Containment Structure Tendon Investigation

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SUMMARY

The paper describes an investigation into the possible causes of lower-than-predicted tendon forces which were measured during past tendon surveillances for a concrete containment. The containment is post tensioned by vertical tendons which are anchored into a rock foundation. The tendons were originally stressed in 1969, and lift-off tests were performed on six occasions subsequent to this date over a period of 11 years. The tendon forces measured in these tests were generally lower than predicted, and by 1979 the prestress level in the containment was only marginally above the design requirement. The tendons were retensioned in 1980, and by this time an investigation into the possible causes was underway. Potential causes investigated include the rock anchors and surrounding rock, elastomeric pad creep, wire stresses, thermal effects, stressing equipment and lift-off procedures, and wire stress relaxation.

The investigation activities included stress relaxation testing of wires pulled from actual tendons. The stress relaxation test program included wire specimens at several different temperature and initial stress levels and the effect of a varying temperature history on the stress relaxation property of the wires. For purposes of future force predictions of the retensioned tendons, the test program included tests to determine the effect on stress relaxation due to restressing the wires after they had relaxed for 1000 hours and 10,000 hours.

Field testing was performed to determine the accuracy of the stressing equipment using a strain gaged stressing ram. The elongations that the rock anchors and tendons exhibited during previous stressing operations were evaluated and compared with predicted values. From the investigation it was concluded that a larger-than-expected stress relaxation property of the tendon wires is the only single cause which would explain the lower-than-predicted forces in the tendons.

1.0 INTRODUCTION

1.1 Tendon Description and Force History

The Robert E. Ginna Nuclear Power Plant is located on Lake Ontario approximately 18 miles east of Rochester, New York. The plant is owned by Rochester Gas and Electric Corporation. The containment structure, shown in Figure 1, is post tensioned by 160 vertical tendons. Each tendon, approximately 115 feet long, consists of 90 wires, each 1/4 inch in diameter. Each tendon is connected below the containment base to another 90-wire tendon, approximately 34 feet long, which is two-stage grouted into rock and functions as a rock anchor. Four of the tendons originally had load cells installed to monitor the tendon force.

The tendons were originally stressed in March and April 1969, and four tendon surveillances were performed over the next 8 years. The tendon lift-off forces measured in the first four surveillances were generally lower than predicted by an average value of 20 kips. This 20 kip discrepancy represented less than 3% of the original stressing force specified for the tendons (742 kips). However, it was significant because by the fourth surveillance in 1977, the average force of the tendons was only marginally above the design requirement of 636 kips.

Because of the lower measurements, additional lift-off tests were conducted on 22 tendons in October 1979. The lift-off forces measured in October 1979 generally confirmed the lower-than-predicted results from past surveillances. As a result, Gilbert/Commonwealth was requested to evaluate all of the lift-off test results (Ref. 1).

1.2 June 1980 Retensioning

As a result of the above evaluation, the decision was made to retension 137 of the 160 tendons in June 1980. The twenty-three (23) tendons which were not included in the June 1980 retensioning program had been previously retensioned in May 1969, approximately 1000 hours after original stressing, and their lift-off force history indicated that another retensioning was not necessary.

The June 1980 retensioning of the 137 tendons increased the average tendon force from 607 kips to 760 kips. The 760 kips average tendon force exceeded the required minimum design average tendon force of 636 kips by 19.5%. The measured and predicted elongations for each tendon were in good agreement which indicated no abnormal behavior of the tendons or rock anchors during the retensioning operations. Based on the force and elongation data, the June 1980 retensioning program was considered successful.

1.3 July 1981 Surveillance

Approximately one year after the retensioning, in July 1981, the forces in 18 tendons were measured as part of the first tendon surveillance subsequent to the June 1980 retensioning. The objectives and conclusions of this surveillance are presented in Section 5.0. The main results were that all 18 tendons had measured force levels above the 636 kip technical specification limit and the measured forces were in reasonable agreement with their predicted values. Based on the forces in the sample tendons, the expected average force for all 160 tendons was 714 kips.

1.4 Purpose

The purpose of this paper is to summarize:

a. The investigation and conclusions from a study of postulated causes for the lower-than-predicted tendon forces which were measured during past tendon surveillances (Section 2.0).

b. The results and conclusions of the stress relaxation tests performed on selected tendon wires (Section 3.0).

c. A study of methodology for predicting stress relaxation losses in the retensioned tendons; consequently, enabling a prediction of their forces at future surveillances (Section 4.0).

d. The results of the July 1981 tendon surveillance performed after the tendon retensioning in June 1980 (Section 5.0).

The complete investigation is reported in Reference 2.

2.0 INVESTIGATION OF TENDON FORCE LOSSES

This section summarizes the investigation of possible causes of the larger-than-predicted tendon losses which were determined during past surveillances. These include: (1) Failure of the Rock Anchors, (2) Rock Creep, (3) Rock Failure, (4) Excessive Tendon Tensioning Stresses, (5) Tendon Thermal Expansion, (6) Stressing Equipment Calibration and Lift-off Procedures, (7) Effect of 6% Overstressing, (8) Elastomeric Pad Creep, (9) Stress Relaxation, and (10) Tendon Type (curved versus straight).

All ten of the possible causes were studied experimentally and analytically using data collected during initial qualification testing, original tensioning, and at tendon surveillances. The rock anchor investigation included an evaluation of tests on small scale rock anchors used to establish slip and pull-out limits, rock creep tests, and analyses of the potential for rock failure. The conclusions were that the rock anchors remain securely engaged in the rock; rock creep is negligible; and rock failure has not occurred.

Also investigated were the possibility of excessive tendon wire stresses at original tensioning and the practice, at tendon surveillances, of applying a 6% overstress to each tendon to verify its ability to withstand the stress increase associated with the postulated accident. It was concluded that at original tensioning all wire stresses remained below their tested yield values and that most of the tendon stresses did not exceed their proportional limit. Both the wire stress relaxation tests and stressing tests performed at the July 1981 surveillance confirmed that stressing each tendon to 6% above its lift-off force did not change the tendon force after reseating.

The effect of temperature differences between the tendons and the containment wall was investigated. However, if the wall and the tendons both were to experience a uniform temperature increase of 40° F, the tendon force would reduce only 5 kips. Local hot spots in tendons located around pentrations were eliminated as a cause since the tendons around the main steam and feedwater penetrations did not exhibit losses any larger than other tendons. There did appear to be a seasonal effect. The lift-off forces for tendons measured in October 1979 generally were above, by as much as 25 kips, the downward trend line established by lift-off readings in June 1977 and June 1980. Therefore, it appears that the tendon forces measured during the winter might be expected to be higher than if measured during the summer. However, considering the surveillance force data collectively, the seasonal variation in tendon force was not considered to be a reason for the larger-than-predicted force losses which the tendons generally experienced.

Stressing equipment calibration and lift-off procedures were investigated as possible causes for the larger-than-predicted tendon force losses which occurred in the past. From a review of past calibration records it was concluded that the ram and pressure gauge which had been used on all four surveillances and for the additional tests in October 1979 were properly calibrated as individual units. However, to check the accuracy of the entire lift-off measurement process, special tests were conducted during the July 1981 surveillance. All lift-off measurements during this surveillance were made using the same stressing ram and pressure gauge as was used in the past. In addition, strain gages were installed on the stressing rod and the rod was calibrated. The determination of the point of lift-off was made with feeler shims, and this method was compared with load cell results for selected tendons. The results from the load cell tendons demonstrated that the point of lift-off determined using the feeler shims was very accurate. The results also demonstrated that the application of the gauge pressure to the effective ram area produced a lift-off tendon force which was as likely to be overmeasured as undermeasured but within ±2.6% of the force measured with the strain gaged stressing rod. It was concluded that the larger-than-predicted tendon force losses were not due to equipment or procedure inaccuracies.

The containment wall was designed to have a hinge at its intersection with the base mat. This hinge is developed with elastomeric pads (55 durometer neoprene) between these structural components. The total pad thickness is 1.63 inches, including the steel shims and a combined neoprene thickness of 1.375 inches. The in-place pads were under approximately 1200 psi bearing stress. The possibility of pad creep, which would reduce the tendon forces with time, was investigated by reviewing creep test results for the original pads and long term creep data reported by the manufacturer. However, these results indicated that long term displacement of the pads would be very small and could not account for past tendon force losses.

The possibility was investigated that the tendon losses could be related to the curvature of the tendons. It was speculated that tendons with the largest curvature (around penetrations) might exhibit a gradual "slackening" if the friction forces along these tendons undergo a redistribution and reduction. However, a comparison of force losses from June 1980 lift-off tests revealed no such correlation. Therefore, tendon type was eliminated as a reason for the larger-than-predicted tendon losses.

Excessive stress relaxation of the tendon wires as a cause of the larger-than-predicted tendon force losses was thoroughly investigated. Stress relaxation tests were performed on individual tendon wires, and these results were compared with the actual tendon losses as described in Section 3.0.

3.0 STRESS RELAXATION

3.1 Objectives

The original objective of the wire tests was to determine if the larger-than-predicted force losses in the tendons were caused by excessive stress relaxation of the tendon wires. For this purpose, stress relaxation tests were initiated at the Fritz Engineering Laboratory of Lehigh University in April 1980. The test specimens were obtained from actual tendon wires. The tests were designed to assess the effects of initial stress level and temperature since the tendons were not all initially stressed to the same level and since the tendons had been exposed to temperatures greater than 68° F during plant operation. A test condition of particular interest was the initial stress level of 0.70 GUTS and 68° F. This is the standard condition generally used by the nuclear industry for classifying relaxation properities of prestressing wire, and the wire for the tendons was supplied on this basis with a specified 40 year stress relaxation of 12%. After the test program was underway, it was decided to retension the tendons in the containment structure. Therefore, the objective of the test program was modified to include a determination of retensioning effects on the stress relaxation behavior of the tendon wires.

3.2 Tests

Each of the 160 tendons contains an extra (sacrificial) wire, 115 feet long, which is unstressed. The extra wire was removed from three tendons (numbers 76, 51, and 150) and was cut into 23 feet lengths on site for shipment to Fritz Lab for stress relaxation testing. These wires represented three of the six different heats of wire supplied, and 46% of the tendons were fabricated with wires from the same heats as the three test wires. A total of 14 specimens, 10 feet each, were tested at temperatures of 68° F, 78° F, and 104° F and at initial stress conditions of 0.70 GUTS and 0.75 GUTS. During these tests, seven of the specimens were retensioned. The test condition for each specimen is given in Table 1. The test equipment consisted of environmental chambers large enough to accept the 10 ft. specimens. The specimens were anchored at each end by supreme chucks and maintained at constant strain. Loads were read by BLH 20 kip load cells.

3.3 Comparison with Tendons

The results from the stress relaxation tests on the wires were compared with the actual tendon losses in the following manner. Tendon forces were available from lift-off tests performed at six points in time which included the four surveillances, the October 1979 tests, and tests on 137 tendons immediately prior to their retensioning in June 1980. For each tendon involved in these tests, the measured lift-off force was subtracted from the original tensioning force of March/April 1969. This force difference was used to subtract predicted elastic shortening, creep, and shrinkage losses. The remaining force difference was assumed to be entirely attributable to a stress relaxation loss of force in the tendon. The stress relaxation was expressed as a percentage of the original tensioning force; and the resulting value, referred to as the effective stress relaxation of the tendon, was superimposed on the stress relaxation curves constructed from the wire tests. Initially, all of the effective stress relaxation values for the tendons were compared with all of the test wire curves, regardless of the wire heat which comprised the tendon. For a more specific comparison, the effective stress relaxation values for only those tendons that were comprised solely of wires from the same heat as a given test wire were superimposed on the stress relaxation curves of the specific test wire. Figures 2 and 3 show the comparison for two of the three wire heats tested. The solid lines represent actual data. The dashed portion is an extrapolation of the data. Each dot is the effective stress relaxation for a specific tendon. Approximately 35% of the 160 tendons are represented by these two heats of wire.

In the figures, most of the effective stress relaxation values (dots) are at 100,000 hrs., which corresponds to the June 1980 lift off tests. Two lines for 85° F and 95° F are indicated. These were constructed by an interpolation between the wire test curves. The 85° F to 95° F represents the expected temperature range which the tendons have experienced over most of their life in the containment due to plant operation. Therefore, based on the wire test results, the tendons would have been expected to exhibit a stress relaxation property in the range from 14% to 17.5% as of June 1980. This is considerably higher than the 10% value from the Theoretical 12% wire assumed for both the design and used for all previous tendon force predictions.

The average of all the June 1980 effective stress relaxation values for the tendons is noted in the figures at approximately 15%. The ±3% marks represent the range of this average if the tendon forces had either been undermeasured or overmeasured by 3% in the June 1980 lift-off tests. The 3% accuracy comes from a statistical analysis of the results of the lift-off force measurement accuracy tests described in Section 5.0. Thus, it is seen that much of the variation in effective stress relaxation could possibly be due to measurement error of the lift-off forces.

The main conclusions drawn from the results in the figures is that the effective stress relaxation values for most of the tendons exceeded those of the Theoretical 12% curve used in previous force predictions, and this would explain the lower-than-predicted tendon forces that were measured in the past. However, the effective stress relaxation values for the tendons are not high compared to the stress relaxation values for the test wires taken from the tendons.

4.0 PREDICTING RETENSIONED TENDON FORCES

To evaluate the lift-off forces measured during the surveillances, the expected force in each tendon is predicted. For tendons that have been retensioned, the usual procedure for calculating losses due to concrete elastic shortening, creep, shrinkage, and stress relaxation must be modified to obtain values for these losses which occurred subsequent to the retensioning. For example, the elastic shortening which the tendons experienced during a retensioning is based on their retensioning sequence and the incremental stress produced in the wall on retensioning. Little information exists concerning the effects of retensioning on wire stress relaxation. The test results in Figure 4 (solid curves) demonstrate that the retensioned wire relaxation is significantly different from its unretensioned relaxation. The results of retensioning seven specimens were analyzed. The relaxation curve before retensioning was used to predict the retensioned wire relaxation assuming that stress relaxation obeys superposition principles.

Superposition of Relaxation

Figure 5 shows a typical stress relaxation curve plotted on a semi-log scale. At time t_r after initial stressing the tendon is retensioned. The original value of tendon force was P_o, which has decreased to P at time t_r. The tendon is retensioned to a force P_r. The tendon force must be predicted at some later time increment, Δt_s, beyond the time of retensioning, or at total time $t_r + \Delta t_s$. Under these conditions the new tendon force can be predicted by considering the relaxation in two parts:

1. The incremental relaxation the tendon would have continued to experience from t_r to $t_r + \Delta t_s$ had it not been retensioned, and
2. The relaxation associated with the force increase from P to P_r.

Usually a tendon is retensioned to its original force; thus, $P_r = P_o$. If the percent stress relaxation of the retensioned force is denoted as SR_r, it can be shown that at time $t_r + \Delta t_s$:

$$SR_r\ (t_r + \Delta t_s) = SR(t_r + \Delta t_s) - SR(t_r)\ [1 - SR(\Delta t_s)/100] \qquad (1)$$

Eq. (1) was applied to the stress relaxation curves (before retensioning) for the seven retensioned specimens to predict a retensioned curve for each specimen for comparison with its actual retensioned curve. The comparison for specimen #3 is shown in Figure 4, and an underestimate of the actual retensioned curve is evident. This characteristic was also evident for the other six specimens, generally by the same amount. However, even with the under-prediction of retensioned wire stress relaxation, eq. (1) provides a more realistic estimate than using the unretensioned data without adjustment.

5.0 JULY 1981 TENDON SURVEILLANCE

5.1 Objectives

The July 1981 tendon surveillance program included the measurement of forces for 18 tendons including the four tendons with load cells. The data collection system used was designed to confirm the lift-off force data and to obtain data needed to continue the investigation into the larger-than-predicted tendon losses. The basic objectives were:

1. To measure lift-off forces in selected tendons and compare with the required design average tendon force of 636 kips.
2. To compare measured lift-off forces with those predicted to detect abnormal force loss.
3. To compare forces obtained with a calibrated pressure gauge and ram area (the method used on previous surveillances) with a calibrated strain gaged stressing rod (considered to be the most accurate).
4. To test the effect of a temporary 6% overstressing, which was part of the procedure on previous surveillances, using load cell tendons.
5. To assess the accuracy of feeler shims to determine the point of lift-off compared to load cell results.

5.2 Results and Conclusions

The results indicated that the temporary 6% overstressing did not change the force in the tendon upon reseating and the feeler shims were very accurate in determining the point of tendon lift-off. The results on the accuracy of the tendon force obtained using ram area and gauge pressures indicated that this procedure became more accurate at higher force levels (objective 3). In all, 36 force measurements were taken at each of three pressure (force) levels: 2000 psig (258 kips), 4000 psig (514 kips), and at lift off where pressures and forces varied but were approximately 5600 psig (720 kips). At lift-off, 32 forces were accurate to within 1.2% and the remaining 4 forces were between 2 to 2.6%. At lift-off, 14 forces were undermeasured and 22 were overmeasured. From the results, it was concluded that at lift-off the forces could be determined to a reasonable accuracy; and considering the data at all three pressure levels, forces were as likely to be undermeasured as overmeasured.

The results corresponding to objectives 1 and 2 are presented in Table II. The results in the last column of the table indicate that most of the measured forces were within 5% of their predicted values, and no abnormal force losses were indicated. The predicted forces were based on the retensioning lock-off forces minus the elastic shortening, shrinkage, creep, and stress relaxation losses occuring subsequent to retensioning. As indicated by note 2 to the table, the retensioned stress relaxation loss calculation used the superposition method represented by eq. (1). The unretensioned stress relaxation curves to which eq. (1) was applied were developed based on the Theoretical 12% curve shown in Figure 2 or 3 but scaled up (or down) to represent the effective stress relaxation values (dots) at 100,000 hours. Thus, a unique retensioned stress relaxation curve was used for each surveillance tendon.

Finally, the results in Table II indicate that based on the forces measured in the sample tendons the average force for all of the 160 tendons is expected to be 714 kips, which is 12.3% above the 636 kip design requirement.

6.0 CONCLUSIONS

The results of the investigation indicated that stress relaxation of the tendon was the only single cause which would explain the larger-than-predicted force loss in the tendons. The original design was based on a relaxation grade of wire which would be expected to exhibit 12% stress relaxation after 40 years under load. However, tests indicated that the wires as they exist in the tendons could exhibit a 40 year stress relaxation in the range of 15% to 18.5%.

Based on the surveillance results one year after the tendons were retensioned, no abnormal force losses were found to have occurred.

ACKNOWLEDGEMENTS

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REFERENCES

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/2/ CONTAINMENT BUILDING TENDON INVESTIGATION FOR ROBERT E. GINNA NUCLEAR POWER STATION, Gilbert Associates Inc. Report No. 2347, for Rochester Gas and Electric Corporation, February 1982.

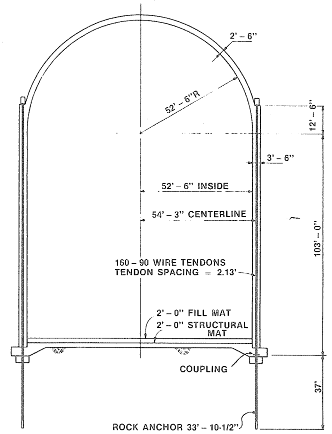

FIGURE 1
CONTAINMENT BUILDING

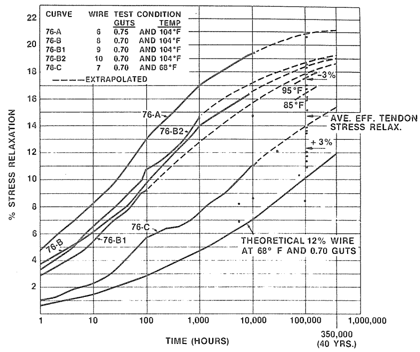

FIGURE 2
EFFECTIVE STRESS RELAXATION OF SURVEILLANCE TENDONS COMPRISED ENTIRELY OF WIRES FROM HEAT #30091

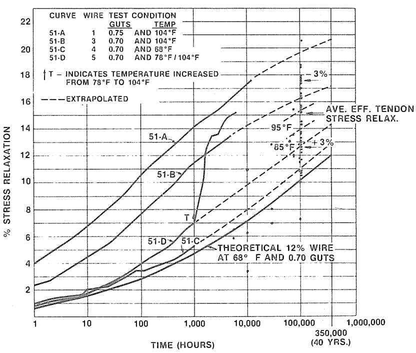

FIGURE 3
EFFECTIVE STRESS RELAXATION OF SURVEILLANCE TENDONS COMPRISED ENTIRELY OF WIRES FROM HEAT #19477

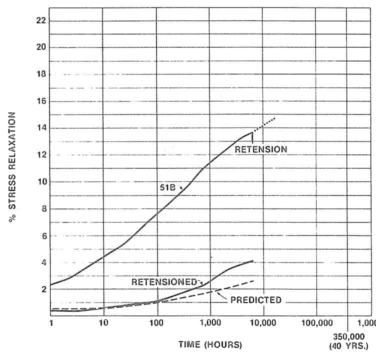

FIGURE 4
EFFECT OF RETENSIONING SPECIMEN #3 (TENDON 51)

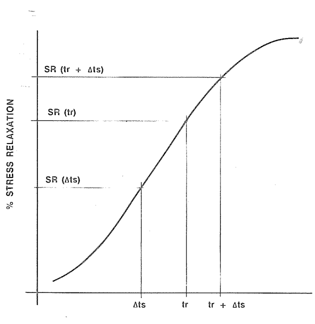

FIGURE 5
STRESS RELAXATION

TABLE I. STRESS RELAXATION TEST CONDITIONS

		Test Conditions					
		Original Stressing			Retensioning		
Tendon Mark	Specimen Number	Stress (% GUTS)	Temperature (°F)	Duration (Hours)	Stress (% GUTS)	Temperature (°F)	Duration (Hours)
51-A	1	75	104	11,376	N/A	-	-
51-B	3	70	104	6,000	70	104	5,688
51-C	4	70	68	1,000	70	68	6,551
51-D	5	70	78/104(1)	6,192	N/A	-	-
76-A	6	75	104	12,096	N/A	-	-
76-C	8	70	104	10,192	70	104	1,656
76-B1	9	70	104	100	70	104	6,498
76-B2	10	70	104	1,008	70	104	6,653
76-B	7	70	68	11,230	70	68	1,000
150-A	11	75	104	11,712	N/A	-	-
150-B	13	70	104	12,072	N/A	-	-
150-C1	15AB-10	70	68	9,960(2)	N/A	-	-
150-C2	12	70	68	5,520	70	68	5,686
150-D	15AB	70	78/104(1)	6,192	N/A	-	-

NOTES: 1. Temperature raised to 104°F at 1008 hours.
2. After 9,960 hours a 6% overstress was applied.

TABLE II. 1981 SURVEILLANCE FORCES COMPARED WITH PREDICTIONS

TENDON NO.	SEQUENCE OF LIFT-OFF	LAST(1) LOCK-OFF (kips)	PREDICTED(2) LIFT-OFF (kips)	MEASURED LIFT-OFF (kips)		MEAS.-PRED. PRED. (%)
13	1	761	737	730		-0.9
155	2	754	745	738		-0.9
17	3	776	760	727		-4.3
21	4	765	749	725		-3.2
51	5	765	748	710		-5.1
53	6	761	742	734		-1.0
62	7	773	754	716		-5.0
63	8	769	740	722	Ave:	-2.4
74	9	749	680	731	722	+7.5
76	10	754	729	713		-2.2
84	11	753	732	714		-2.5
93	12	761	740	713		-3.6
125	13	768	755	705		-6.6
133	14	757	734	734		0.0
33*	15	770	655	679		+3.7
36*	16	763	667	657	Ave:	-1.5
111*	17	744	637	646	668	+1.4
116*	18	757	634	690		+8.8
AVERAGE				714(3)		-1.0

NOTES: (1) In June 1980 except for tendons marked * which were retensioned in May 1969 at 1000 hours. Note: There were 23 tendons which were retensioned in May 1969 out of 160 total tendons.
(2) Predicted by applying the superposition method to the effective stress relaxation of each tendon.
(3) Weighted average considering the 23 tendons retensioned in May 1969 at 1000 hours.