# Research Report

EVERGREEN POINT BRIDGE
MAINTENANCE PROBLEMS

FINAL REPORT

SEPTEMBER 1980

## Public Transportation and Planning Division

Washington State
Department of Transportation
In cooperation with
U.S. Department of Transportation
Federal Highway Administration

WA-RD-44.1

TECHNICAL REPORT STANDARD TITLE PAGE

| Field | Value |
|---|---|
| 1. Report No. | WA-RD-44.1 |
| 2. Government Accession No. | |
| 3. Recipient's Catalog No. | |
| 4. Title and Subtitle | Evergreen Point Bridge Maintenance Problems |
| 5. Report Date | September 1980 |
| 6. Performing Organization Code | |
| 7. Author(s) | C. B. Brown |
| 8. Performing Organization Report No. | |
| 9. Performing Organization Name and Address | University of Washington<br>Seattle, Washington 98195 |
| 10. Work Unit No. | |
| 11. Contract or Grant No. | Y-1640 |
| 12. Sponsoring Agency Name and Address | Washington State Department of Transportation<br>Highway Administration Building<br>Olympia, Washington 98504 |
| 13. Type of Report and Period Covered | Final<br>1975 - 1980 |
| 14. Sponsoring Agency Code | |
| 15. Supplementary Notes | This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration |

16. Abstract

The 1974-79 study of the maintenance problems of the drawspan mechanism of the Evergreen Point Bridge across Lake Washington is reported. The approach was to predict the life of elements by Miner's hyposthesis. For this the strains at critical points and the wind vector were measured over two sessions. These results were correlated with long term wind data to provide the number of cycles in a year at various stress levels. The fatigue capacity of anchor rods was determined by the Prot test on six specimens. The resulting S-N curve was compared to the field measurements to determine the expected life of the rods from the Miner criterion. The methods developed provide useable maintenance procedures for the prevention of fatigue failure of critical structural elements.

| Field | Value |
|---|---|
| 17. Key Words | bridge, fatigue, reliability, wind |
| 18. Distribution Statement | None |
| 19. Security Classif. (of this report) | Unclassified |
| 20. Security Classif. (of this page) | Unclassified |
| 21. No. of Pages | 39 |
| 22. Price | |

Form DOT F 1700.7 (8-69)
HWY FORM 341-004 6/72

# EVERGREEN POINT BRIDGE MAINTENANCE PROBLEMS

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Final Report

Research Project Y-1640

Prepared for
Washington State Transportation Commission
Department of Transportation
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

September 1980

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## INTRODUCTION

Over the period 1974-79 a study of the damage to critical elements of the drawspan mechanism of the Evergreen Point Floating Bridge across Lake Washington near Seattle was conducted in the Department of Civil Engineering of the University of Washington. The project had the following phases:

1) design, manufacture and installation of the instrumentation on the bridge. These instruments measured the wind, wave and strain characteristics on the bridge and the drawspan elements.

2) measurement of the above characteristics over a four-year period.

3) compilation and analysis of these measurements.

4) determination from the above analyses of the number of cycles at various oscillatory stress levels.

5) design and construction of fatigue test equipment for the employment of the Prot method for the determination of S-N curves from a limited number of specimens.

6) conduct of these tests on trunnion anchorage rods from the drawspan mechanism.

7) construction of the S-N curve for the anchorage rods from the test results.

8) determination of the expected life of the anchorage rods from (4) and (7).

This sequence of work is reported here.

The original proposal included step 5 through 8 on other critical elements of the drawspan. However, only the uni-axial tests on the trunnion anchor rods supplied by the Washington State Department of Highways were completed. Test arrangements on other elements, involving moments and forces were not developed.

These statistics have been developed from the data provided in the four annual progress reports submitted to the Washington State Department of Highways in the years 1975, 1976, 1977 and 1978. These reports are commented on and form a part of Appendix D. This appendix has been deleted in distributed copies of this Report.

The work was completed in 1978 with the determination of the S-N curve for machine-threaded anchor rods. At a review of the final work it transpired that these rods originally supplied by the Washington State Department of Highways were not of the type in use on the bridge because of design changes and replacement. Therefore, the fatigue tests were repeated for roll-threaded anchor rods. Thus, the delay in the issue of this report.

Messers. D. Christiansen, J. Heavner, M. A. Landy, and R. Vasu worked on this project under the direction of the Principal Investigator. In particular, Mr. Christiansen was responsible for phases (1), (2) and (3) and was involved in phases (4) and (5). Mr. Landy was responsible for phase (5), Mr. Landy and Mr. Heavner for Phases (6) and (7), and Mr. Vasu was active in phases (4) and (8).

ORGANIZATION

The first part of this study involved designing a scheme which allowed the life of critical elements to be found. This was based on Miner's hypothesis where the fatigue life in years is*

$$T_f = \left[\Sigma \frac{\omega_i \alpha_i t_i}{N_i}\right]^{-1} \qquad (1)$$

where $\omega_i$ is the frequency in Hertz, $\alpha_i$ number of occurences in a year, $t_i$ the duration in seconds of applied oscillatory stress amplitude $S_i$ and $N_i$ the number of cycles to failure at that amplitude. The equation (1) requires on-site measurements to describe the features $\omega$, $\alpha$ and t together with laboratory tests of full-scale elements to determine the characteristics of the S-N curve.

It should be noted that eq. (1) is deduced for a stationary narrow frequency band input where Miner's damage criterion holds. In this work the elements are exposed to a narrow frequency range and fall within the perview of the theory. The use of Miner's criterion is critical to the establishment of an S-N curve with only six samples available. This criterion has been applied in a consistant manner in all parts of the study. Bright (1977) has compared the Miner criterion with other postulates for accumulative fatigue damage. He has concluded that in the light of limited data, Miner's hypothesis is as valid as any other. Certainly in this work the data were limited and the use of Miner's criterion appears justified.

Eleven years of wind data were available and it was necessary to develop a relationship between these data and stresses in the critical elements. To accomplish this the strains in the elements and the wind vector were measured over a four-year period and then a relationship between measured wind and strains developed. This relationship was then applied to the eleven-year wind record

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* Derivation in Appendix B.

in order to obtain corresponding estimates of long term strain. Then a linear stress : strain law was used to obtain long term stress records.

The laboratory tests to construct the S-N curve were performed on anchorage rods. There were tested in an arrangement that simulated the loading conditions on the bridge. The Prôt method, with the extension of Basavaraju and Lim (1977), was used in the tests to obtain the S-N curve. Two types of rods, with machined and rolled threads, were tested.

With the long term in situ stress information and the S-N curve available, estimates of the element life were obtained from eq. (1). This gave a direct indication of the maximum time that a critical element could be left in the bridge without failure occurring.

FIELD INSTRUMENTATION

The instrumentation centered around the recorder system which was designed for this project. The recorder has 44 8-bit imput channels and a 12-bit clock channel. The 8-bit shift registers have a maximum count of 256 (including the zero bit), which give a resolution of 2/256 of the maximum output allowed for in calibration adjustment of each transducer. Each data sample (word) is made up of a 5-step gap, 2-step preamble, 91-step data block (2 steps per 8-bit register times 44 inputs, plus 3 steps for the clock), and a 1-step longitudinal character check. This provides a total of 99 4-bit steps for each sample (the recorder has 4 tracks and 4 bits are recorded for each 3·3 ms step) and is the maximum allowable word length. Two modes of sampling, continuous and discrete, were available; in this study the discrete mode was used. For a discrete sampling mode two channels were sampled twice a second and for each start up of the recorder, 2047 samples were taken. The individual records were 17 minutes long, giving 14 records for each cassette. The mode of operation required that the recorder was initiated when the wind speed reached a definite level (20 mph); sampling then continued for one minute and if the wind speed persisted at over 20 mph, then the system was turned on and 2047 samples taken. After one hour the wind speed was checked and if over 20 mph then the process was repeated. This continued until the wind speed dropped below 20 mph.

The 44 channels were utilized as follows:

2 - wind speed and direction (W1, W2)

2 - wave pressure transducers (P1, P2)

4 - anchor cable displacements (A1-A4)

18 - horizontal trunnion strains (1HL1-4HL1, 1HT1-4HT1, 3HL2, 4HL2, 3HT2, 4HT2, 3HRL1-3HRL3, 3HRT1-3HRT3)

12 - vertical trunnion anchor rod strains (1V1-4V1, 1V2-4V2, 3V3, 3V4, 4V3, 4V4) Fig. 1 shows the in-place arrangement.

3 - center lock strains (C1-C3)

1 - end lock strain (L1)

2 - support beams of vertical trunnions strains (S1, S2).

These are marked on Fig. 2..

FIELD RESULTS AND ANALYSIS

The field results consisted of 429-68 minute records collected over the 1974-78 period of study. Such a collection was comprised of

a) wind speed, direction and duration

b) strains on the horizontal trunnions, vertical anchors, locks and support beams located as shown in Fig. 2.

The readings were only taken for wind speeds over 20 mph and were treated in the following manner:

1) The mean of the wind speed and direction in each hourly interval was computed.

2) The maximum, minimum, mean and standard deviations of the strains were computed in each interval.

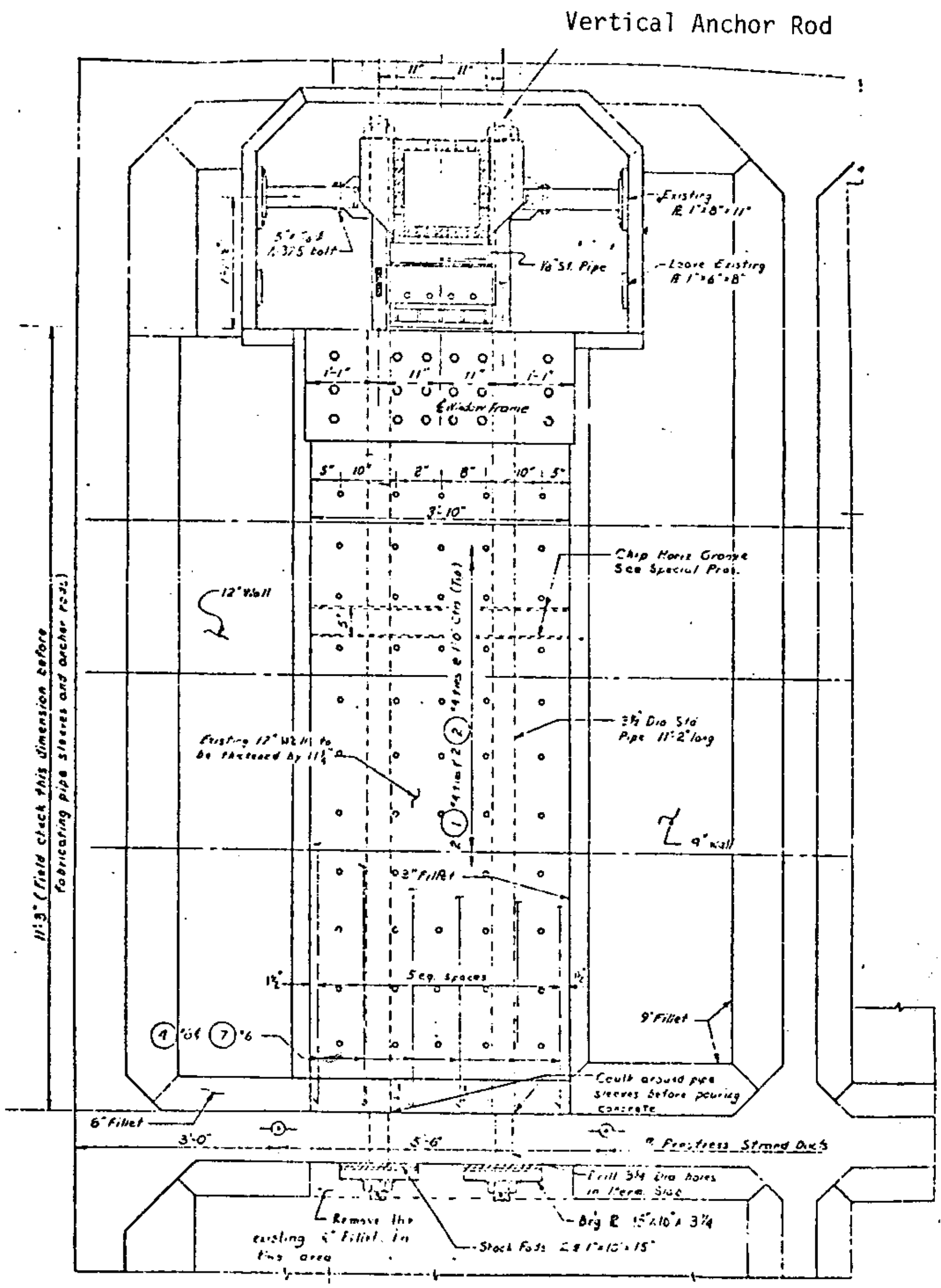
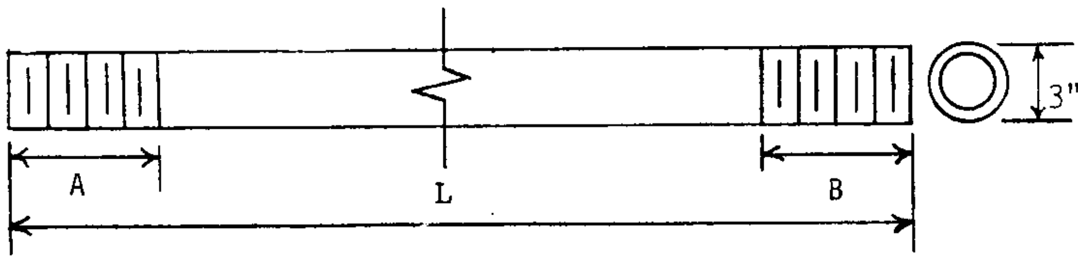
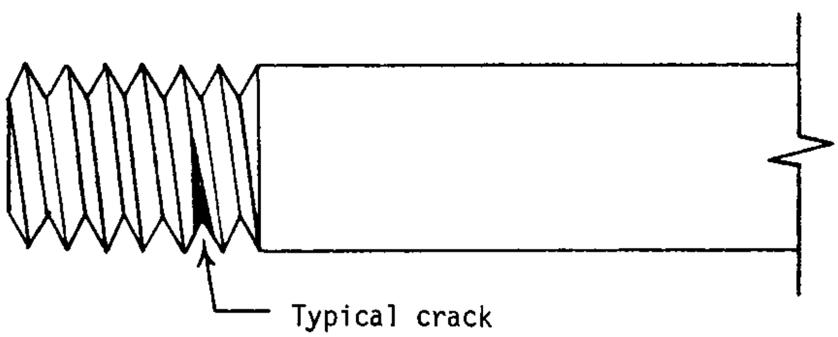



Fig. 1a - Vertical Anchor Rod Location.




Schematic View




| | Machined Threads | | Rolled Threads |
|---|---|---|---|
| L | 15' - 3-3/4" | to | 16' - 7" |
| A | 6" | | 6" |
| B | 6" | | 15" |
| Threads | 3-4UNC-2A | | 3-8UN-2A |

Fig. 1b - Details of Vertical Anchor Rod.

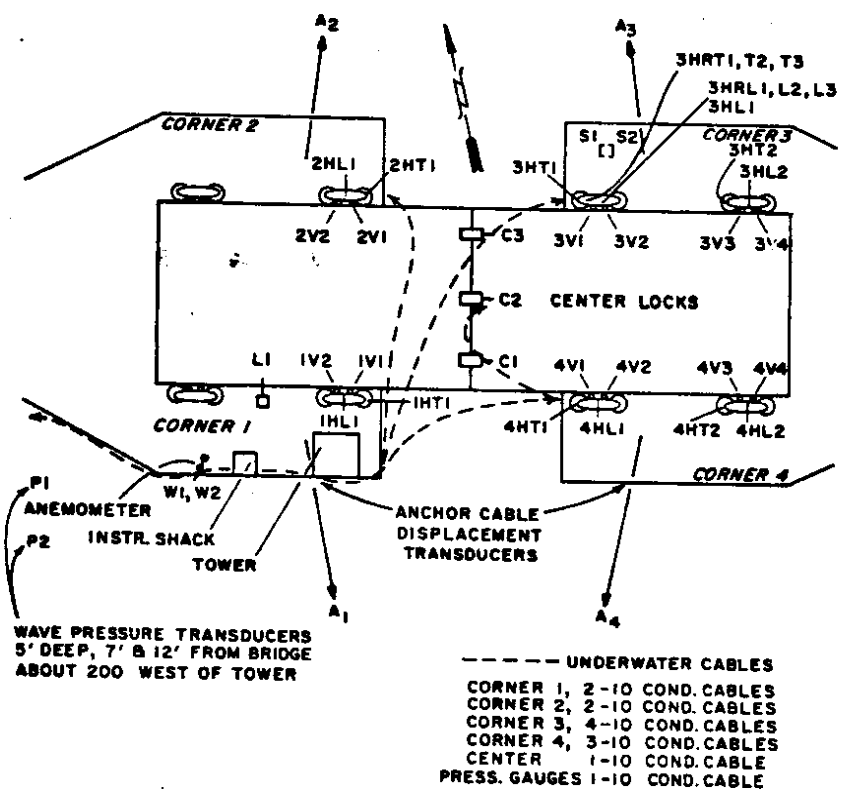



Figure 2 - Location Key

In order to determine a relationship between wind and strain the above results were included in regression analyses for the vertical trunnion anchorage rods. The form of the first regression was

$$y = c + mx + nz \qquad (2)$$

where

$y$ = |max-min| strain

$x$ = mean wind speed

$z$ = wind direction relative to the normal to the longitudinal bridge axis (radians)

$m, n, c$ are regression constants

The results are shown in Table 1. R is the multiple correlation coefficient

| Member | R | c | m | n |
|---|---|---|---|---|
| 1V1 | .672 | -923 | 49.9 | |
| 2V1 | .641 | -847 | 45 | |
| 3V1 | .600 | -552.7 | 29.6 | |
| 3V3 | .487 | -375.6 | 19.4 | |
| 4V1 | .486 | -335.8 | 24.3 | |
| 4V3 | .470 | -526 | 25.8 | .43 |

Table 1. Regression Results for Vertical Anchorage Results (|max-min| strain versus wind speed and direction)

for a zero mean system, where,

$$R = \sum \frac{\varepsilon^2{}_m}{\varepsilon^2{}_c} \qquad (3)$$

and $\varepsilon_m$ and $\varepsilon_c$ are the measured and computed |max-min| strains.

Similar regression analysis was performed where

$y$ = standard deviation of strain

Then the results of Table 2 were obtained where $\varepsilon_m$ and $\varepsilon_c$ are the standard deviation of strain in the calculation of R.

| Member | R | c | m | n |
|---|---|---|---|---|
| 1V1 | .705 | -151.4 | 6.95 | .112 |
| 2V1 | .681 | -120.1 | 6.09 | |
| 3V1 | .696 | - 79.4 | 4.03 | |
| 3V3 | .529 | - 45.2 | 2.22 | |
| 4V1 | .633 | - 87.7 | 5.03 | |
| 4V3 | .646 | - 58.9 | 3.16 | |

Table 2. Regression Results for Vertical Anchorage Rods (standard deviation of strain versus wind speed and direction).

The correlations provided can be compared to the correlation between the strains of adjacent anchorage rods of 0.99. Similar analyses were carried out using z = Ln (mean wind speed) and y = Ln (wind direction). The results did not improve the correlations.

The horizontal trunnions were analysed in the same manner. The results are included in the Fourth Annual Report but are excluded here inasmuch as no fatigue characteristics for the members were obtained.

Only 196 of the 429 records were employed in the regression analyses. The excluded records were those which were non-stationary in the wind and the strain. Such non-stationary conditions occur at the beginning of the storms where transient behavior was involved. To remove these records the first two hours of each storm record were deleted. This amounted to 168 deletions for the 84 storms included in the 429-68 minute records. Additionally, deletions were made of records with mean wind speeds under 20 mph and when wind and strains did not increase or decrease together.

The duration of storms is given in Table 3. This provided for 84 storms and gives the mean wind speed, duration in hours and maximum gust speed. The average storm duration was 4.712 hours.

| Mean Wind Speed (m.p.h.) | Duration (hrs) | Maximum Gust (m.p.h.) |
|---|---|---|
| 20.42 | 1 | 31.9 |
| 24.88 | 1 | 31.3 |
| 27.82 | 5 | 37.6 |
| 21.82 | 5 | 32.9 |
| 18.18 | 1 | 29.0 |
| 27.43 | 3 | 38.3 |
| 23.92 | 6 | 31.6 |
| 23.29 | 1 | 35.4 |
| 23.92 | 5 | 35.4 |
| 19.57 | 3 | 31.6 |
| 25.31 | 3 | 32.5 |
| 24.99 | 3 | 39.6 |
| 21.90 | 3 | 40.8 |
| 25.52 | 1 | 37.0 |
| 28.71 | 1 | 38.0 |
| 29.54 | 5 | 44.0 |
| 26.48 | 7 | 37.6 |
| 26.16 | 2 | 45.0 |
| 26.39 | 7 | 45.3 |
| 26.16 | 6 | 44.0 |
| 28.66 | 13 | 50.4 |
| 16.27 | 6 | 38.6 |
| 19.46 | 7 | 41.2 |
| 29.72 | 11 | 40.8 |
| 31.42 | 2 | 45.0 |
| 15.63 | 6 | 24.2 |
| 13.72 | 1 | 17.5 |
| 16.75 | 2 | 19.8 |
| 19.30 | 2 | 26.2 |
| 17.39 | 2 | 24.5 |
| 23.29 | 1 | 37.0 |
| 17.39 | 2 | 25.2 |
| 17.23 | 2 | - |
| 14.99 | 1 | 19.5 |
| 29.41 | 11 | 66.5 |
| 26.16 | 2 | 33.5 |
| 19.14 | 5 | 30.3 |
| 17.74 | 5 | 32.5 |
| 16.27 | 1 | 21.7 |
| 26.43 | 7 | 45.9 |
| 17.04 | 12 | 27.1 |
| 16.67 | 4 | 29.1 |
| 19.32 | 14 | 43.7 |
| 17.16 | 14 | 27.1 |
| 15.63 | 2 | 29.7 |
| 14.67 | 1 | 17.5 |
| 15.63 | 1 | 21.1 |
| 15.79 | 2 | 21.7 |

(cont.)

Table 3. Storm Duration and Wind Speeds.

Table 3. (cont.)

| Mean Wind Speed (m.p.h.) | Duration (hrs) | Maximum Gust (m.p.h.) |
|---|---|---|
| 12.44 | 1 | 20.6 |
| 16.38 | 6 | 22.3 |
| 15.35 | 8 | 36.4 |
| 17.74 | 10 | 27.7 |
| 22.01 | 7 | 34.8 |
| 20.62 | 8 | 29.0 |
| 36.11 | 12 | 81.3 |
| 24.74 | 11 | 47.5 |
| 15.50 | 1 | 20.4 |
| 20.81 | 8 | 37.3 |
| 21.05 | 9 | 38.6 |
| 18.18 | 1 | 37.3 |
| 18.08 | 6 | 25.8 |
| 18.18 | 1 | 23.9 |
| 20.58 | 2 | 29.0 |
| 25.17 | 11 | 69.5 |
| 24.47 | 7 | 41.8 |
| 23.98 | 11 | 80.7 |
| 26.8 | 1 | 80.1 |
| 18.61 | 9 | 37.0 |
| 16.51 | 4 | 25.5 |
| 28.82 | 3 | 49.1 |
| 20.87 | 12 | 38.0 |
| 20.42 | 8 | 35.4 |
| 26.16 | 2 | 35.4 |
| 19.08 | 10 | 30.6 |
| 19.46 | 3 | 27.8 |
| 16.91 | 3 | 23.9 |
| 22.33 | 1 | 28.7 |
| 21.88 | 5 | 32.2 |
| 17.86 | 2 | 23.9 |
| 15.9 | 2 | 22.3 |
| 16.9 | 1 | 26.5 |
| 21.5 | 2 | 40.5 |
| 17.1 | 2 | 46.6 |
| 25.73 | 9 | 35.4 |

LONG-TERM WIND

Measurements at 8-hourly intervals were made on the Evergreen Point Bridge between March 1964 and June 1975. These 12150 results are listed in Table 4.

| Speed m.p.h. | Under 20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | over 70 |
|---|---|---|---|---|---|---|---|
| S | 2274 | 848 | 484 | 129 | 26 | 5 | 3 |
| SE | 1245 | 179 | 59 | 15 | 2 | | |
| SW | 774 | 264 | 124 | 36 | 6 | 3 | |
| E | 238 | 6 | 1 | | | | |
| W | 220 | 5 | 1 | | | | |

Table 4. Long Term Wind Speeds at Evergreen Point Bridge (8 readings at 8 hour intervals from March 1964 to June 1975).

S-N CHARACTERISTICS

The final aspects of eq. (1) are the S-N curve characteristics. These have been determined for the vertical trunnion anchorage rods with both rolled and machined threads. The conventional single maximum amplitude cyclic test would have been inappropriate with the six specimens of each thread type available. In its place the Prôt method (1948) with its extension by Basavaraju and Lim (1977) was used to generate two S-N curves with the specimens of each type tested.

In the Prôt method the amplitude of stress, S, is increased from zero at a rate $\mathring{S}$, until failure occurs at stress $S_d$ at $N_d$ cycles beyond crossing of the endurance limit $S_f$. For various $\mathring{S}$ and $S_d$ a relationship

$$S_d = S_f + K\,\mathring{S}^k \tag{4}$$

exists which allows the endurance limit, $S_f$, as well as the parameters K and k, to be found by using an iterative, non-linear, least squares regression fit routine.

The conventional S-N curve can be expressed in the form

$$(S-S_f)^m\,N = C \tag{5}$$

and Basavaraju and Lim (1977) developed relationships for m and C in terms of K and k. These are

$$m = \frac{1-k}{k} \tag{6}$$

and

$$C = k\, K^{1/k} \tag{7}$$

The assumptions for this method of obtaining S-N curves with very few specimens are:

1) The S-N curve and the $S_d$-$N_d$ curve are a higher order hyperbola asymptotic to the endurance limit, $S_f$, and the increasing stress axis at N = 0, and $N = N_d$, respectively.

2) no damage occurs for cycling at $N < N_d$ (or $S < S_f$).

3) Miner's hypothesis is valid.

Tests were at 1Hz and the loading replicated the bridge state of oscillating axial tension. The various rates $\mathring{S}$ obtained by maintaining the lowest value of S at each cycle as zero. The rods tested were 3" diameter and between 15'-3 3/4" and 16'-7" long. The material was AISI steel with a yield of 111.7 k.s.i. and an ultimate tension strength of 137.4 k.s.i. Six rods had machined 3-4 UNC-2A threads over the end 6". Six rods had cold rolled 3-8 UN-2A Threads over 6" at one end and 15" at the other. Table 5 shows the test results for the machined rods. Appendix C shows the properties of the rods.

| Specimen | $\mathring{S}$ (psi/cycle) | $S_d$ (ksi) |
|---|---|---|
| 1 | 4·567 | 31·719 |
| 2 | 2·634 | 30·281 |
| 3 | 1·365 | 25·531 |
| 4 | 0·771 | 22·656 |
| 5 | 0·467 | 19·438 |
| 6 | 0·237 | 16·719 |

Table 5. Fatigue Test Results for Machined Thread Rods.

From these results eq. (4) becomes

$$S_d = 16484 + 6280\ \overset{\circ}{S}^{.6342}$$

in units of psi and $S_f$ = 16484 psi. The parameters of eqs. (6) and (7) are m = 0.5768 and C = 618000, which lead to the S-N curve for eq. (5), namely

$$(S - 16484)^{.5768} N = 618000$$

where the units are psi.

Table 6 shows the test results for the rolled threads

| Specimen | $\overset{\circ}{S}$ (psi/cycle) | Sd (ksi) |
|---|---|---|
| 1 | 0.1262 | 40.522 |
| 2 | 0.0884 | 37.938 |
| 3 | 0.0624 | 36.225 |
| 5 | 0.0375 | 34.375 |

Table 6. Fatigue Test Results for Rolled Thread Rods

From these results eq. (4) becomes

$$S_d = 29000 + 42500\ \overset{\circ}{S}^{.6342}$$

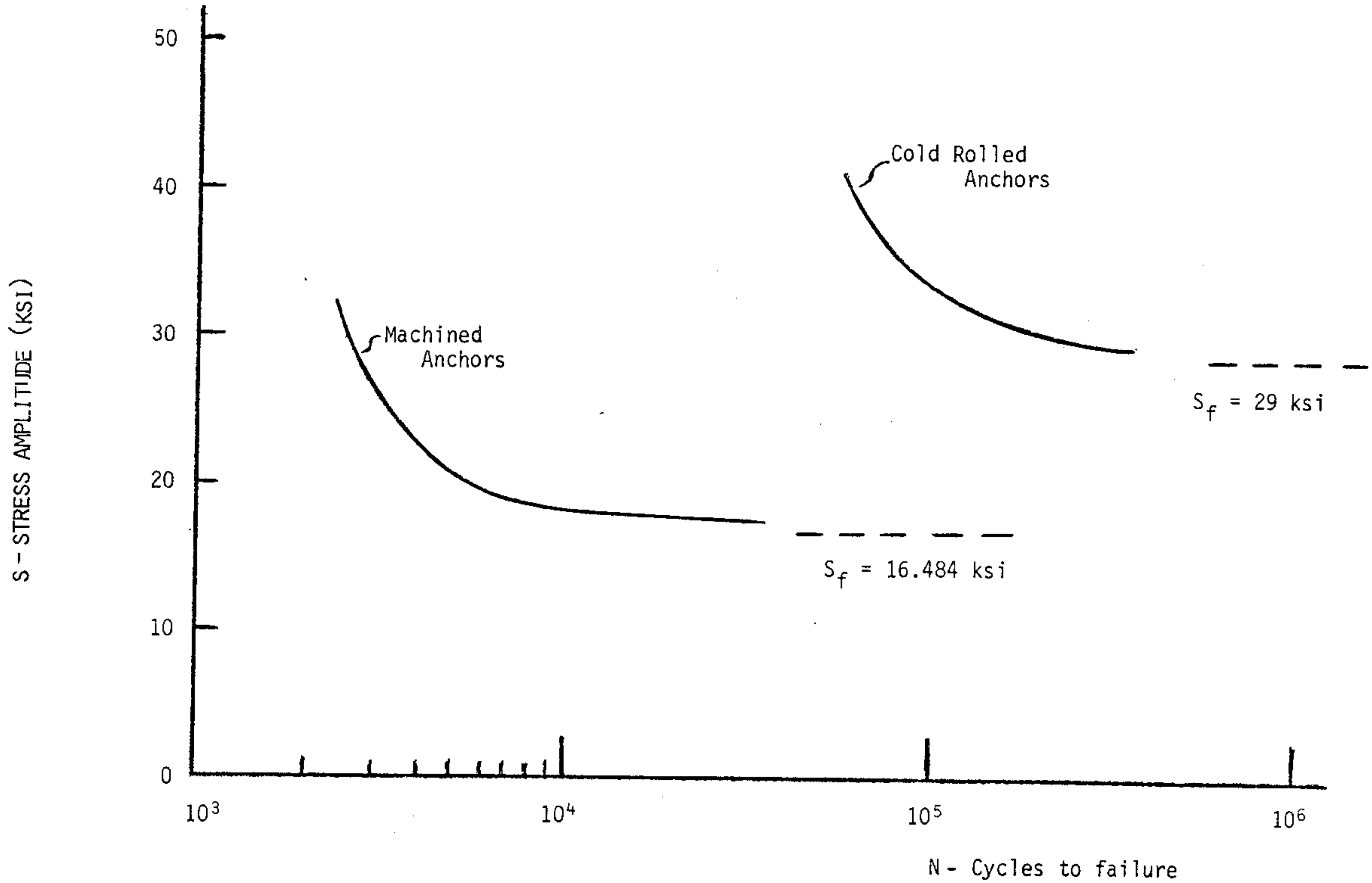
in units of psi and $S_f$ = 29000 psi. The parameters of eqs. (6) and (7) are m = 0.5768 and c= 12600000, which leads to the S-N curve for eq. (5), namely

$$(S - 29000)^{.5768}\ N = 12600000$$

where the units are psi.

Fig. 3 shows the S-N curves from these tests.

Specimen 4 of the rolled thread rods was tested at $\overset{\circ}{S}$ = 0.0435 and before $S_d$ had been reached, the testing device failed. Subsequent repair work involved the heating of the thread region of the rod and affected the metallurgy. For this reason that test was abandoned.




S-N CURVES FOR ANCHORS

FIG. 3

Specimen 6 was reduced in diameter by 0.05" over the end 18" inside the threads. This specimen was tested at $\mathring{S} = 0.056$ and at 690,000 cycles the rod had not broken. However, at that time the testing apparatus completely failed. Therefore, it can only be concluded that $S_d > 38{,}500$ psi.

STRUCTURAL LIFE

The previous information and analyses allow estimates of the structural life of the anchorage rods to be constructed. The S-N information provides the number of cycles, $N_i$, to failure at stress reversal amplitude $S_i$. It is necessary to develop the number of cycles encountered, $\tilde{n}_i$, on the anchorage rods at the stress amplitude, $S_i$. In this way a measure of damage

$$D_i = \frac{\tilde{n}_i}{N_i} \qquad (8)$$

can be made and failure estimated from Miner's hypothesis when

$$\sum_i D_i = 1 \qquad (9)$$

The first part of this determination of $n_i$ is to convert the long term wind data of Table 4 to long term strain information. This is accomplished by operating with the regression equations on the long term wind data. For instance two (2) records of wind speeds of between 50 and 60 m.p.h. (average 55 m.p.h.) from the south east exist for the 1964-75 period of Table 4. Using the standard deviation as a measure of strain then for member 1V1 the standard deviation of strain, $\varepsilon_D$, is, from eqn (2) and Table 2,

$$\varepsilon_D = -151{\cdot}4 + 6{\cdot}95x + 0{\cdot}112y$$

where x = 55 mph and $y = \pi/4$. Hence $\varepsilon_D = 230{\cdot}98 \times 10^{-6}$ and using a value of $E = 30 \times 10^3$ k.s.i., then $\sigma_D = 6{\cdot}928$ k.s.i. In this way the strains associated with the wind data of Table 4 can be computed. Using the standard deviations of the stresses, Table 7 is obtained and using |max-min| stresses, Table 8.

| Wind Speed (m.p.h.) | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 75 |
|---|---|---|---|---|---|---|
| 1V1 | .67 | 2.75 | 4.84 | 6.92 | 9.01 | 11.09 |
| 2V1 | .96 | 2.79 | 4.61 | 6.45 | 8.28 | 10.1 |
| 3V1 | .63 | 1.84 | 3.05 | 4.25 | 5.46 | 6.66 |
| 3V3 | .31 | .98 | 1.64 | 2.31 | 2.97 | 3.64 |
| 4V1 | 1.14 | 2.65 | 4.16 | 5.67 | 7.18 | 8.69 |
| 4V3 | .6 | 1.55 | 2.50 | 3.45 | 4.40 | 5.34 |

Table 7. Standard Deviation Stresses (k.s.i.) For Various Wind Speeds for Anchor Rods

| Wind Speed (m.p.h.) | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 75 |
|---|---|---|---|---|---|---|
| 1V1 | 9.73 | 24.7 | 39.67 | 54.65 | 69.6 | 84.6 |
| 2V1 | 8.34 | 21.8 | 35.34 | 48.84 | 62.34 | 75.84 |
| 3V1 | 5.62 | 14.5 | 23.38 | 32.26 | 41.14 | 50.02 |
| 3V3 | 3.28 | 9.10 | 14.92 | 20.74 | 26.56 | 32.38 |
| 4V1 | 8.15 | 15.44 | 22.72 | 30.02 | 37.31 | 44.60 |
| 4V3 | 3.57 | 11.31 | 19.05 | 26.79 | 23.53 | 42.27 |

Table 8. |max-min| Stresses (k.s.i.) for Various Wind Speeds for Anchor Rods

These results are nearly independent of the angle of attack.

The results for |max-min| stresses enclose $6\sigma_D$. This information provides some confirmation of the measurements and analyses inasmuch as $\pm 3\sigma_D$ should include over 99% of the occurences but the extremes should include 100% of the occurences. Table 9 shows the number of occurences in one year for each wind range and the stresses as $3\sigma_D$. The occurences are obtained by assuming the winds attacking from the south arc are independent of angle. Then in one year 1095 eight hourly intervals occur and the numbers of Table 4 are mulitplied by 1095/12150.

| Wind Speed (m.p.h.) | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 75 |
|---|---|---|---|---|---|---|
| occurences per year | 116.44 | 60.29 | 33.17 | 3.97 | .72 | .27 |
| $3\sigma_D$ for (ksi) | | | | | | |
| 1V1 | 2.01 | 8.25 | 14.52 | 20.76 | 27.03 | 33.27 |
| 2V1 | 2.88 | 8.37 | 13.83 | 19.35 | 24.84 | 30.3 |
| 3V1 | 1.89 | 5.52 | 9.15 | 12.75 | 16.83 | 19.98 |
| 3V3 | .93 | 2.94 | 4.92 | 6.93 | 8.91 | 10.92 |
| 4V1 | 3.42 | 7.95 | 12.48 | 17.01 | 21.54 | 26.07 |
| 4V3 | 1.8 | 4.64 | 7.50 | 10.35 | 13.20 | 16.02 |

Table 9. Number of Annual Occurences and Stresses ($3\sigma_D$, k.s.i.) for Various Wind Ranges and Anchor Rods.

The duration of the winds can be considered from the 84 storm occurences listed in Table 3. Dividing the maximum wind in each occurence into 10 m.p.h. intervals and ignoring the single hourly input which produced a 80.1 m.p.h. maximum, then the average duration for each range of maxima is as given in Table 10.

| Maximum Gusts (m.p.h.) | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 75 |
|---|---|---|---|---|---|---|
| Average Duration (hrs) | 2.89 | 4.76 | 5.71 | 8* | 8* | 8* |

Table 10. Storm Duration
* The 8 hourly readings of the long term data limit these results.

The process of eqn. (1) is narrow band and to determine the number of cycles sensed in a year the frequency for the wind speed range has to be determined. Here the modified Barnet formula.

$$\omega = k \; F^{-0.31} u^{-0.38}$$

is employed where k = 27.23, F is the fetch in feet, u the wind speed in ft/sec and $\omega$ the frequency in Hertz. The fetch is 3.4 miles and Table 11 provides the frequencies.

| Wind Speed (m.p.h.) | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 75 |
|---|---|---|---|---|---|---|
| Frequency (Hertz) | 0.216 | 0.194 | 0.180 | 0.169 | 0.160 | 0.153 |

Table 11. Member Frequency for Various Wind Speeds

The developed arguments allow the number of cycles in each wind range to be determined from the equation

$$n_i = \omega_i \cdot \alpha_i t_i$$

where $\omega_i$ is the frequency in Hertz, $\alpha_i$ the number of occurences in a year, $t_i$ the duration in seconds and $n_i$ the number of occurences in a year. Using Tables 9,10and 11, Table 12 is constructed.

| Wind Speed (m.p.h.) | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 75 |
|---|---|---|---|---|---|---|
| n (cycles) | 261671 | 200427 | 122731 | 19323 | 3318 | 1190 |

Table 12. Number of Cycles in a Year for Each Wind Range

In order to complete the picture of the damage incidence on the members it is necessary to determine the stress amplitude, $S_i$, associated with each wind speed range of Table 12 and each anchorage rod. Storms producing the wind speeds of Table 12 will incur member stresses varying from zero to over $3\sigma_D$ in amplitude. However, over 99% of these stresses will be included in $\pm\ 3\sigma_D$. Stresses below the endurance limit, $S_f$, will incur no damage. Interest must be focussed on the values of $S_f < \sigma < 3\sigma_D$ as damaging the member. Stresses greater than $3\sigma_D$ are infrequent and are ignored. As an estimate, the value of stress amplitude in each wind storm range will be taken as $\frac{(3\sigma_D + S_f)}{2} = S_i$. Here $3\sigma_D$ is obtained from Table 9. Table 13 is constructed from Table 9 for rods with machined threads where $S_f$ = 16.484 k.s.i.

| Wind Speed (m.p.h.) | 50-60 | 60-70 | 75 |
|---|---|---|---|
| Occurences per year ($n_i$) | 3.97 | .72 | .27 |
| $S_i = (3\sigma_D + S_f)/2$ for (k.s.i.) | | | |
| 1V1 | 18.62 | 21.78 | 24.88 |
| 2V1 | 17.92 | 20.66 | 23.39 |
| 3V1 | | | 18.23 |
| 4V1 | 16.75 | 19.01 | 21.28 |

Table 13. Yearly Occurences ($n_i$), stress amplitude ($S_i$) for Various Wind Speeds and Anchor Rods with Machined Threads

Using the formula for fatigue S-N curve developed earlier for rods with machined threads,

$$N_i = \frac{617746}{(S_i - 16484)^{0.5768}} \quad ,$$

the value of $N_i$ for each $S_i$ in Table 13 can be computed or obtained from Fig. 2. In this way Table 14 is assembled.

| Wind Speed (m.p.h.) | 50-60 | 60-70 | 75 |
|---|---|---|---|
| $n_i$(from Table 12)/year | 19323 | 3318 | 1190 |
| $N_i$ for | | | |
| 1V1 | 7419 | 4393 | 3368 |
| 2V1 | 9327 | 5039 | 3770 |
| 3V1 | | | 8333 |
| 4V1 | 24668 | 6734 | 4652 |

Table 14. $N_i$ and $n_i$ for Various Wind Speeds and Anchor Rods with Machined Threads

Eqn. (8) and (9) allow the life of the members to be estimated. For each member failure will occur when $\sum_i \frac{n_i}{N_i} = 1$. As an example, for member 1V1:

$$\sum_i \frac{n_i}{N_i} = \frac{19323}{7419} + \frac{3318}{4393} + \frac{1190}{3368} = 3.71$$

Hence, the life is 1/3.71 = 0.27 years. Completing such calculations on all the members the life expectancy of Table 15 is computed.

| Member | Life (years) |
|---|---|
| 1V1 | 0.27 |
| 2V1 | 0.33 |
| 3V1 | 7 |
| 3V3 | Indefinite |
| 4V1 | 0.65 |
| 4V3 | Indefinite |

Table 15. Estimated Life of Anchor Rods with Machined Threads

A similar procedure may be adopted for the rods with rolled threads. Here, $S_f$ = 29000 psi and Table 16 is constructed with this value for $S_f$ and the information in Table 9

| Wind Speed (m.p.h.) | 75 |
|---|---|
| Occurrences/year ($n_i$) | .27 |
| $S_i = \frac{(3\sigma_D+S_f)}{2}$ | |
| for (ksi) | |
| 1V1 | 31.14 |
| 2V1 | 29.65 |

Table 16. Yearly Occurrences ($n_i$), Stress Amplitude ($S_i$) for Various Wind Speeds and Anchor Rods with Rolled Threads

Using the formula for the fatigue S-N curve developed earlier for rods with rolled threads

$$N_i = \frac{12600000}{(S_i-29000)^{0.5768}} ,$$

then Table 17 is obtained

| Wind Speed (m.p.h.) | 75 |
|---|---|
| $n_i$ (from Table 12)/year | 1190 |
| $N_i$ for | |
| 1V1 | 151143 |
| 2V1 | 300526 |

Table 17. $N_i$ and $n_i$ for Various Wind Speeds and Anchor Rods with Rolled Threads

As before the life expectancy can be calculated as given in Table 18

| Member | Life (years) |
|---|---|
| 1V1 | 127 |
| 2V1 | 252 |
| 3V1 | Indefinite |
| 3V3 | Indefinite |
| 4V1 | Indefinite |
| 4V3 | Indefinite |

Table 18. Estimated Life of Anchor Rods with Rolled Threads

## DISCUSSION

The final results in Tables 15 and 18 show the marked advantages of rods with cold rolled threads as opposed to the machined variety. Essentially the anchorage rods with cold rolled threads will be safe from fatigue damage in the lifetime of the bridge; the machined threaded rods will be vulnerable. This confirms the wisdom of the Washington State Highway Commission in replacing rods with machined threads with ones with rolled threads. However, it must be pointed out that although there is extensive literature on the superiority of rolled threads for use with bolts in the aircracft industry, the recent work by Frank (1980) shows no such advantage for structural anchor bolts. Frank's experiments were obtained by uniform amplitude stress repetitions; those reported here were for uniform monotonically increasing amplitude stress cycles. These results were then converted to the conventional S-N format by the arguments of Prôt. It must be admitted that the non-linear iterative regression scheme did not lead to unique values of K and k in eq. (4). However, k = 0.6342 appeared the best value for the machined threaded case and the K = 6280 followed from this value of k. In the rolled case, other values of k were possible in the range $0.5 \leq k \leq 0.8$ and these lead to $27000 \leq S_f \leq 31000$ psi. In all cases $S_f$ was much larger than for the machine threaded case. The actual comparison in the report used k = 0.6342 for both cases.

An additional feature difference between the machined and rolled threads in these experiments was the threaded description. The machined threads had a larger pitch and were coarser.

The Prôt procedure is attractive if a small number of specimens are available. The complete verification of the process does not exist. However, for comparison purposes it is an excellent measure of fatigue capacity.

The test on the rod with a reduced shank was not completed to failure. The partial result does indicate that this feature could lead to superior structural fatigue performance.

## CONCLUSION

The methods developed provide useable maintenance procedures for prevention of fatigue failure of critical structural elements. Particularly, the development of the Prôt method will allow the construction of a S-N curve for a structural element based on very few tests. On site short term measurements of strain and wind will provide the basis for the wind : stress relation. Long term wind data can be introduced to give long term S-N curves which may be compared to the S-N results to determine the fatigue life of the elements.

## REFERENCES

Basavaraju, C. and C. Lim, (1977), An Analytical Approach to Determine Conventional S-N Curves from Accelerated-Fatigue Data, Experimental Mechanics, 17, 10, 375-380.

Bright, A. (1977), A Comparison of Fatigue Theories and Design Recommendations for Fatigue, M.S.C.E. Thesis, University of Washington.

Frank, K. H. (1980), Fatigue Strength of Anchor Bolts, Journal of the Structural Division, A.S.C.E, 106, ST 6.

Prôt, E. (1948), Fatigue Testing Under Progressive Loading, a New Technique for Testing Materials, Revue de Metallugie, 45, 481-489 (Translation, WADG TR-52-148, 1952).

# APPENDIX A

## STATISTICS OF STRAIN MEASUREMENTS

This appendix lists the statistics of measurements on strain from 196 stationary records. It also displays the location of the various gauges. The units are in micro-strain ($10^{-6}$).

| VARIABLE | MEAN | VARIANCE | MIN. | MAX. |
|---|---|---|---|---|
| VERTICAL TRUNNION ANCHOR RODS (Fig. A1) | | | | |
| 1V1 | 368.274 | 82836.4 | 52.92 | 1106.9 |
| 2V1 | 319.119 | 70823.8 | 0 | 1099.8 |
| 3V1 | 215.041 | 32785.1 | 15.8 | 802.6 |
| 3V3 | 126.964 | 17320.8 | 0 | 802.6 |
| 4V1 | 292.846 | 27130.5 | 37.65 | 938.7 |
| 4V1 | 207.986 | 32714.7 | 30.12 | 935.0 |
| SUPPORT BEAMS OF VERTICAL TRUNNIONS (Fig. A2) | | | | |
| S1 | 37.546 | 1902.23 | 6.99 | 270.3 |
| S2 | 58.115 | 2394.58 | 5.85 | 265.6 |
| HORIZONTAL TRUNNIONS (Fig. A3) | | | | |
| 1HL1 | 6.52913 | 320.463 | 0 | 189.9 |
| 1HT1 | 1.75132 | 19.1668 | 0 | 42.5 |
| 2HL1 | 23.7087 | 10.48 | 0 | 178.5 |
| 2HT1 | 1.6369 | 17.13 | 0 | 50.2 |
| 3HL1 | 9.032 | 214.26 | .89 | 123.1 |
| 3HT1 | 1.4641 | 7.851 | 0 | 31.7 |
| 3HL2 | 10.879 | 205.09 | .93 | 11.3 |
| 3HT2 | 1.4195 | 7.425 | .24 | 31.1 |
| 3HRL1 | 2.6779 | 18.14 | .26 | 29.0 |
| 3HRL2 | 3.4217 | 71.00 | 0 | 65.4 |
| 3HRL3 | 2.6726 | 20.91 | 0 | 26.9 |

| VARIABLE | MEAN | VARIANCE | MIN. | MAX. |
|---|---|---|---|---|
| HORIZONTAL TRUNNIONS (Cont'd.) | | | | |
| 3HRT1 | 1.6254 | 8.17 | 0 | 26.2 |
| 3HRT2 | 1.8787 | 9.01 | 0 | 25.2 |
| 3HRT3 | 2.0484 | 22.65 | 0 | 32.8 |
| 4HL1 | 17.814 | 541.98 | .95 | 136.4 |
| 4HT1 | 2.0588 | 12.34 | .36 | 40.1 |
| 4HL2 | 11.496 | 329.32 | 0 | 122.8 |
| 4HT2 | 1.625 | 11.08 | 0 | 36.7 |

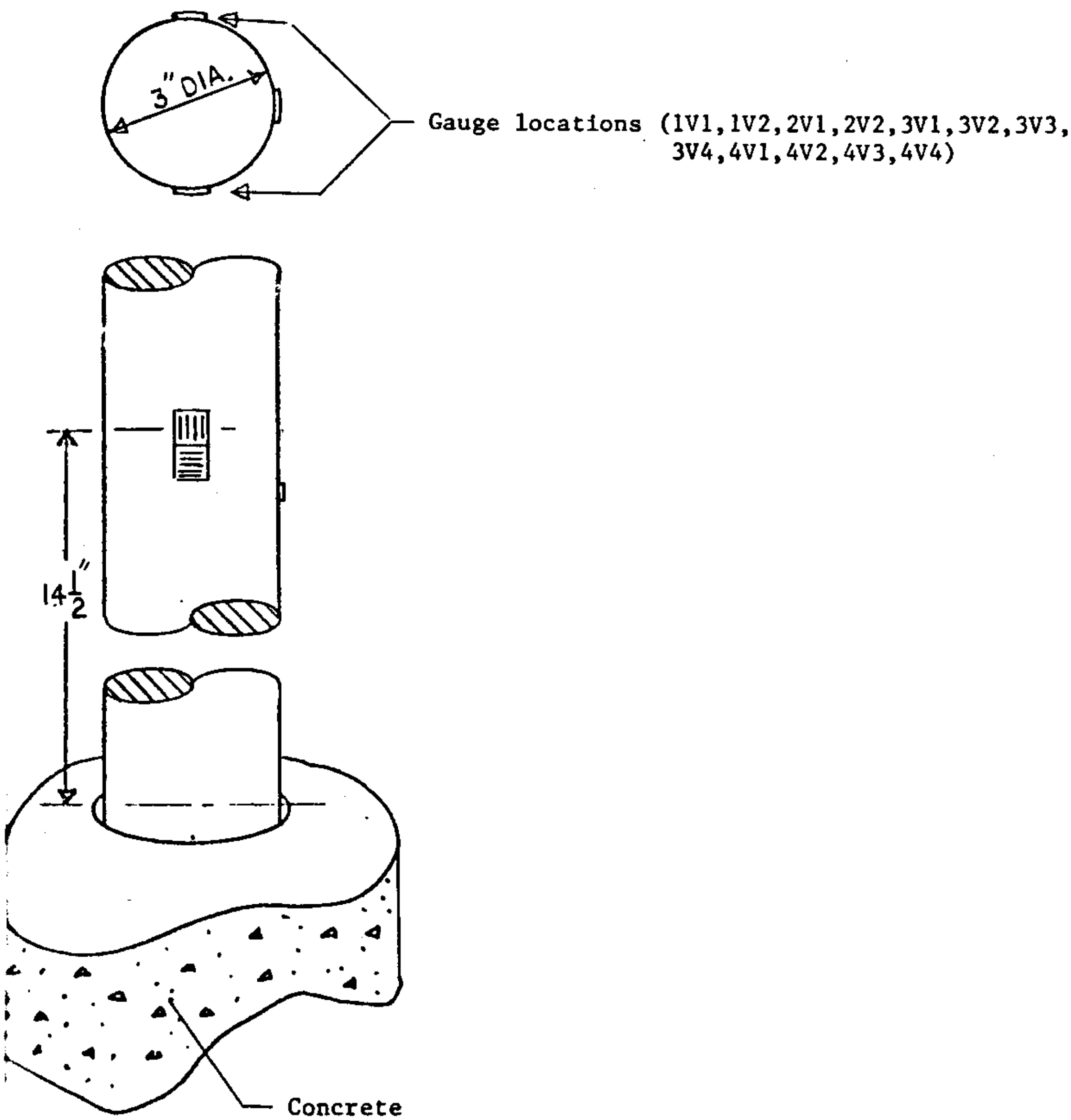



Fig. A1 - Location of Gauges on Vertical Trunnion Anchor Rods.

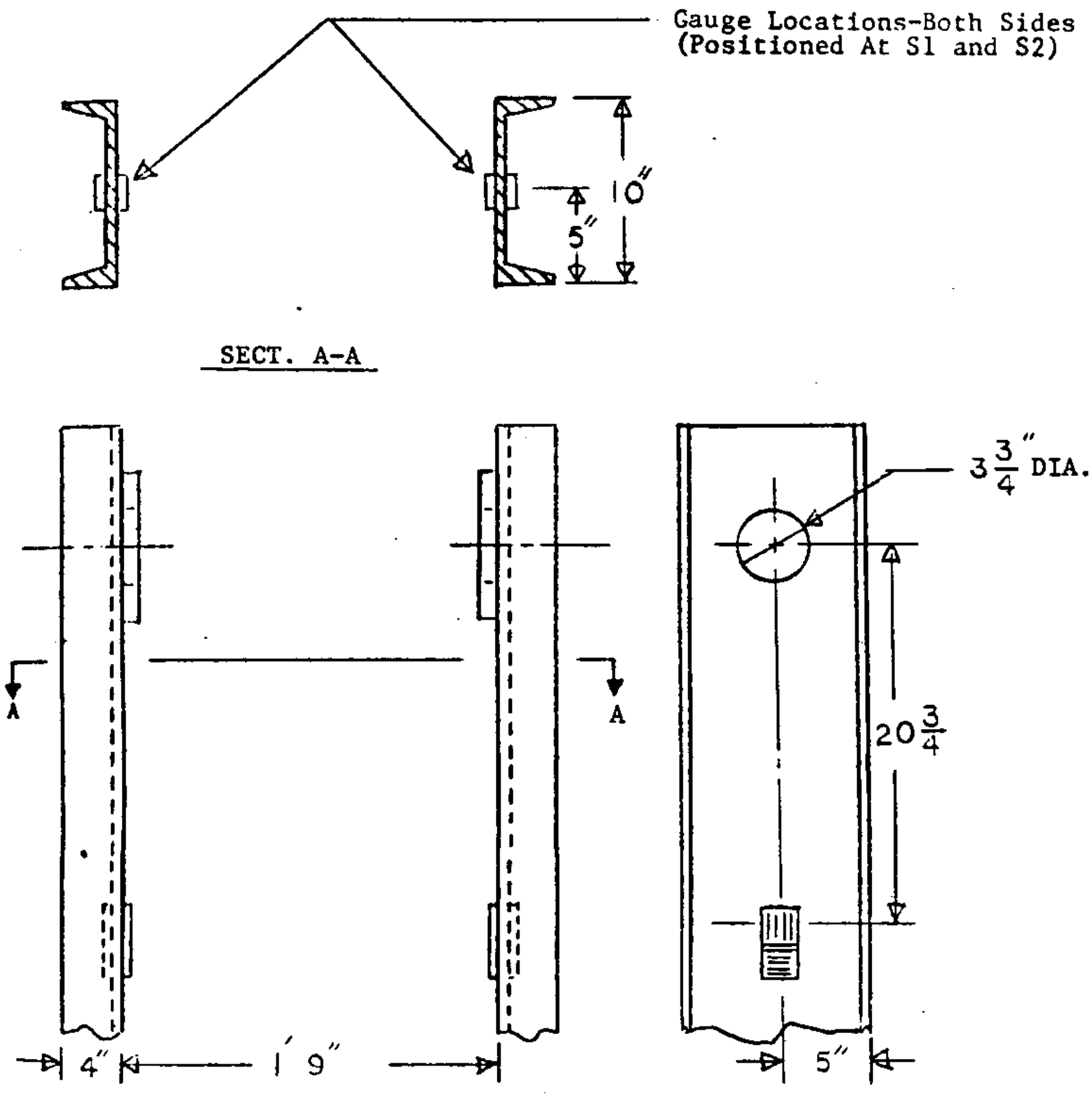



Fig. A2 - Location of Gauges on Support Beams of Vertical Trunnions.

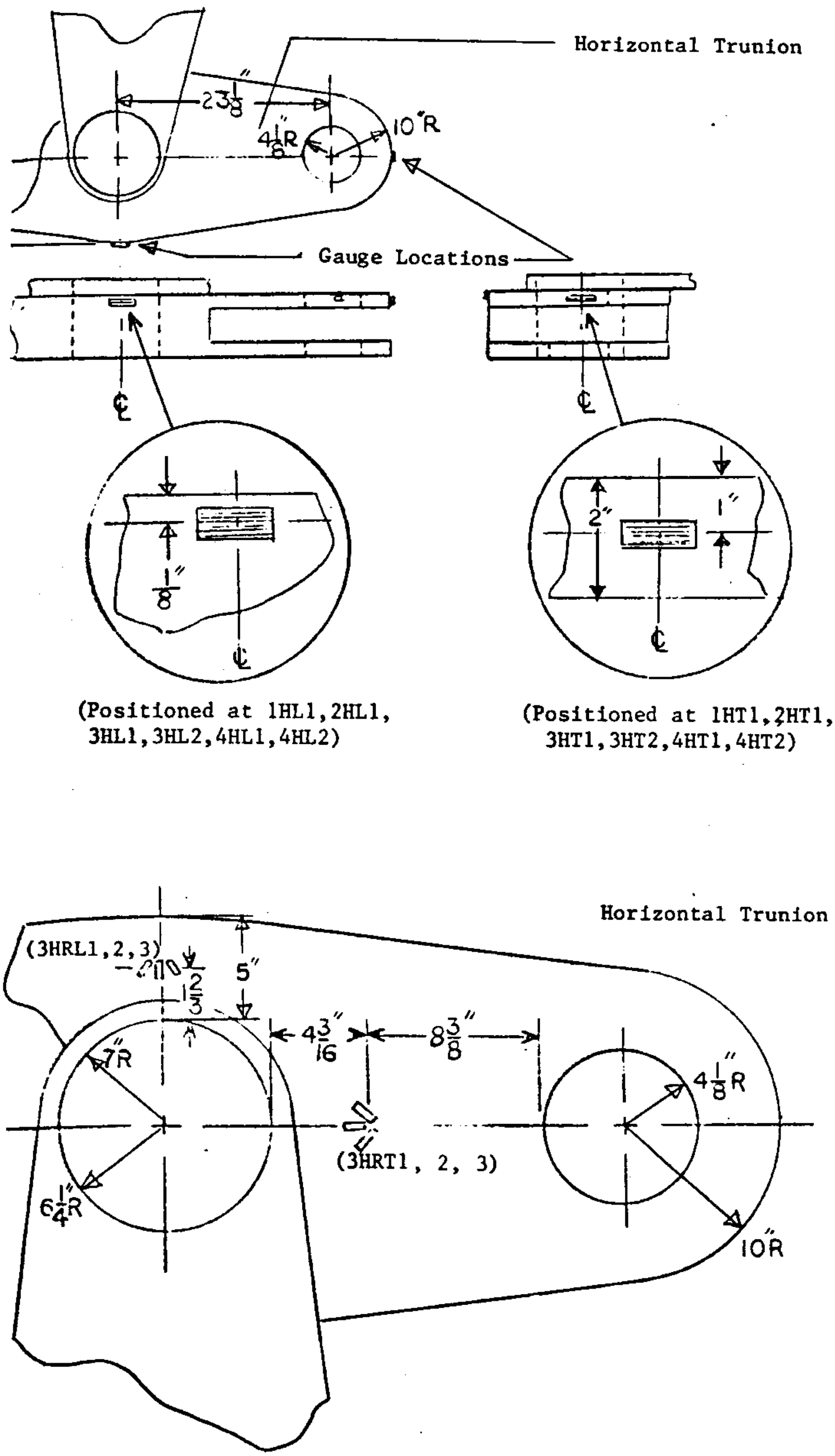



Fig. A3 - Location of Gauges on Horizontal Trunnions.

# APPENDIX B

## FATIGUE LIFE EQUATION

Equation (1) is

$$T_f = \left[ \sum_i \frac{\omega_i \alpha_i t_i}{N_i} \right]^{-1} \qquad \text{B 1}$$

where $\omega_i$ is the frequency (Hertz), $\alpha_i$ the number of occurrences in a year and $t_i$ the duration of such an occurrence (seconds) at an applied oscillatory stress amplitude $S_i$ , and $N_i$ the number of cycles to cause failure at that amplitude. From equations (8) and (9), Miner's hypothesis gives the damage at $S_i$ as

$$D_i = \frac{\tilde{n}_i}{N_i} \qquad \text{B 2}$$

and failure as

$$\sum_i D_i = 1 \qquad \text{B 3}$$

where $\tilde{n}_i$ is the number of cycles at $S_i$ encountered in the field in the life of the element. If

$$\tilde{n}_i = n_i \; T_f \qquad \text{B 4}$$

where $n_i$ is the number of cycles in a year at $S_i$ encountered in the field and $T_f$ the number of years to failure, then

$$D_i = \left( \frac{n_i}{N_i} \right) T_f \qquad \text{B 5}$$

and

$$T_f = \left[ \sum_i \frac{n_i}{N_i} \right]^{-1} \qquad \text{B 6}$$

In order to determine $n_i$ the process was assumed to be narrow banded around some natural frequency $\omega_i$ for the element, which varied with $S_i$. As $S_i$ was related to wind speed (as for instance in Table 9), therefore $\omega_i$ was related to wind speed by observation and the modified Barnet formula (Table 11). The average length of occurrence at the wind speed of interest from 84 storm occurrences is tabulated in 10. This gives $t_i$ the duration in seconds at $S_i$ from Table 9. The number of occurrences of the wind speed of interest in a year is given in Table 9. Again, this is related to $S_i$, as is $N_i$. Hence

$$n_i = \alpha_i w_i t_i \qquad \text{B 7}$$

and from B 6 and B 7 the equation (1) is recovered.

# APPENDIX C.

## MATERIAL OF ANCHOR RODS

| | | |
|---|---|---|
| Summerville Steel Company Reports<br>Machine Threaded Ends. | —— | 1974 |
| Cardinal Foundary & Suppy Company<br>Rolled Ends. | —— | 1976 |

# Cardinal

**FOUNDRY & SUPPLY COMPANY**

THREADING DIVISION

5200 HARVARD AVENUE + PHONE 216 / 341-5700
CLEVELAND, OHIO 44105

TO:

WASHINGTON DEPT OF HIGHWAYS
10833 Northrup Way N. E.
Bellevue Washington 98004
Attn: L. Waite

**REPORT OF CHEMICAL AND PHYSICAL TEST**

### DESCRIPTION OF MATERIAL AND SPECIFICATIONS

| ITEM NO. | QUANTITY | DESCRIPTION | CUSTOMER ORDER NO | OUR ORDER NO | SPECIFICATION | SHIPPING DATE |
|---|---|---|---|---|---|---|
| 1 | 10 | 3" - 8 x 17' B7 | F624089 | CF 22239 | ASTM A193 B7 | 7/30/76 |
| | | Double end stud | | | | |
| | | 6" Thread one end | | | | |
| | | 15" Thread one end | | | | |

### CHEMICAL ANALYSIS

| ITEM NO. | GRADE | HEAT NO | C | Mn | P | S | Si | Ni | Cr | Mo | V | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A-4140 | 193704 | .42 | .93 | .018 | .025 | .26 | | .98 | .19 | | |

### MECHANICAL PROPERTIES

| ITEM NO. | TENSILE STRENGTH PSI | YIELD STRENGTH PSI | PROOF LOAD LBS | ELONGATION PERCENT IN 2" | PER CENT RED AREA | HARDNESS BHN | HARDNESS R/C | MINIMUM TEMPERING TEMP |
|---|---|---|---|---|---|---|---|---|
| 1 | 137,400 | 111,740 | | 19.5 | 58.4 | 280 | | 1100°F |

Modulus of Elasticity = $31.25 \times 10^6$ psi

CARDINAL FOUNDRY & SUPPLY CO.

Quality Control Supervisor

NOTARIAL SEAL — CUYAHOGA COUNTY, OHIO

18th AUG 76

RICHARD R. [illegible]

# TEST REPORTS

## Summerville Steel Company

1061 6TH AVENUE SOUTH — SUMMERVILLE SS STEEL Company — SEATTLE WASHINGTON 98134

CUSTOMER: NORTHERN MANUFACTURING CO.

ADDRESS: 301 S. WEBSTER

CITY: SEATTLE, WASH. 98108

CUSTOMER'S ORDER NO. 3176

OUR NO. 2 15 19

DATE SHIPPED

| | MATERIAL DESCRIPTION | SPECIFICATION | COLOR IDENT. | SIZE | WEIGHT |
|---|---|---|---|---|---|
| 1. | 4 BARS HR 4140 HT | A 193 ASTM GRADE B-7 | ½ PURPLE ½ WHITE | 3" RD. 20'R | |
| 2. | | | | | |
| 3. | | | | | |
| 4. | | | | | |

## CHEMICAL ANALYSIS

| | MILL AND HEAT NUMBER | C | MN | P | S | SI | CR | NI | MO | VA | CU | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | CRUCIBLE 3103117 | .42 | 1.00 | .021 | .019 | .29 | 1.05 | | .19 | | | |
| 2. | | | | | | | | | | | | |
| 3. | | | | | | | | | | | | |
| 4. | | | | | | | | | | | | |

## PHYSICAL PROPERTIES

| | YIELD LBS/SQ IN | TENSILE STRENGTH LBS./SQ. IN. | PER CENT ELONGATION | RED IN AREA PER CENT | BRINELL | GRAIN SIZE | ROCK | JOMINY 16THS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | /16 | /16 | /16 | /16 |
| 1. | 11[illegible],300 | 137,075 | 19.5 | 62.4 | 269 | | | | | | |
| 2. | | | | | | | | | | | |
| 3. | | | | | | | | | | | |
| 4. | | | | | | | | | | | |

The Summerville Steel Company hereby certifies that the above information is taken from chemical and metallurgical reports on file at our office.

SUMMERVILLE STEEL COMPANY

By *E. E. Anderson*

E. E. ANDERSON 2-15-74

# GILMORE STEEL CORPORATION

RECORD OF PHYSICAL and CHEMICAL TESTS

CUSTOMER: Northern Manufacturing
ADDRESS: 301 South Webster
CITY and STATE: Seattle, Wa 98104

DATE: 2-15-74
CUSTOMER'S ORDER NO. 3176
OUR ORDER NO. 8-82349

| ITEM | PRODUCER | HEAT NUMBER | Yield Point Lbs. Per Square inch | Tensile Strength Lbs. Per Square inch | % Elong. Inch. | RED. % | BEND TEST | HOMO TEST |
|---|---|---|---|---|---|---|---|---|
| 12 Bars 4140 ASTM-A193/Gr.B7<br>1 3" Rd. H.R. HT & SR<br>Leaded x 20'R | REpublic Steel | 321738 | 113,500 | 135,000 | 20.0 | 60.1 | | |
| 2 | | | | | | | | |
| 3 | | | | | | | | |
| 4 | | | | | | | | |
| 5 | | | | | | | | |
| 6 | | | | | | | | |
| 7 | | | | | | | | |

| CHEMISTRY | CARB | MANG | PHOS | SUL | SIL | NI | CR | MO | CU | V | | BHN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 321738 | .38 | .88 | .015 | .029 | .30 | .23 | 1.03 | .19 | | | | SURFACE 285-293<br>BHN/R 285-277 |
| 2 | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | |



Gilmore Steel Corporation

Shirley Hogan

Shirley Hogan

[illegible]tify [illegible] above [illegible] ma[illegible] be C[illegible] to [illegible] Best of [illegible] Know[illegible] and [illegible]

# APPENDIX D.

## ANNUAL PROGRESS REPORTS

First Annual Report, 1975

This report completely describes the instrumentation on the bridge. Pages 4-17 show the location of all strain gages, displacement transducers and wind gages. The justification for these positions is also provided. Appendix A* involves the design and construction of the data recording system. This commences with statements of desiderata and then examines the viable alternatives. The actual system utilized is shown to have advantages.

Pages 4-17 and Appendix A* give a complete account of the instrumentation, calibration and recording system employed on the bridge for four years. All of these features are synthesized in this Final Report.

The remainder of the 1975 report involves initial data collection and preliminary analytical schemes. These schemes were not utilized in the final assessment. The data are included in the later annual reports and the statistics are constructed in this Final Report.

Second Annual Report, 1976

This report reflects a year of data gathering on the bridge together with the completion of programs to analyze these data. The programs are listed in Appendix B* (page 18) and include

Initial tape conversion

Data re-arrangement and selection

FFT coefficient computation

In Appendix C* (page 19) the statistics for all tapes obtained are listed. These results are included in later reports and synthesized in this Final Report.

*Annual Report Appendix

Also included in Appendix A*(page 17) is a copy of the paper entitled, "Evergreen Point Bridge Maintenance Problems," by C. B. Brown, D. Christiansen and G. Demich, which was presented at the National Structural Engineering Conference, A.S.C.E., Madison, Wisconsin, 1976.

Third Annual Report

This report for 1976-77 reflects the data gathering, new instrumentation and analytical work.

This was a year of calms and though continual operation of the measurement and recording system was maintained, little data were made available. Such data, combined with that previously obtained, are provided in Appendix A*of this report.

New instrumentation included an array of pressure transducers.

An analytical scheme was completely developed. This scheme has been fundamental to the final analysis used and given in this Final Report. However, simplifications have been included where possible.

Fourth Annual Report

This was a productive year. A complete collection of field data was made. It was reduced statistically and displayed in Appendix A*of the report. This Appendix shows the field data from the whole of the project. They are synthesized in this Final Report. These involve 422 hourly events, of which 351 occurred in the 1977-78 season. Appendix A*is stored separately because of the filing room required.

The basis for the project is the validity of Miner's hypothesis. This is justified in the report.

*Annual Report Appendix

The development of the Prôt approach to generate S-N fatigue information and full details of the design and construction of the fatigue tests apparatus for the anchorage rods are provided. Results for machine threaded rods (S-N curve) are reported. All of this information is given in this Final Report.

Subsequent Work

This Final Report includes subsequent S-N results for roll threaded rods and completes the life expectancy predictions.