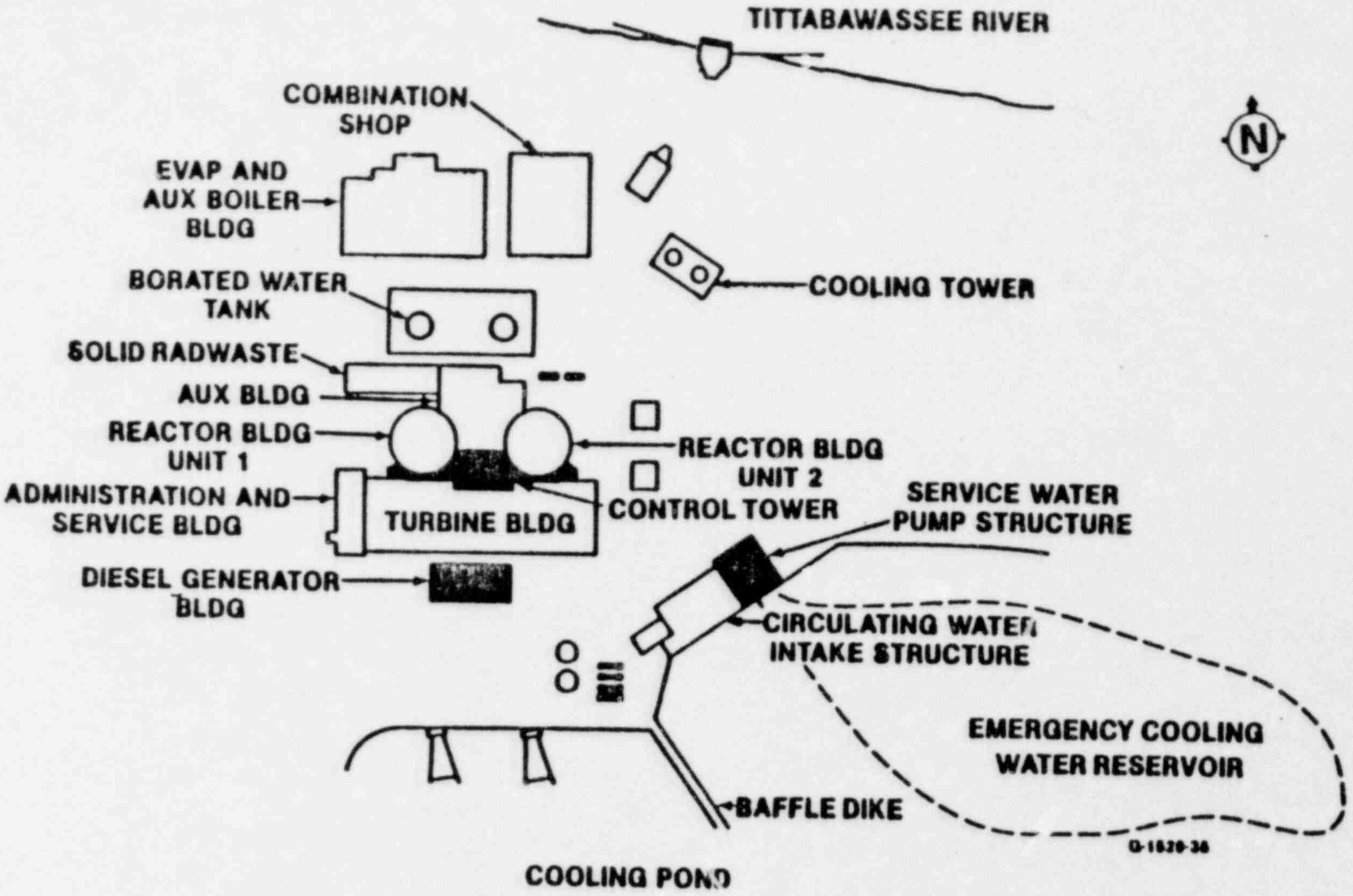


FIG. 1 SITE PLAN

volume changes, although occurrence of settlement related cracking could not be entirely dismissed.

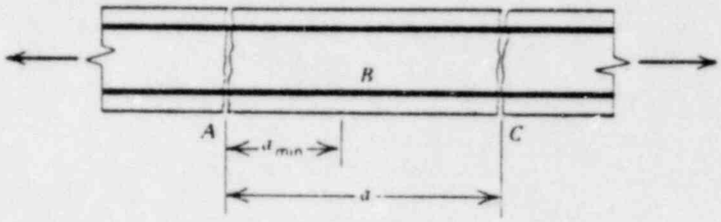
Nuclear Regulatory Commission staff members reviewed the reports listed as References 1 through 5. After review, staff members requested more detailed information on the relationship between observed cracks and potential residual stresses in reinforcement. In addition, information on significance of spacing and width of multiple cracks was requested. This report was prepared in response to the staff request.

PREFACE

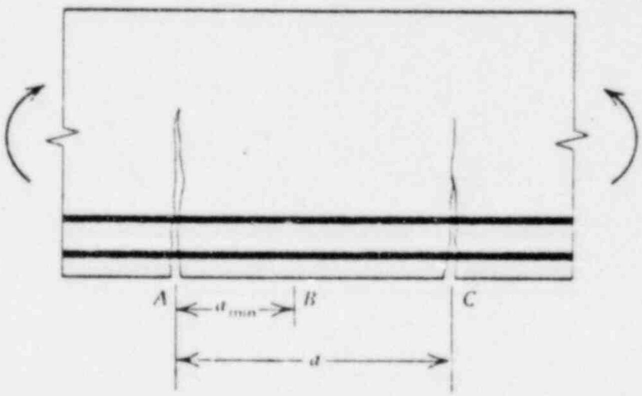
As a preface in this report to material presented on crack widths and steel stresses, it is emphasized that only rough estimates of residual steel stresses can be obtained from measured crack widths and spacings. Relationships used to estimate crack widths as a function of steel stress, reinforcing bar size, and concrete cover are generally used for evaluation of serviceability requirements. They are not normally used to determine residual stresses.[3] Because of inherent variability in crack widths and crack spacings in concrete members, and because of the significance of time-dependent effects, any estimate of residual steel stress made from observed crack widths and spacings must be considered as an indication of order of magnitude rather than a quantitative value.

DEVELOPMENT OF CRACKS IN REINFORCED CONCRETE

Figure 2, adapted from Ref. 6, illustrates the development of cracks in reinforced concrete tensile and flexural members. As described in Ref. 6, initial cracks in rein-



(a) Axial Tension



(b) Bending

Fig. 2 Cracking in Reinforced Concrete Members[6] forced concrete members will form at an irregular spacing when tensile strength of concrete is exceeded at "weak sections" which are randomly distributed. As loads are increased, additional cracks will form. However, there is a certain minimum crack spacing, a_{min}. This minimum is reached because, at some point, a tensile force of sufficient magnitude to cause additional cracks between two existing cracks can no longer be transmitted by bond between reinforcing bars and concrete.(6)

Consider the case illustrated in Figure 2 where two cracks form initially at Sections A and C.(6) The crack spacing "a" is slightly greater than twice the minimum spacing. For this case it is possible for a new crack to form at Section B. However, if the two initial cracks had formed at a spacing smaller than twice the minimum spacing, a new crack would not be expected to form. Thus, crack spacing can be expected to vary from a_{min} to $2a_{min}$.(6) The average spacing would be approximately $1.5a_{min}$. Therefore, crack spacings that range from 0.67 to 1.33 of the average spacing are theoretically possible. In fact, variability in manufacture, curing, and loading of structures will increase this scatter even further. Spacings from 50% over to 50% under the average spacing are entirely normal.(6) Thus, it can be seen that crack formation is inherently subject to large scatter.

Figure 3 illustrates stress conditions in a uniaxially loaded tensile member after formation of cracks.(7) These idealized stress distributions are based on the classical mechanism assumed for cracking in reinforced concrete members.

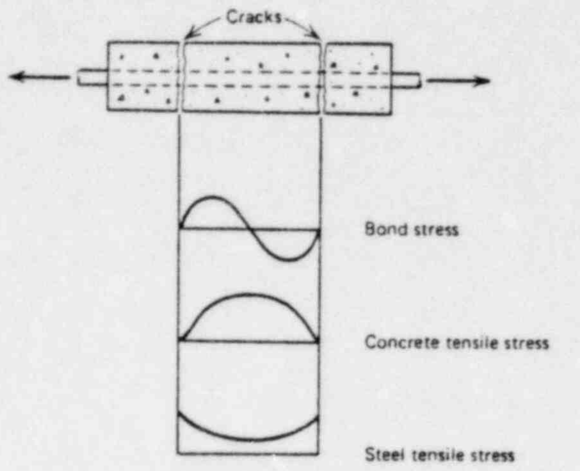


Fig. 3 Cracking Mechanism Under Uniaxial Tension(7)

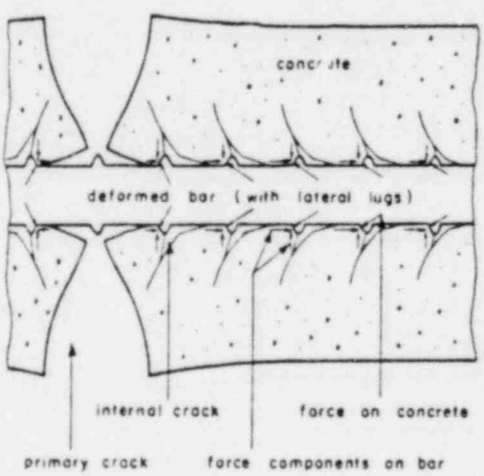


Fig. 4 Idealization of Crack Formation Illustrating Difference in Crack Width at the Surface and at the Bar Face(8)

Tensile stresses in the concrete are assumed to be uniformily distributed over the cross-sectional area of the member.

The classical model assumes that initial cracks form at random sections where tensile strength of concrete is exceeded. At crack locations, slip occurs between concrete and the reinforcing bar. Thus, at the location of cracks, forces are carried by reinforcement alone. Concrete tensile stresses are present between the initial cracks because of bond between concrete and reinforcing steel. Magnitude and distribution of stresses in the reinforcing steel between cracks are a function of the assumed distribution of bond stresses. As noted previously, new cracks will form under increasing load as concrete tensile strength is exceeded. Cracks will continue to form until spacing between cracks is so small that bond stresses developed do not exceed tensile strength of the concrete.

The mechanism illustrated in Figure 3 is the same as discussed in Reference 3. Reference 3 also includes a derivation of the following equation for estimating crack spacing:

$$l_c = (d_b/\rho)(f_t/2u) \qquad (1)$$

where:

l_c = crack spacing

d_b = bar diameter

ρ = reinforcement ratio

f_t = tensile strength of concrete

u = bond stress (assumed uniform)

Derivation of Eq. 1 involves the assumption that tensile stress in the concrete is uniform over the cross-sectional area perpendicular to the applied load. Tests have shown that this assumption is questionable.[6] Basically, Eq. 1 illustrates that crack spacing is a function of concrete tensile strength, bond stress between reinforcement and concrete, bar diameter, and reinforcement ratio for the section considered.

Once an estimate of crack spacing has been made, classical theory suggests that crack widths can be estimated by assuming that the average steel strain is uniformly distributed along a crack spacing l_c. This results in the following expression.

$$w = (f_s/E_s)\, l_c \qquad (2)$$

where:

w = crack width

f_s = stress in reinforcement

E_s = modulus of elasticity of reinforcement

Equation 2 is based on the assumption that elongation of concrete between cracks can be neglected. Thus, crack width is attributed solely to elongation of steel between cracks.

Because crack widths are a function of crack spacing, which has been shown to be inherently variable, it is not surprising that data on crack widths are subject to large scatter.[6] This is verified by experimental data.[6,8,9,10]

Implicit in the classical theory of cracking in reinforced concrete is the assumption that a crack width at the surface of the concrete is the same as the width at the location of the steel. Figure 4 is an idealized sketch of the detailed mechanism of crack formation which illustrates that crack width at the surface of concrete can be considerably larger than that near the steel-concrete interface.[8] Tests have shown that surface crack widths may be as much as three times greater than cracks at the steel-concrete interface, and that the difference in crack widths is a function of the magnitude of stress in the reinforcement.[8]

Equations 1 and 2 are derived for "instantaneous" loading conditions. Long-term effects, such as shrinkage and creep, are not considered. Tests have shown, however, that crack widths are significantly affected by long-term sustained loading.[11,12] Although spacing of cracks has been found to remain essentially unchanged, crack widths have been found to double after two years of sustained loading.[11] Therefore, long-term effects must be considered in evaluating crack widths in existing buildings.

The purpose of the previous discussion of crack development has been to illustrate several important factors regarding use of crack widths and crack spacings for assessment of the condition of reinforced concrete members. These factors include:

1. The mechanism of crack formation in reinforced concrete members is such that significant scatter in crack widths and crack spacings inherently exists.[6]
2. Crack widths measured at the surface of a concrete member are not necessarily equal to those at the location of the reinforcement. Thus, estimates of residual steel stresses from surface crack measurements must be interpreted with care.

3. Long-term effects should be considered when evaluating significance of crack widths.

4. Crack spacing and crack width are inherently related. Thus, evaluation of residual steel stresses must be based on consideration of crack spacing as well as crack width. Implicit in such an evaluation is that existence of multiple cracks must be considered.

5. Expressions for prediction of reinforcement stresses from crack width and crack spacing can be expected to provide only very approximate results.

With the above mentioned caveats regarding estimation of residual steel stresses from crack width and crack spacing, it should be understood that observed cracks do provide important data for evaluation of the condition of existing structures. Overall crack patterns provide a guide to the load carrying mechanism of the structure. Crack patterns and crack widths also pinpoint areas of structural distress.

The following sections of this report will address several questions:

1. How do observed cracks in the Midland Plant structures compare with what would be expected based on engineering estimates of crack width and spacing?

2. During underpinning of buildings at the Midland Plant, cracks will be monitored as part of the program for monitoring structural integrity during implementation of remedial measures. In conjunction with this monitoring program, it is necessary to define a level of

cracking that would be indicative of impending structural yielding. What acceptance criteria should be used for observed cracks?

3. What methodology will be used to evaluate structural integrity if observed cracks in any area exceed the acceptance criteria?

Prior to discussion of specific cracks observed in the Midland Plant structures, the following section will illustrate the relationship between measured crack widths and steel stresses as determined from a laboratory test program.

RELATIONSHIP BETWEEN CRACK WIDTHS AND STEEL STRESSES

As part of the monitoring program during underpinning of the Midland Plant structures, selected areas will be inspected to provide a record of crack width and crack spacing. The objective of the program is to use observed crack width and crack spacing as a measure of condition of the structures while construction operations progress. The obvious question with regard to such monitoring is what acceptance criteria should be used for evaluation of observed cracks. The implicit assumption is that magnitude and distribution of cracks are indicative of stress conditions in the structure. Thus, to determine acceptance criteria, it is necessary to estimate the magnitude and distribution of cracks that would imply impending structural distress.

Because of inherent variability in measured crack width and spacing, it is necessary to select acceptance criteria that will provide a reasonably conservative bound with regard to structural safety. To provide an estimate of variability, it is instructive to first try out the proposed approach on a "well def' ed" set of data.

Figure 5 shows a laboratory test specimen that was used to evaluate cracking as part of a research project on "Shear Transfer in Large Scale Reinforced Concrete Containment Elements."(13) The test specimen consisted of a 24 x 12 x 60-in. test block in which No. 18 or No. 14 reinforcing bars were cast. Tests were conducted by applying uniaxial tensile force to ends of the two reinforcing bars embedded in each specimen. Measurements were made to determine applied force, steel strains, crack widths, and crack spacings at various load levels.

Figure 6 shows the relationship between applied steel stress and maximum measured crack width for the four specimens tested. Specimens U1 and U4 contained No. 14 bars, and Specimens U2 and U3 contained No. 18 bars. Concrete strength for all specimens was approximately 4,000 psi. Two or three transverse cracks developed in each specimen. As can be seen in Fig. 6, maximum transverse crack widths were approximately 0.035 in. at a steel stress of 35 ksi and 0.050 in. at a steel stress of 55 ksi for both No. 14 bar and No. 18 bar specimens.

Observed crack spacing varied considerably ranging from 10 to 22 in. Calculated crack spacing for these specimens is approximately 12 in.

Table 1 provides a comparison of applied and estimated reinforcement stresses for the test specimens. For each specimen,

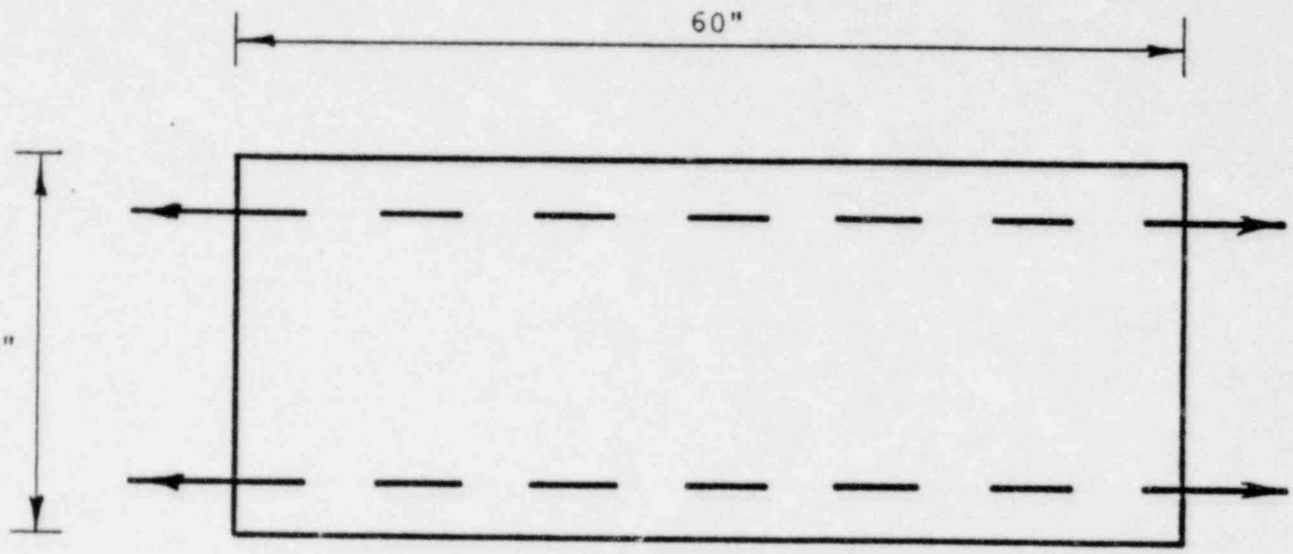


Fig. 5 Laboratory Tensile Test Specimen[13]

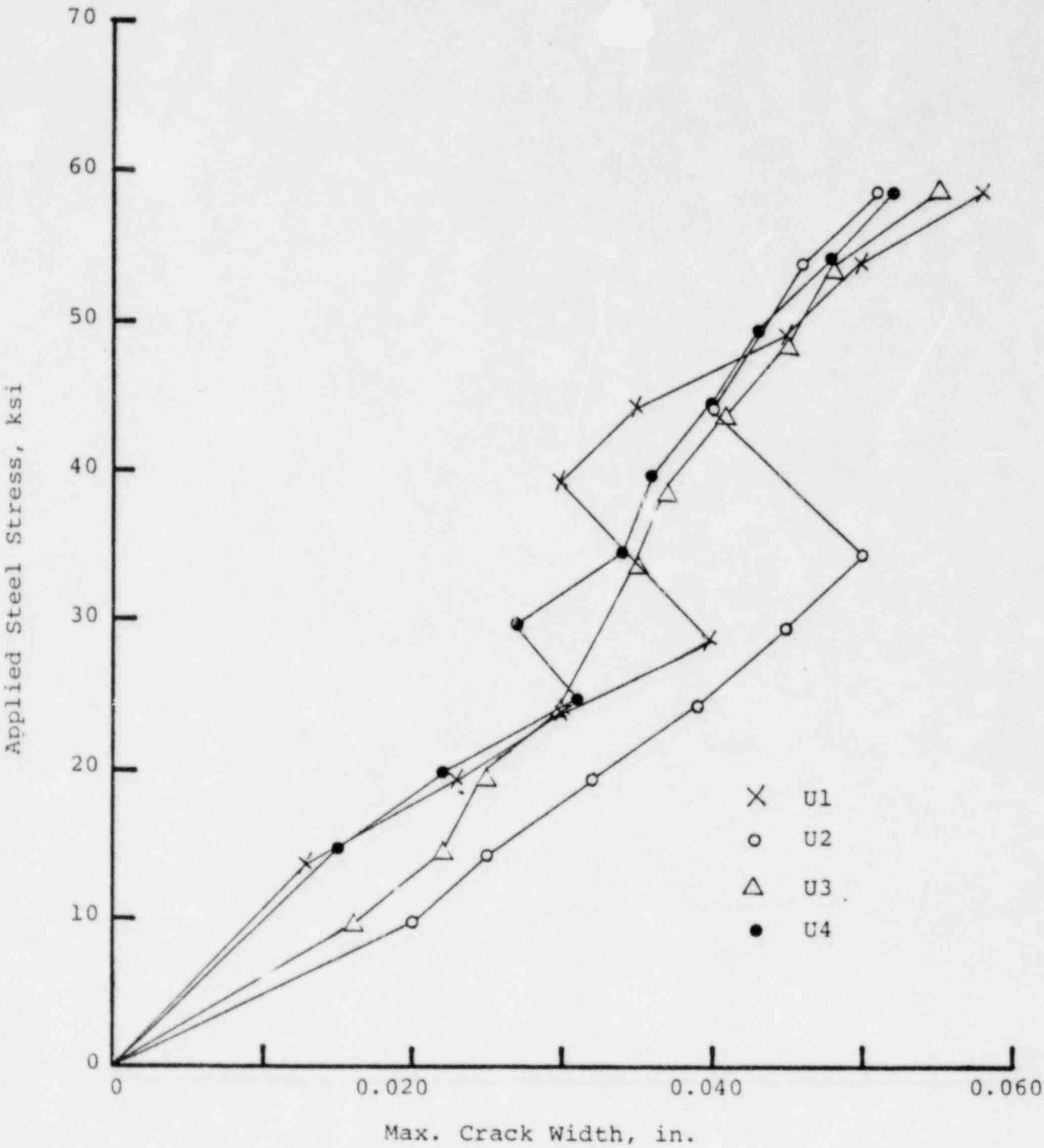


Fig. 6 Measured Crack Widths in Laboratory Tensile Test Specimens

TABLE 1 COMPARISON OF APPLIED AND ESTIMATED REINFORCEMENT STRESSES FOR LABORATORY TENSILE TEST SPECIMENS

Specimen Bar Type Approximate Crack Spacing, in.		U1 No. 14 20	U2 No. 18 17	U3 No. 18 22	U4 No. 14 10
Case 1	Applied Stress, ksi	39.5	44.0	43.3	39.8
	Est. Stress - S, ksi	43.5	68.2	54.0	104.4
	Est. Stress - S, / Applied Stress	1.10	1.55	1.25	2.62
	Est. Stress - M, ksi	35.2	45.8	41.9	60.2
	Est. Stress - M, / Applied Stress	0.89	1.04	0.97	1.51
Case 2	Applied Stress, ksi	58.5	58.6	58.5	58.7
	Est. Stress - S, ksi	84.1	87.0	72.5	150.8
	Est. Stress - S, / Applied Stress	1.44	1.49	1.24	2.57
	Est. Stress - M, ksi	57.6	59.4	54.8	98.6
	Est. Stress - M, / Applied Stress	0.93	1.01	0.94	1.68

Notes:

1. Est. Stress - S = stress based on strain calculated from maximum individual crack width and approximate crack spacing.
2. Est. Stress - M = stress based on strain calculated from sum of average crack widths of all transverse cracks and a multiple of approximate crack spacing (the multiple equals number of cracks).

applied stresses were calculated from measured forces in each bar. Estimated stresses were determined using two approaches. In the first approach, individual maximum crack widths were used to estimate steel strains and corresponding stresses. In the second approach, average widths measured along transverse cracks were used to calculate an average steel strain. In both approaches, measured crack spacings were used to calculate strains. An assumed value of 29,000 ksi was used for modulus of elasicity. Calculations were made at two levels of applied stress. The first level, Case 1, was for steel stresses in the vicinity of 40 ksi. The second level, Case 2, was for steel stresses in the vicinity of 59 ksi.

The calculation procedure used for Table 1 essentially applies Eq. 2 "in reverse." Reinforcement stresses are derived from measured crack widths and crack spacings.

As shown in Table 1, the ratio of estimated stress to applied stress varies considerably for the estimate based on individual crack width measurements. Except for Specimen U4, stress estimates based on summation of crack widths agree reasonably well with applied stresses. Evaluation of these data indicate that crack spacing has a considerable effect on the results. Crack spacing for nominally identical No. 14 bar test specimens varied by a factor of 2.0.

Table 1 illustrates that even under controlled laboratory conditions, and for simple loading conditions, estimates of steel stresses from measured crack widths and spacings have low reliability. This is particularly true when individual crack width measurements are used. It can be expected that estimates based on field measurements of existing buildings would be less accurate than is implied by results in Table 1.

However, for purposes of monitoring the condition of the Midland Plant structures, the approach used above can be considered applicable on a general basis. Measured crack width and crack spacing can be used as qualitative indicators of condition of the structures, without the need to obtain quantitative residual stress values. The relationship between crack width, crack spacing and steel stress can be used to provide approximate data for selection of acceptance criteria. The approximate data must be tempered by engineering judgement and experience.

OBSERVED CRACKS IN WALLS OF MIDLAND PLANT STRUCTURES

Cracks observed in the Midland Plant structures were described in References 1 through 4. Table 2 contains a summary of observed cracks in walls of the Feedwater Isolation Valve Pits, Auxiliary Building, Diesel Generator Building, and Service Water Pump Structure. Walls listed in Table 2 were selected because they contained the most significant cracks. Except for the center east and center west walls of the Service Water Pump Structure, data given in Table 2 are based on inspections made by CTL personnel.

Average crack spacings and crack widths given in Table 2 were determined from all recorded cracks in the wall element under consideration. For walls in the Auxiliary Building,

TABLE 2 SUMMARY OF OBSERVED CRACKS IN SELECTED WALLS

Building and Wall Description	Approx. No. of Cracks	Crack Spacing, in.		Crack Width, in.		Sum of Crack Widths Over 10 ft Gage Length
		Min.	Avg.	Max.(1)	Avg.(2)	
1. Feedwater Isolation Valve Pits						
(a) Unit 1 (West Unit) - Wall 4	2	31	-	0.006	0.005	0.01
(b) Unit 2 (East Unit) - Wall 1	2	78	-	0.003	0.003	0.01
2. Auxiliary Building						
(a) West Electrical Penetration Area - Column Line K	4	-	-	0.010	-	0.01
(b) East Electrical Penetration Area - Column Line K	2	-	-	0.010	-	0.01
3. Diesel Generator Building Center Wall	21	6	33	0.025	0.009	0.13
4. Service Water Pump Structure						
(a) East Wall - North End	9	43	56	0.015	0.008	0.04
- South End	4	80	129	0.015	0.005	0.02
(b) Center East Wall	9	9	58	0.020	0.017	0.07
(c) Center West Wall	5	35	92	0.030	0.026	0.06
(d) West Wall - North End	9	24	63	0.025	0.011	0.06
- South End	7	50	60	0.020	0.016	0.05

averages were not calculated because only a few cracks were observed, and these were at different elevations within the overall height of the wall.

Also shown in Table 2 is the sum of crack widths over a 10-ft gage length for the selected walls. This sum was determined by "sliding" the gage length horizontally along the wall until the maximum value of the sum was found. Selection of a 10-ft gage length was essentially arbitrary. However, it does provide a multiple of from seven to ten times the spacing of vertical reinforcement in the walls. If stress related vertical cracks were to occur, it is expected that their spacing would be influenced by the location of vertical reinforcement. It is also believed that the 10-ft gage length is sufficiently large to incorporate the influence of multiple cracks.

Data on the sum of crack widths over a 10-ft gage length can be used to evaluate the influence of multiple cracks and also serve as a basis for acceptance criteria for use in monitoring future crack development.

Using an approach similar to that defined in the discussion of Eq. 1, crack spacings were estimated for the walls listed in Table 2. This was done using a bond stress distribution developed in Ref. 8.* Crack spacings calculated for the walls in Table 2 range from approximately 12 to 18 in. Calculations were based on reinforcement details and material properties listed in Ref. 1 through 4.

*The procedure for estimating crack spacings and crack widths was developed by R. G. Oesterle, Manager, Structural Analytical Section, Construction Technology Laboratories.

As can be seen in Table 2, measured crack spacings are generally larger than the calculated range. This confirms earlier observations that relate observed cracks to restrained volume changes rather than external forces. It indicates that the observed cracks are much sparser than would be expected if cracks had occurred because of significant applied loads or building settlement. It also implies that future crack development, if related to applied forces or settlement, would require formation of additional cracks in addition to some increase in widths of existing cracks.

Maximum crack widths observed in the structures range from 0.003 to 0.030 in. Average crack widths range from 0.003 to 0.026 in. The largest crack widths were observed in the center west wall of the Service Water Pump Structure. This wall has the lowest reinforcement ratio and the largest bar spacing of all walls evaluated. Thus, it is not surprising that volume change cracking would result in larger widths.

In Ref. 3, crack widths measured in the center wall of the Diesel Generator Building were used as a measure of reinforcing bar extension to estimate residual steel stresses. Using measured crack widths over a gage length of approximately 150 in., residual steel stresses in the range of 20 to 30 ksi were derived. Approximately the same result is obtained by using the sum of crack widths over a 10-ft (120 in.) gage length as listed in Table 2. Considering the Diesel Generator Building center wall as a base, results for other walls in Table 2 imply considerably lower levels of residual reinforcement stresses.

As mentioned above, the average calculated crack spacing for walls listed in Table 2 ranged from 12 to 18 in. Using these crack spacings with Eq. 2, and using the knowledge that crack width variability will result in a maximum crack width approximately twice the calculated average width, a maximum crack width of approximately 0.06 is obtained for a stress of 60 ksi. Using a similar approach for evaluation of total crack width over a 120-in. gage length at a stress of 60 ksi gives a value of 0.25 in.* It is suggested that these values be used as a basis for acceptance criteria during monitoring of cracks in the Midland Plant structures.

ACCEPTANCE CRITERIA FOR CRACK MONITORING PROGRAM

As outlined in Ref. 1 through 4, the program for monitoring cracks in the Midland Plant Structures serves as a supplement to the displacement monitoring program. Periodic visual inspections of the structures will be made to determine if new cracking has developed or if existing cracks have changed in width or length. The following criteria were established for evaluation of observed crack widths:

1. If a new crack develops that is wider than 0.010 in., an engineer knowledgeable in reinforced concrete behavior and design should evaluate significance of the new cracking.

*In estimating the limit for total crack width over a 120 in. gage length the multiple of 2.0 was not used because the gage length selected is arbitrary and is not intended to represent crack spacing.

2. If any crack exceeds 0.030 in. in width, an engineer knowledgeable in reinforced concrete behavior and design should evaluate significance of the cracking.*

3. If development of yield strain in the reinforcement is inferred from any observed crack, underpinning operations should be stopped immediately. Based on discussions given previously in this report, it is recommended that a maximum crack width of 0.06 in. for any individual crack be used as an indication of the development of incipient yielding. In addition, if the sum of crack widths over a horizontal gage length of 10 ft exceeds 0.25 in., underpinning operations should be stopped. The effects of these cracks should be evaluated by a consultant and further course of action should be recommended.

The above are intended to provide reasonable criteria for evaluation of condition of the structures during underpinning. If unanticipated loads or settlements were to occur, it is expected that the number and size of cracks would increase significantly over those currently existing. In combination with the displacement monitoring program, it is believed that the crack monitoring program will provide a conservative method to indicate occurrence of incipient structural disturbances.

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*A maximum crack width of 0.030 in. has been reported in the center west wall of the Service Water Pump Structure. This structure has been evaluated since that crack was reported.(4)

If acceptance criteria are exceeded, it does not necessarily mean that structural integrity has been lost. A detailed evaluation must be made to determine effects of cracks relative to structural integrity. General criteria for evaluation of significance of cracks are given below.

CRITERIA FOR EVALUATION OF CRACKS THAT EXCEED ACCEPTANCE LIMITS

As stated in previous reports, the following criteria should be used to evaluate the significance of cracks that develop in the Midland Plant Structures:

1. Geometry of member
2. Amount and distribution of reinforcement in member
3. Material properties of member
4. Function of member
5. Magnitude and distribution of loads on member
6. Construction technique
7. Sequence of construction
8. Crack location and distribution
9. Crack size
10. Interaction of multiple cracks

Basically these criteria outline a procedure that requires the function and load transfer mechanism of the member or structure to be first defined. Then the influence of cracks on the path of load distribution is determined. In this way the cause of cracking is defined and the influence of cracking on future load carrying capacity of the structure can be evaluated. This can be done by creating a structural model that adequately reflects loading or settlement conditions that may be assumed to have occurred. Observed crack distributions will help to verify the assumed structural model and loading conditions.

In evaluating cracks in reinforced concrete structures it is not sufficient to base conclusions on a single criteria such as crack width. The overall crack pattern including location and direction of cracks, length and width of cracks, and interrelationship between multiple cracks must be considered. The pattern of cracking provides significant clues to causes of cracks and their effects on future performance.

SUMMARY AND CONCLUSIONS

Previous reports have presented an evaluation of the structural significance of cracks observed in buildings at Midland Nuclear Plant Units 1 and 2.[1-5] Observed cracks in these structures were described and the significance of the cracks with regard to future load carrying capacity was discussed.

This report presents a discussion of the observed cracks in the Midland Plant structures with particular reference to the relationship between observed crack widths and residual steel stresses implied by observed cracks. The significance and evaluation of spacing and width of multiple cracks are also discussed. Within the context of the significant inherent variability in crack width and crack spacing, acceptance criteria for the Midland Plant crack monitoring program are derived. These criteria provide a basis for using observed crack width and crack spacing as a measure of condition of the structures during implementation of remedial measures.

Although measured displacements are recommended for use as the primary means of monitoring behavior of the structure, periodic visual inspections to monitor cracks will supplement displacement data. It is believed that the displacement and crack monitoring program will provide a safe and reasonable method for assessing condition of each structure during underpinning operations.

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