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16. Abstract

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A FATIGUE STUDY OF PRESTRESSING STRAND

by

Conrad Paulson, Jr.
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and
John E. Breen

Research Report No. 300-1

Research Project 3-5-80-300
"Fatigue Strength of Prestressed Concrete"

Conducted for

Texas
State Department of Highways and Public Transportation

In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This is an interim report on Project 3-5-80-300, "Fatigue of Prestressed Concrete Girders," sponsored by the State Department of Highways and Public Transportation of the State of Texas, and the Federal Highway Administration. It was administered by the Center for Transportation Research. The research was conducted at the Phil M. Ferguson Structural Engineering Laboratory, Balcones Research Center, The University of Texas at Austin, Austin, Texas.

The dedicated staff of the Ferguson Laboratory are thanked for their assistance in the project. George Moden, Dan Perez, and Richard Marshall helped fabricate, assemble, and calibrate the equipment. Maxine DeButts and Laurie Golding helped with project administration. Gorham Hinckley helped to obtain many of the needed tests and devices and helped with the assembly of the load frame. Blake Stasney, undergraduate assistant Dan Boyles, and graduate students Chi-Kao Hsu and Farrel Zwerneman helped run many of the tests.

Liaison with the Texas State Department of Highways and Public Transportation was maintained through their contact representative, Mr. A. B. Matejowsky. Mr. D. E. Harley was the contact representative for the Federal Highway Administration. Their help in obtaining test specimens and suggestions during the testing is greatly appreciated.

SUMMARY

This study reviews the literature which reports on fatigue studies of prestressing strand and also presents the results of a series of strand fatigue tests. The fatigue tests compared tests on samples of strand from several manufacturers with tests on a sample of strand to be used in construction of girder fatigue specimens. Strand fatigue data from the literature and from the tests were combined to form a strand fatigue data base which was analyzed using regression analysis techniques. A stress range vs. fatigue life curve for prestressing strand was developed and was used as the basis for a strand fatigue design equation. The design equation was compared with current AASHTO code provisions for fatigue of structural steel and was found to lie midway between Category A and Category B curves for redundant structures.

Category B is recommended for checking the allowable fatigue stresses in uncracked girders. Designing to this category provides an extreme lower bound to all the strand data collected and should ensure no fatigue problems regardless of the size, strength, and relaxation properties of the strand. Girders which are cracked and then subjected to fatigue loads may produce fatigue failures at much lower strand stress ranges than Category B. Recommendations for cracked girders will be developed from the girder tests to be performed as part of the research project.

The results also indicate that Category B is satisfactory for designing strand tension systems, such as cable stays, when considering the life of the strand. The fatigue performance of the socketing or grip system must be evaluated separately.

IMPLEMENTATION

The results of this study indicate that the fatigue of strand is different for different manufacturers and also among the strand from one manufacturer. In addition, the fatigue strength of a test specimen decreases with specimen length. In current prestressed girder construction, no fatigue requirements are imposed on the strand. Therefore, the fatigue performance of the strand used in girders is unknown. In order to provide a conservative fatigue design stress for the strand, a lower bound approach must be taken which accounts for the variability of fatigue performance due to manufacturing variables and length of sample. The AASHTO Category B fatigue design stresses provide the necessary conservative lower bound and are recommended for checking the performance of strand in uncracked girders. The current ACI Committee 215 recommendations for uncracked girders are that the strand stresses be kept below 10% of f_{pu}, or 27 ksi for Grade 270 strand. This is assumed to be a fatigue limit recommendation; that is, a stress range which causes no fatigue damage. Our recommendation that uncracked girder fatigue be treated by using AASHTO Category B fatigue design steel stresses for redundant load path structures provides a conservative design recommendation which meshes with overall highway structure design practices. Unlike the ACI Committee 215 recommendations, application of the AASHTO Category B values allows higher variable stresses for lightly traveled secondary bridges and lower stresses for heavily traveled major routes. It must be emphasized that these values are only for uncracked girders. If there is any reasonable probability that the girders will be cracked in service, much lower limits may be necessary. Current research is underway to further clarify such provisions.

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NOTATION

f'_c	Concrete compressive strength.
f_{conv}	See Note 2 of Table 2-1.
f_{pu}	Ultimate tensile stress of prestressing strand.
K	Factor for tolerance limit for normal distributions.
Log N	Log of fatigue life.
$\overline{\text{Log N}}$	Arithmetic mean of Log N values.
N	Fatigue life in number of cycles.
R	Stress interval defined as $S_{max} - S_L$.
S	A stress level in general.
s_{LogN}	Standard deviation of Log N.
S_L	Fatigue limit at a specfic S_{min} value.
S_{max}	Level of maximum stress.
S_{min}	Level of minimum stress.
S_r	Stress range; $S_r = S_{max} - S_{min}$.

Chapter 1

INTRODUCTION

Engineering applications of prestressing have existed in the U. S. since the late 1800's. The first primitive application to concrete occurred in the 1880's [22]. Advancement of prestressed concrete engineering was carried out between 1925 and 1945 by several Europeans, most notably Freyssinet, Hoyer, and Magnel. In the U. S., the milestone event marking the beginning of the use of mass-produced prestressed concrete was the construction of the Walnut Lane Bridge in Philadelphia in 1948. During the years since Walnut Lane, prestressed concrete construction in the U. S. has expanded rapidly. Applications of prestressed concrete include not only bridge structures, but also building components (wall panels, beams, and floor systems), tanks, containment vessels, pavements, piles, and foundation systems.

Perhaps the most visible prestressed concrete product is the pretensioned girder, as used in highway bridges. These bridges, like any other highway bridge, are subject to repeated heavy truck loading and occasional overloading. Thus, fatigue is a potential problem in these bridges.

Lane and Ekberg [21] attribute it to T. Y. Lin for observing that:

> Fatigue. . . of prestressed concrete may be studied from three approaches: That of concrete itself, that of high tensile steel, and that of the combination of both.

All three approaches have been covered in published literature. In the next section, comments and conclusions from part of the literature will be reviewed and compared. In the next chapter, those studies which have adopted the second approach will be reviewed in more detail.

1.1 Prestressed Concrete Fatigue: Some Historical Notes

One of the earliest studies of fatigue of prestressed concrete bridge structures was by P. W. Abeles [2]. He studied three composite slabs, typically used for railway bridges in Great Britain, pretensioned with high-strength wire. In his conclusions, Abeles mentions that where the bond between the wire and the concrete was good, was continuous, and did not degrade, fatigue had little effect on the static behavior of the structure, even after millions of cycles of loading; and that where the bond is "interrupted," there will be an "early fracture" of the wire at that location.

In the U.S., Ozell and Diniz [29] tested in fatigue six rectangular beams pretensioned with 1/2 inch strands. All but one failed by fatigue of the strand, with lives varying from 186,000 to 2,441,000 cycles. The authors state: "The cracks in the concrete acted as stress raisers and the consequent stress concentrations in the strands contributed to the fatigue failure of the wires at those points."

At about the time the Ozell and Diniz report was published (1958), the first tests in the U.S. on prestressing strand as an isolated element were being conducted. Nuwaysir (as mentioned by Lane and Ekberg [21]) performed a pilot study aimed at developing a method by which strands as isolated elements could be fatigued. Lane and Ekberg, using Nuwaysir's methods, continued on to develop a set of S-N curves and a fatigue envelope for one million cycles. At the conclusion of their tests, the total number of strand fatigue data points available in the U.S. was about forty.

The first major strand investigation, in terms of numbers of specimens, was reported by Warner and Hulsbos [36], who tested over 60 specimens. Tests included constant cycle tests and cumulative damage tests. The latter tests led the authors to say that

> . . .beam loadings which cause flexural cracks to open should not shorten fatigue life provided the stresses induced in the strand are smaller than the fatigue limit.

This quote runs somewhat counter to the quote of Ozell and Diniz, who seem to feel that repeated opening of cracks will eventually result in strand fatigue failure.

A significant girder test involving multiple specimens of a larger scale was reported in 1970. Hanson, Hulsbos, and VanHorn [17] studied the fatigue behavior of six precast, pretensioned half-scale I-beams. The beams were first loaded statically so that inclined cracks occurred in the beams, and then repeated loading was applied to the beams. The authors state:

> All test beams reported herein sustained without damage 2,000,000 cycles of repeated [design] loading, producing a maximum tensile stress up to $6\sqrt{f'_c}$. . . The test beams failed when the maximum load in the repeated load cycles was subsequently increased, so that the tensile stress was greater than $8\sqrt{f'_c}$. . .

Failures in four out of the six beams were due to fatigue of the strand. One beam failed by fatigue of the shear reinforcement. The remaining beam suffered both strand and shear fatigue damage, with failure attributed to strand fatigue.

During the early 1970's, several published strand test reports came from Europe. Cullimore [10] studied stress levels in the long life region of the S-N curve and found that there was no endurance limit which assured non-failure in less than ten million cycles. Although it is not stated directly, the author seems to be implying that a fatigue limit does not exist.

Edwards and Picard [12] reported at about the same time the results of 189 strand specimens, including some with applied lateral loads. They comment that "free air" strand tests can be used to predict beam fatigue life if the effects of the length of the constant moment region and of cracks in the concrete are accounted for. A 20 percent reduction of free air test results is suggested as a reasonable estimate of those effects.

Rabbat, et al [30], fatigue-tested six full-size Type II AASHTO-PCI girders with a cast-in-place slab. Two of the beams had draped strands; the remaining four had blanketed (debonded) strands. Three of the girders (one with draped strands, two with blanketed strands) were tested under repeated loads causing a maximum stress of zero tension in the precompressed tensile zone, while the remaining girders (again, one with draped strands, the other two with blanketed strands) were tested under repeated load causing a maximum stress of $6\sqrt{f'_c}$ tension in the precompressed tensile zone. In their conclusions, the authors state: "The fatigue life of specimens for a tensile stress of $6\sqrt{f'_c}$ under full service load was significantly less than that of specimens designed for zero tension." The girders with zero tension lasted 5,000,000 cycles with no sign of fatigue damage; the three girders with a tension of $6\sqrt{f'_c}$ failed by fatigue in the strands with lives from 3,200,000 to 3,700,000 cycles.

The results of the tests by Rabbat, et al, conflict with the results of Hanson, Hulsbos, and VanHorn, which showed that fatigue failures occur only when the tensile stresses exceed $6\sqrt{f'_c}$. However, it is doubtful that the two test series can be directly compared. The earlier tests (Hanson, Hulsbos, and VanHorn) were on half-scale I-beams, without deck slabs. The latter tests (Rabbat, et al) used full-scale I-girders with a composite deck slab. The effect of scale, cross section geometry, and materials is potentially significant. Differences in losses, strain gradient, stresses in the strand, and fatigue properties of the strand all could have an effect on the fatigue lives observed.

Additionally, it is not known what would have happened if the earlier tests had maintained the $6\sqrt{f'_c}$ stress levels beyond 2,000,000 cycles. It is conceivable that failure could have been observed at about the same time as the latter tests, just beyond 3,000,000 cycles.

A curious observation can be noted. It is the authors of reports about strand tested as an isolated element who recommend ways of dealing with fatigue of strand at cracks in beams. Yet the authors of reports on beam tests say little about the matter, other than reporting their observations that cracked beams (which are loaded to open the cracks repeatedly) eventually fail.

1.2 Prestressed Concrete Fatigue: The Present Status

For all of the research conducted on fatigue of prestressing strand and of prestressed concrete, there is surprisingly little mention of prestressed fatigue in code provisions, materials standards, or committee reports. At the present time, none of the codes (AASHTO Specifications [1], ACI-318-77 [5]) or standards (ASTM A416-80 [6]) directly addresses the problem of prestressing strand fatigue, whether it is strand as a part of a prestressed concrete member or strand as a structural member in itself (i.e., stay cables, suspension hangers).

One committee report does mention the problem. ACI Committee 215 [4] provides some guidance for strand in prestressed concrete. Recently, the recommendations were revised to distinguish between cracked and uncracked members [18].

1.3 Objectives

In an effort to compile information from the literature and to develop more information where needed, research on fatigue of prestressed, pretensioned concrete girders was undertaken at The University of Texas at Austin. The study was sponsored by the Texas State Department of Highways and Public Transportation (SDHPT) and the Federal Highway Administration. The overall scope of the project includes strand fatigue tests and girder fatigue tests. Only the strand tests are included in this report.

The next chapter is a more detailed review of literature concerned with fatigue studies of prestressing strand as an isolated element. Fatigue data are collected from the various references and a data base of strand fatigue information is built. Included is an evaluation of the published data.

The two subsequent chapters report the fatigue studies of prestressing strand conducted at The University of Texas as a part of the research on fatigue of prestressed girders. Strand samples were obtained from several prestressed concrete product manufacturers who supply girders to the SDHPT. The samples represent six different strand manufacturers. Reported are fatigue tests on these samples and also fatigue tests on a sample from the coil of strand used in construction of the girder specimens. The girder specimens' strand fatigue results are compared with the fatigue results of the other strand samples to characterize the girder specimens' strand in relation to strand used in the field.

The final chapters present an analysis of strand fatigue data and the conclusions and recommendations from the study. The data from the fatigue tests conducted at The University of Texas are added to the data base developed in the early part of this report. Several regression analyses are performed using the information in the data base. The analyses are used to characterize the effects of minimum stress and strand type on fatigue life. Information useful to the design engineer is developed and is compared with code provisions for fatigue of structural steel and with the committee recommendations for fatigue of prestressed concrete. The design information is directly applicable to stay cables and suspension hanger cables which use prestressing strand, and it is shown how the design information could be applied to fatigue of uncracked prestressed girders. Recommendations concerning the direction of future research are made.

Chapter 2

PREVIOUS TESTS INVOLVING SEVEN-WIRE PRESTRESSING STRAND

As part of the research project on the fatigue of prestressed concrete, a literature search was conducted. The first section of this chapter reviews the literature which involved studies of seven-wire strand as an isolated component. The last part of the chapter is devoted to an examination of the data found in these references and to a preliminary analysis of the data.

2.1 Review of Previous Tests

The literature reviewed in this section represents fatigue tests conducted on over 700 individual specimens of seven-wire prestressing strands. Nearly all published U.S. tests and several major European tests are included.

It is necessary to establish some terms used in this review. The individual pieces of data are one of two kinds: failure data points and non-failure data points. Their definitions are as their names imply: failure points are specimens which failed during testing; non-failure points are cases where the testing of the individual specimen was halted before the specimen failed.

Stress values can be expressed in three different ways: as absolute stresses and as two different indexed stresses. Absolute stresses are in terms of ksi, kPa, etc. Indexed stresses are expressed as a fraction or percent of the strand's ultimate stress. There are two different indexed values because there are two different ultimate stresses: the minimum specified ultimate stress (the strand's grade value or the catalog strength) and the actual ultimate stress as determined by tests on specimens.

In this report, stresses will be restricted to absolute stresses. In the literature review which follows, some exceptions were made when the particular author being reviewed used a different convention. The motivation to use just one convention was based on practicality: it avoided the cumbersome problem of running three sets of parallel computations in the analysis portion of this report. Absolute stresses were chosen because some authors of the reviewed literature did not provide enough information to translate from their stress convention to the other stress conventions. For the instances where the stresses are reported as indexed values, the appropriate ultimate stress value used to convert from indexed stress to absolute stress is shown as f_{conv} in Table 2-1.

To handle all of the data, an accounting system was developed. The data from each reference were separated into replicate groups (all data in a replicate group are specimens which were tested under identical conditions) and each group was given a three-digit identificaton number. Table 2-1 indicates which groups are associated with which reference, in addition to summarizing characteristics of the strands tested. Table A-1 of Appendix A lists group numbers, corresponding absolute stress levels, and, if appropriate, indexed stress levels for the various references. Table A-2 of Appendix A gives the lives of the data points for the various groups. Not all data points from every reference were used. In general, only data points which the original authors used for analysis in their papers are listed. Any data points which the original authors rejected are not listed in the appendix.

2.1.1 <u>Nuwaysir.</u> The earliest fatigue tests conducted in the U.S. on individual strand specimens are mentioned in a report by Lane

References	Group Numbers	Strand Diameter (inch)	Grade (ksi)	F_{pu} (ksi) (Note 1)	**	F_{conv} (ksi) (Note 2)	Number of Specimens (Note 3)
Nuwaysir (Note 4)	101-104	7/16	250	---	B	250.0	7/11
Lane and Ekberg [21]	151-163	7/16	250	---	B	250.0	16/45
Slutter and Ekberg [33]	201	1/2	250	270.	A	---	2/2
Fisher and Viest [13]	251-256	3/8	250	270.4	A	---	18/18
Warner and Hulsbos [36]	301-313	7/16	250	264.4	C	264.4	67/120
Hilmes [19]	351-355	7/16	250	257.	A	---	47/56
Tide and VanHorn [34]	401-493	1/2	270	---	B	270.0	156/178
Cullimore [10]	501-506	0.6	---	246.8	A	---	37/59
Edwards and Picard [12]	551-558	1/2	---	274.3	C	274.3	53/189
Muller and Zeller [23]	701-709	1/2	256.1	---	A	---	13/21
	711-719	0.6	256.1	---	A	---	14/20

(Continued)

Table 2-1: Summary of Published Tests

References	Group Numbers	Strand Diameter (inch)	Grade (ksi)	F_{pu} (ksi) (Note 1)	**	F_{conv} (ksi) (Note 2)	Number of Specimens (Note 3)
Storebaelt Bridge [32]	751-753	0.6	---	---	A	---	5/5
Frank and Hsu [15,16]	801-813	0.6	---	---	A	---	29/42

** A - Reference reports absolute stresses.
B - Reference reports stresses indexed to strand grade.
C - Reference reports stresses indexed to actual ultimate stress.

Note 1: Actual ultimate stress based on tests of the strand used in the fatigue tests, as reported in the references.

Note 2: These are the values used to convert from the indexed values reported in the references to the absolute stresses listed in Appendix A.

Note 3: The first number is the number of specimen tests, taken from the particular reference, which are listed in Appendix A of this report. The second number is the total number of specimen tests reported in the reference.

Note 4: As mentioned by Lane and Ekberg [21].

Table 2-1 (Concluded)

and Ekberg [21]. They state that "In 1956 a series of pilot tests was conducted by F. S. Nuwaysir to determine the best methods for [fatigue] testing strands. . ." Nuwaysir's test equipment and gripping methods are not described, but it is implied that his methods were used by Lane and Ekberg. (The test equipment and gripping methods used by Lane and Ekberg are described in Section 2.1.3.)

Lane and Ekberg also provided a summary of Nuaysir's results. The summary indicates that 15 Grade 250 specimens were tested: 13 were 7/16 inch diameter; the remaining two were 1/2 inch diameter. Of the 13 smaller diameter strands, 7 were used to construct a S-N (stress vs. life in cycles) curve for a minimum stress (S_{min}) of 0.556 f_{pu} (139.0 ksi). The data used to construct the curve are the points listed in Appendix A.

2.1.2 Slutter and Ekberg. In conjunction with fatigue tests on three full-scale railway bridge slabs, Slutter and Ekberg [33] report the results of some strand fatigue tests. Samples of the strand used in the beams (1/2 inch diameter, Grade 250) were tested. Static tests indicated an ultimate stress of 270 ksi. The reported lives of the two fatigue specimen tests indicate that these strands were the two 1/2 inch strands tested by Nuwaysir, but there is a discrepancy in the stress levels as reported by the two sources. The data listed in Appendix A are based on the information provided by Slutter and Ekberg. The strand fatigue test machine is not described, but the authors describe the gripping method:

> To provide a satisfactory means of loading the wire into the testing machine, the ends were gripped in mild-steel pipes, partly by action of wedge anchorages and partly by bond with high-strength cement-mortar grout.

Slutter and Ekberg give a number of conclusions and some recommendations for future research. Two notable conclusions were:

> Design should be based on having no tensile stress in the bottom fiber of concrete. . .
>
> No warning of impending fatigue failure of prestressed concrete beams can be expected other than the opening and closing of cracks. However, if no visible cracks occur under load, no danger of fatigue failure exists.

The authors recommend research towards development of ". . .a S-N diagram for the combination of steel and concrete in flexure."

2.1.3 Lane and Ekberg. Nuwaysir's study was the foundation work for Lane and Ekberg's own series of fatigue tests [21]. They studied both fatigue and creep (under repeated loading) of prestressing strand. For the fatigue tests, they studied 45 Grade 250 specimens: 13 were 3/16 inch diameter, the remainder were 7/16 inch diameter. Of the specimens tested, 27 had been tested under varying conditions in an effort to optimize the testing method, and thus were not used by the authors in any analysis. The remaining 18 specimens, all 7/16 inch diameter, were felt by the authors to be valid data points. These data points are listed in Appendix A. Lane and Ekberg's testing frame is shown in Figure 2-1 and the gripping method is shown in Figure 2-2.

The data points were used to develop two S-N curves, one at $S_{min} = 0.545\ f_{pu}$ (136.3 ksi) and the other at $S_{min} = 0.625\ f_{pu}$ (156.3 ksi). The authors stated that their curve and Nuwaysir's curve were in good agreement. They also developed a failure envelope at one million cycles for 7/16 inch strand. In their concluding remarks, they commented on the need to improve the building code specifications pertaining to fatigue of prestressing steel, as practical guidance for the design engineer was essentially non-existent.

2.1.4 Fisher and Viest. In conjunction with the AASHO Road Test project, Fisher and Viest [13] reported on fatigue of bridge materials which included 18 specimens of 3/8 inch diameter seven-wire prestressing strand. The test frame and gripping method were similar to

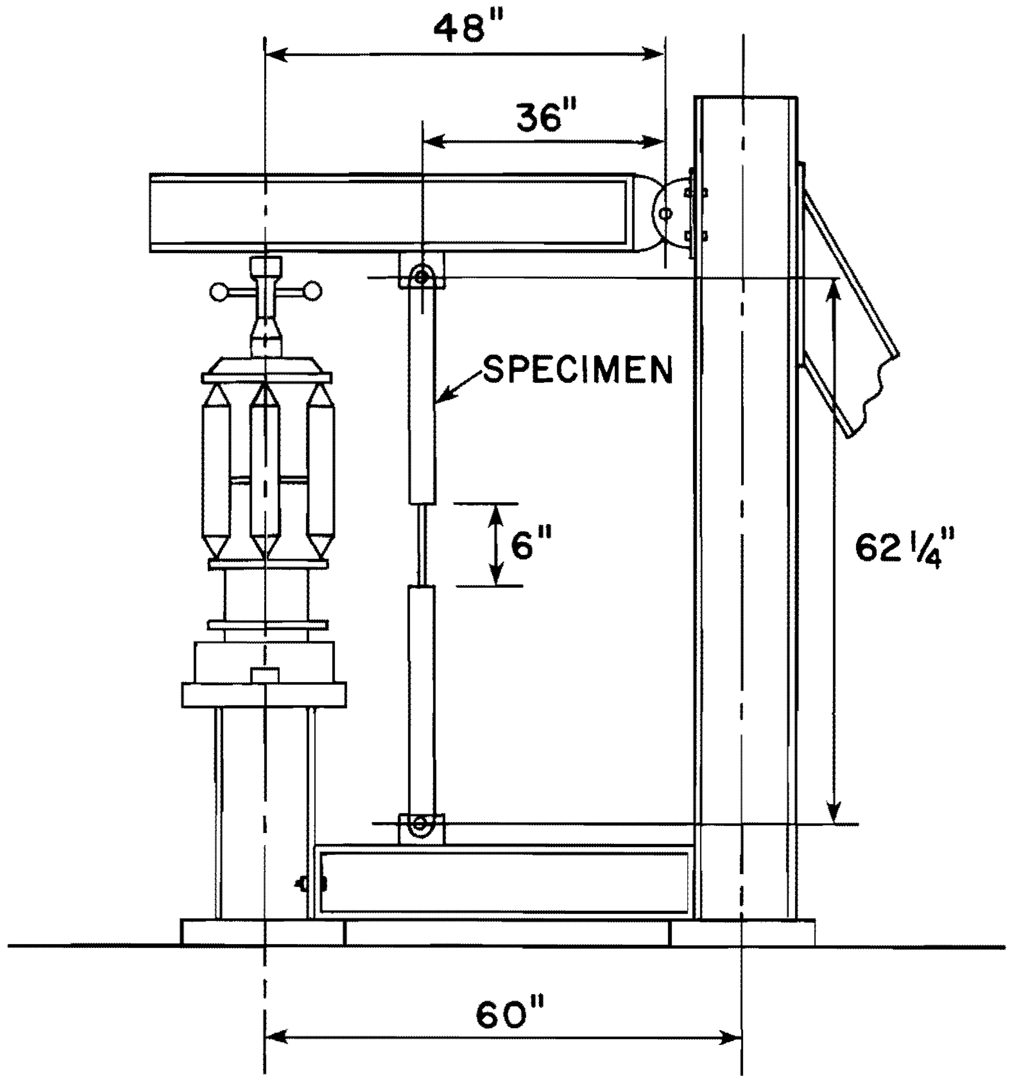


Figure 2-1: Lane and Ekberg's Test Frame

(After Figure 9, Reference [21])

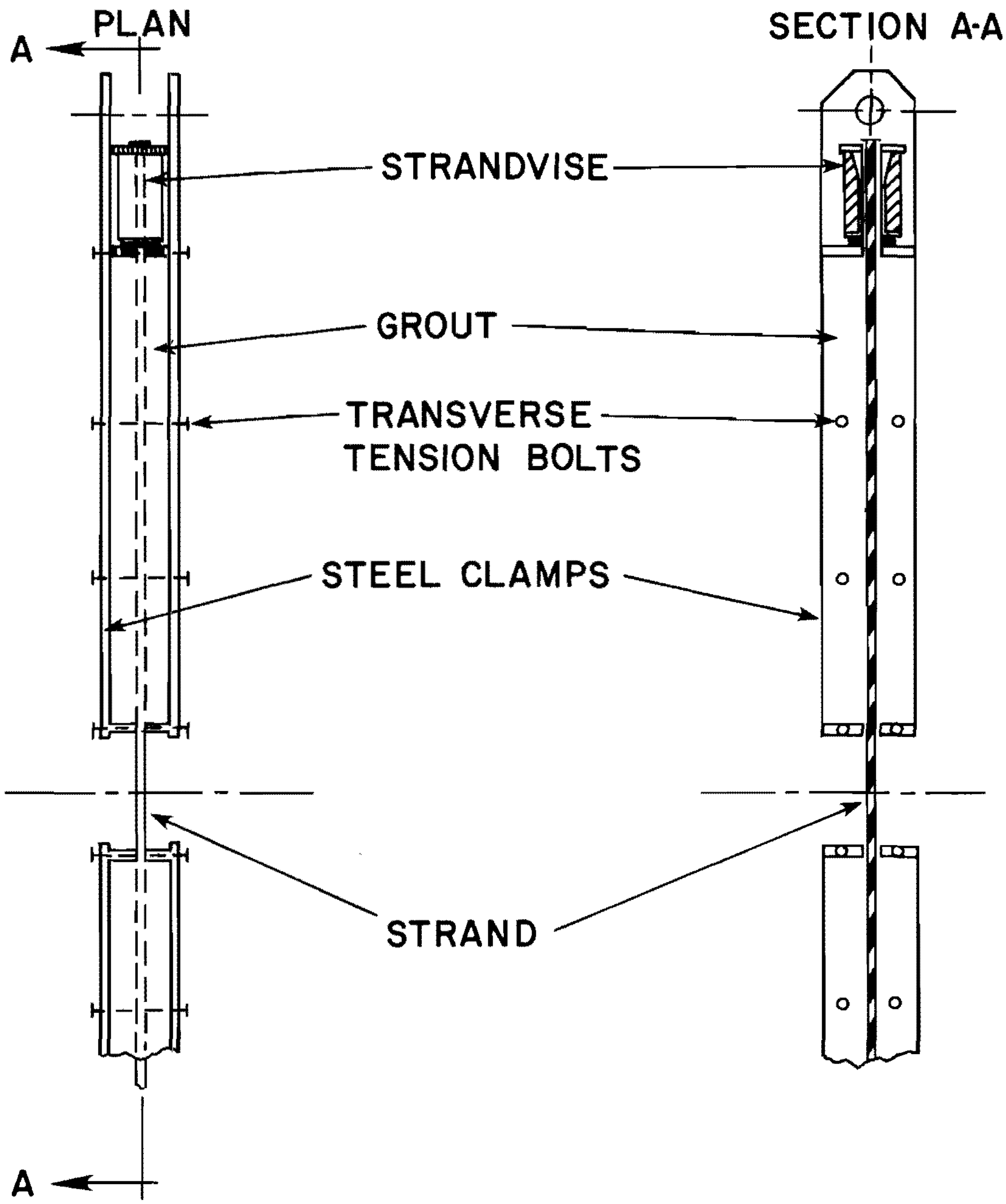


Figure 2-2: Lane and Ekberg's Grip Method

(After Figure 6, Reference [21])

Lane and Ekberg's. The report does not mention explicitly what grade of strand was tested, although it is mentioned that static test results indicated a mean ultimate stress of 270.4 ksi. Other authors, in their literature reviews, give conflicting values for the grade of strand used by Fisher and Viest. One report [19] mentions 270 ksi, while another report [34] mentions 250 ksi. Considering that at the time the tests were conducted, 270 ksi strand generally was not available, it is felt that the value of 250 ksi is correct. The stress levels were selected such that the tests encompassed two 2 x 2 factorial experiments. In their analysis, the authors present S_r-N (stress range vs. life in cycles) curves for S_{min} = 162.5 ksi and S_{min} = 132.5 ksi and develop a mathematical model for the log of fatigue life (log N) as a linear function of S_r and S_{min}.

2.1.5 Warner and Hulsbos. The first major U.S. study, in terms of the number of specimens tested, was reported by Warner and Hulsbos [36]. They reported the results of 69 constant cycle tests and 51 cumulative damage tests. The constant cycle tests were conducted at two minimum stress levels (0.40 f_{pu} and 0.60 f_{pu}) and five stress ranges. The test frame and gripping method were similar to Lane and Ekberg's. The strands tested were 7/16 inch diameter, but the authors do not state the grade used nor the value of f_{pu} used to determine load levels from the indexed stress levels. All of their stress levels were reported as indexed stress values. The literature reviews of other authors [19, 34] mention the grade as being 250. The authors report a mean ultimate load of 28,560 pounds, giving a mean ultimate stress of 264.4 ksi when using the nominal area for 250 ksi, 7/16 inch strand. This value (264.4 ksi) will be used for f_{conv}. In Appendix A, 67 of the 69 constant cycle tests are tabulated. Of the two tests not listed here, the authors state that one test was a premature failure in the grip and that the other was a failure at a weldment in the strand, and thus were not used in their analysis.

In their analysis of the constant cycle data, the authors perform two chi-square goodness of fit tests on their data and conclude that log N is normally distributed. The authors develop an expression for the standard deviation of log N as a linear function of the stress interval R and develop a regression equation for log N as a function of R. ($R = S_{max} - S_L$, where S_L is the fatigue limit corresponding to a specfic S_{min}.) Conclusions related to the cumulative damage tests are that the "tests showed good correlation with mean fatigue life predicted by the linear theory proposed by Palmgren and Miner," and that the tests "indicated that stress cycles in the loading history which are smaller than the fatigue limit will not contribute to fatigue failure. . ." Warner and Hulsbos also caution that:

> It is important to emphasize the limited applicability of the strand fatigue test data obtained in this investigation. All of the data obtained in this investigation were conducted on unrusted 7/16-in. diameter strand from one manufacturer. . . .Some differences in the fatigue properties for strand of different sizes, [surface conditions, and manufacturers] must. . .be expected.

2.1.6 Hilmes. As part of a statistical study of the fatigue of prestressed beams, Hilmes [19] conducted tests on 56 specimens of 7/16 inch diameter, Grade 250, seven-wire strand. All tests were at a minimum stress level of 128.5 ksi, using five different stress ranges. A mean ultimate stress of 257.0 ksi was indicated. The 47 specimens which the author considered valid data points are listed in Appendix A. The test frame and gripping method were similar to Lane and Ekberg's.

Hilmes combined his data with that of the AASHO Road Test and Warner and Hulsbos to develop S_r-N curves and fatigue failure envelopes for probabilities of survival of 50 percent and 90 percent. In addition, he observed that the plot of log S_r vs. log N is linear. In the conclusions relating to the strand tests, Hilmes says: "The distribution of the fatigue strengths about the median in the long-life region of the

S-N curve is approximately a normal distribution. A chi-square goodness of fit test indicated close correlation. . ."

2.1.7 Tide and VanHorn. Tide and VanHorn [34] report an extensive series of tests on 1/2 inch, grade 270 ksi strand. There were 38 specimens from five manufacturers tested at S_{min} of 0.56 f_{pu} at two different temperatures (laboratory temperature of 70 degrees Fahrenheit and a reduced temperature of 0 degrees Fahrenheit) and 140 specimens from three manufacturers tested at two different S_{min} levels (0.40 F_{pu} and 0.60 F_{pu}) and five different stress ranges (all at laboratory temperature). The stress levels reported were indexed stresses based on the strand's grade, giving a f_{conv} value of 270.0 ksi. The test frame and gripping method were similar to Lane and Ekberg's. In Appendix A, the data listed are all of the tests conducted at laboratory temperature. [Note: The group numbering system used in the appendix indicates the various manufacturers by the last digit of the group number. Groups 401, 411, . . ., 491 correspond to manfacturer A of Tide and VanHorn's report; groups 402, 412, . . ., 492 correspond to manufacturer B; etc.]

The authors observed that fatigue life increased with reduced temperature, but that the increase was not very significant because the temperature range observed (70 degrees Fahrenheit) was small. The authors also state that fatigue life of 270 ksi strand is similar to that of 250 ksi strand, that using the specified minimum ultimate load rather than the actual ultimate load causes no significant change in the results of the fatigue analyses, and that the static properties of the strand of various manufacturers are approximately the same.

2.1.8 Baus and Brenneissen. A general report on fatigue of prestressing steel, including bars, wires, and strands, was presented by Baus and Brenneissen [7]. Many tests are mentioned, but no specific references are given and no data points are listed. Information is mostly in the form of figures and diagrams: fatigue limit curves and

Wholer curves. Thus, no data from this report are listed in Appendix A or are used in analysis of strand fatigue behavior.

2.1.9 Cullimore. In a study of cables for suspension bridge hangers, Cullimore [10] conducted a series of tests on 0.6 inch diameter, seven-wire prestressing strand. The test equipment is mentioned only as being a Losenhausen testing machine. Two grip methods were used. One method, using white metal cones fitted on the ends of the strand, proved unsatisfactory because flux used in the white metal affected the strand. The second method used is described as:

> . . .a pair of plain half-round cylindrical steel collets about 3-1/2 in. (90 mm) long which fitted around the cable and were separated from it by pieces of 16 swg (1.6 mm) half-hard aluminium shim, pre-formed to fit inside the collets. The collets were held in the standard wedge grips of the testing machine and the initial gripping was assisted by a small bush lightly welded to the end of the wire which rested on top of the collets, so pulling them into the grips. This bush was shown to play very little part in transmitting load. . .

The author does not explicitly mention the grade of the strand, but does report an ultimate tensile strength of 112.2 tons force per square inch (or 246.8 ksi, using 2.2 kips per long ton). There were 59 specimens tested in all. Of this total, 15 had the white metal grips and 16 other specimens were cumulative damage tests. The remaining specimens are the ones listed in the appendix. All were tested at the same mean stress (40 tons per square inch, or 88 ksi), with the stress ranges being varied. Cullimore states that the stress ranges were selected so that results would be in the long life region (greater than 2 to 4 million cycles) of the S-N curve. Specimens were tested to failure with stress ranges as small as 31.2 ksi. Cullimore concludes that ". . .for the stress levels examined, there is no lower value of the stress fluctuation below which failure will not occur in less than ten million cycles. . ."

2.1.10 Edwards and Picard. Another extensive series of tests was reported by Edwards and Picard [12]. The authors report on some 189 tests; variables included specimen gage length, minimum stress, stress range, lateral pressure, and abrasion. The test frame was similar to Lane and Ekberg's test frame, but the method of gripping was different:

> The gripping units were constructed of steel shafts and plates and included self-aligning spherical roller bearings so that rotation was completely free in two directions at right angles. The specimen was gripped by four steel wedges acting in a 100 mm thick steel plate. In order to obtain failure within the gauge length, two pairs of 2.6 mm thick soft aluminum angles were placed between the strand and the wedges and the lead-in length was surrounded by a piece of plastic 1 mm thick.

The strand is described as 12.7 mm (1/2 inch) diameter seven-wire strand, but the grade of the strand is not reported. For the longest gage length, a mean static ultimate strength of 175,875 N is reported. Nominal steel areas for 12.7 mm strand are 93 mm^2 and 99 mm^2, corresponding to Grade 250 and Grade 270, respectively. These areas give an ultimate stress of 1891 N/mm^2 (274.3 ksi) and 1777 N/mm^2 (257.7 ksi). The value of 274.3 ksi was used for f_{conv}.

In addition, the analyzed results (mean life, standard deviation, sample sizes) of the data within a replicate group are presented, not the raw data points themselves. The data presented in Appendix A were reconstructed from the given means, standard deviations, and sample sizes using order statistics. Section B.2 of Appendix B gives an example of the reconstruction procedure. Only free air tests (no lateral loads) with the longest gage length were reconstructed because the testing conditions of those strands were closest to the conditions of the previously reviewed references.

Edwards and Picard state in their conclusions that fatigue life decreases with length because of size effect and also because

". . .fretting conditions. . .are more critical when the test length increases." They further note that fatigue life is reduced by lateral pressure, but the reduction is not as significant as the length effect. An additional comment is that

> . . .it is possible to make a safe estimate of the fatigue life of prestressed concrete beams using the fatigue properties of strand tested in free air if the test length is at least equal to the length of the constant moment region of the beams and if one makes allowance for a reduction in the fatigue strength of strand due to lateral pressure which acts on the reinforcement at cracks. From the results of this investigation a reduction of 20% seems realistic.

2.1.11 Muller and Zeller. Muller and Zeller [23] report the results of 41 fatigue tests on 12.4 mm and 15.2 mm (1/2 inch and 0.6 inch) strands having a rated ultimate stress of 180 kg/mm^2 (256.1 ksi). The majority of the specimens (13 of the 12.4 mm strands and 14 of the 15.2 mm strands) were over various stress ranges with the maximum stress being held constant at 99 kg/mm^2 (140.8 ksi). These are the points listed in Appendix A. The remaining specimens were tested with each specimen at its own unique stress levels, the stress levels being a function of each specimen's yield strength. There is minimum text with the report, so nothing is known about the test method, break locations, or if all the strand came from one reel.

2.1.12 Storebaelt Bridge Tests. A series of fatigue tests was conducted at the Structural Research Laboratory, Technical University of Denmark, on cable stay assemblies and their wire and strand components for the Storebaelt Bridge, Denmark [32]. Tested in fatigue were ten parallel wire cable specimens, five parallel strand specimens, several individual wire specimens, and five individual strand specimens. The five individual strand tests are listed in Appendix A. The grip method was a steel "trumpet" tube with epoxy grout as the force transmitting device.

2.1.13 Frank and Hsu. Research was commissioned at the Ferguson Structural Engineering Laboratory, The University of Texas at Austin, by the Secretariat of Human Settlements and Public Works of Mexico to study the fatigue and static behavior of 0.60 inch diameter, seven-wire prestressing strand [15, 16]. Specimens from four different samples of strand representing three different countries of manufacture were tested in two series of fatigue tests. The gripping procedures and test equipment used were as described later in this paper.

The first series of tests investigated fatigue in the long life region. Some 30 specimens from three of the samples of strand were tested, 18 of which were considered valid tests and are listed in Appendix A.

For the second series of tests, the stress range was greater, giving lives generally between 100,000 and 200,000 cycles. Twelve specimens were tested, eleven of which were considered valid tests and are listed in the appendix. Prior to the beginning of the second series of tests, one of the original three samples of strand was found to be of a smaller cross-sectional area than specified, so another sample of desired area was obtained from the same country of origin and was used in the second series of tests.

In Appendix A, Group 801 are the specimens from the sample with the reduced cross-sectional area. Group 811 represents specimens from the replacement sample. Groups 802 and 812 are specimens from the second of the original three samples and Groups 803 and 813 are specimens from the third of the original three samples.

2.2 Evaluation of Published Data

For each replicate group with three or more failure points, the arithmetic mean log N and standard deviation of log N (for the failure points) was found. These are presented in Table 2-2. (The information for Edwards and Picard's data is as it appeared in their paper.)

Of particular note are the data of Hilmes and Cullimore. Both sets of data exhibit the unusual observation that mean fatigue life increases with increasing stress range. Typically, fatigue data have mean fatigue lives which decrease with increasing stress range. Hilmes' data have a mean Log N of 5.788 for a stress range of 41.5 ksi and a mean Log N of 5.907 for a stress range of 47.0 ksi. Cullimore's data have a mean Log N of 6.317 for a stress range of 42.7 ksi and a mean Log N of 6.378 for a stress range of 48.8 ksi. Because it is impossible to discern what is causing this unusual behavior, it cannot be determined which of Hilmes' and Cullimore's data are in error and which are not. Thus, the data of Hilmes and Cullimore are not used in analysis of experimental data in the remainder of this paper.

A preliminary analysis of the collected data was performed. The data used were all of the published data listed in Appendix A, excluding non-failure points, the Hilmes data, and the Cullimore data. Reasons for excluding non-failure points are given in Section 5.1 of Chapter 5. A multivariate relationship analysis using the least squares method [24] was performed on the data, and the following preliminary mean fatigue life model was found:

$$\text{Log } N = 11.28 - 3.40 \text{ Log } S_r.$$

The correlation coefficient was 0.868 and the standard error of estimate (the estimated standard deviation) was 0.225. There were 341 failure points analyzed. Figure 2-3 is a plot of the data used. The solid line is the mean line of the model; the dashed line represents the 97.5% survival line with a confidence of 95%. It was found by subtracting K times the standard error from the mean fatigue life model, where

Group Number	S_{min} (ksi)	S_r (ksi)	Mean Log N	Std. Dev. of Log N
Lane and Ekberg				
152	136.2	33.8	6.073	0.4257
Fisher and Viest				
251	135.2	48.4	5.938	0.1657
252	135.2	62.1	5.391	0.3111
253	135.2	75.7	4.701	0.1261
255	162.5	48.4	5.545	0.2170
256	162.5	62.1	5.163	0.1890
Warner and Hulsbos				
302	105.8	46.3	5.928	0.1548
303	105.8	52.9	5.539	0.1162
304	105.8	66.1	5.176	0.0768
305	105.8	79.3	4.946	0.0671
311	158.6	39.7	5.783	0.2602
312	158.6	52.9	5.223	0.1793
313	158.6	66.1	4.908	0.0708
Hilmes				
352	128.5	36.0	6.298	0.0891
353	128.5	41.5	5.792	0.2989
354	128.5	47.0	5.907	0.3442
355	128.5	49.8	5.280	0.5726
Tide and VanHorn				
401-3	108.0	32.4	6.187	0.1717
411-3	108.0	43.2	5.897	0.1335
421-3	108.0	54.0	5.407	0.1672
431-3	108.0	67.5	5.038	0.1085
441-3	108.0	81.0	4.842	0.0697
451-5	151.2	64.8	4.996	0.1667
461-3	162.0	32.4	6.140	0.1484
471-3	162.0	43.2	5.566	0.1654
481-3	162.0	54.0	5.245	0.1885
491-3	162.0	67.5	4.965	0.1170

Table 2-2: Preliminary Evaluation of Published Data

Group Number	S_{min} (ksi)	S_r (ksi)	Mean Log N	Std. Dev. of Log N
Cullimore				
502	66.6	42.7	6.317	0.1754
503	63.6	48.8	6.378	0.4212
504	60.5	55.0	5.957	0.4113
505	57.6	60.7	5.817	0.4120
506	54.6	66.9	5.595	0.3528
Edwards and Picard				
551	109.7	46.6	5.792	0.0836
552	109.7	49.4	5.654	0.1591
553	109.7	54.9	5.499	0.0887
554	109.7	68.6	5.048	0.1265
555	164.6	39.8	5.876	0.1474
556	164.6	43.9	5.580	0.1702
557	164.6	54.9	5.292	0.0928
558	164.6	68.6	4.980	0.0304
Frank and Hsu				
802-3	73.0	26.5	6.569	0.2694
811-3	75.3	62.7	5.198	0.1704

Table 2-2 (Continued)

K = 2.122 and is the factor for the one-sided tolerance limit for a population of size 341 where it is 95% confident that 97.5% of the distribution falls above the limit [26].

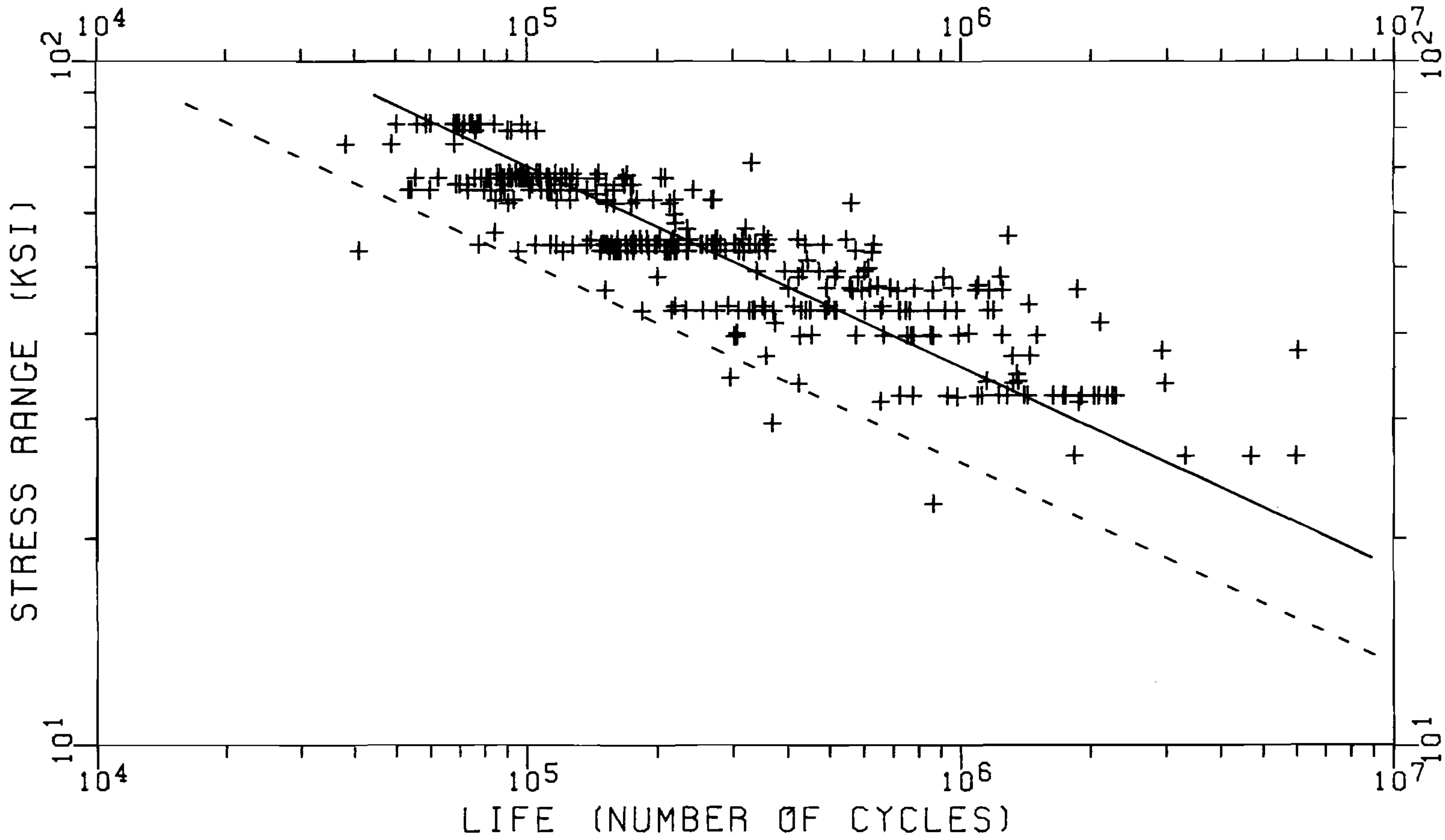


Figure 2-3: Regression Analysis of Published Data

Chapter 3

TEST METHOD: APPARATUS AND TECHNIQUES

Fatigue testing of individual specimens of prestressing strands poses several problems to the experimental investigator. A loading system which is reliable and can withstand the rigors of fatigue tests is required. The method of gripping the specimen is of paramount importance. All aspects of the specimen's behavior must be either controlled or measured in some manner. The following sections explain how these problems were resolved in the investigation at hand.

3.1 The Fatigue Equipment

A test system concept developed previously for a cable stay fatigue study [11, 14] was used for the tests in this study. The test system (Figs. 3-1 and 3-2) consisted of a centerhole ram and extension chair. They functioned as a hollow compression element or column with the strand or tension element passing through the system and reacting at either end. The extension chair was machined to match the base of the ram and load cell mounting holes. The load cell used was a flat load cell with a hole in the center which allowed the strand to pass through the load cell. Interface discs were machined to hold the strand grips in position between the piston and the load cell. They were positioned such that the centerline of the strand was the same as the centerline of the ram, extension chair, and load cell unit. This meant that the elements of the load system were in either tension or compression; essentially no moment was introduced into the system. The interface discs were self-aligning, ensuring accurate positioning of each specimen.

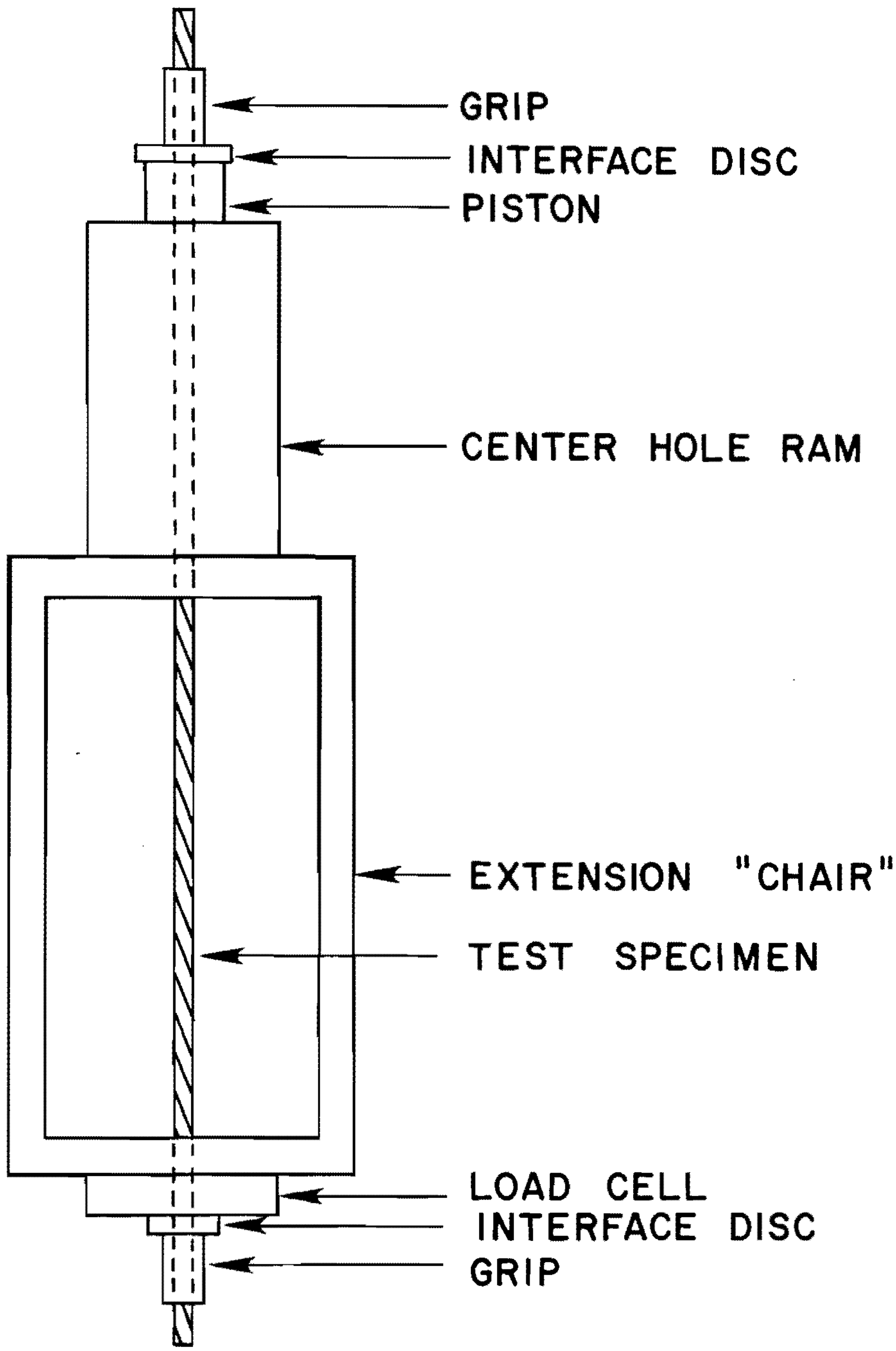


Figure 3-1: Strand Fatigue Set-Up

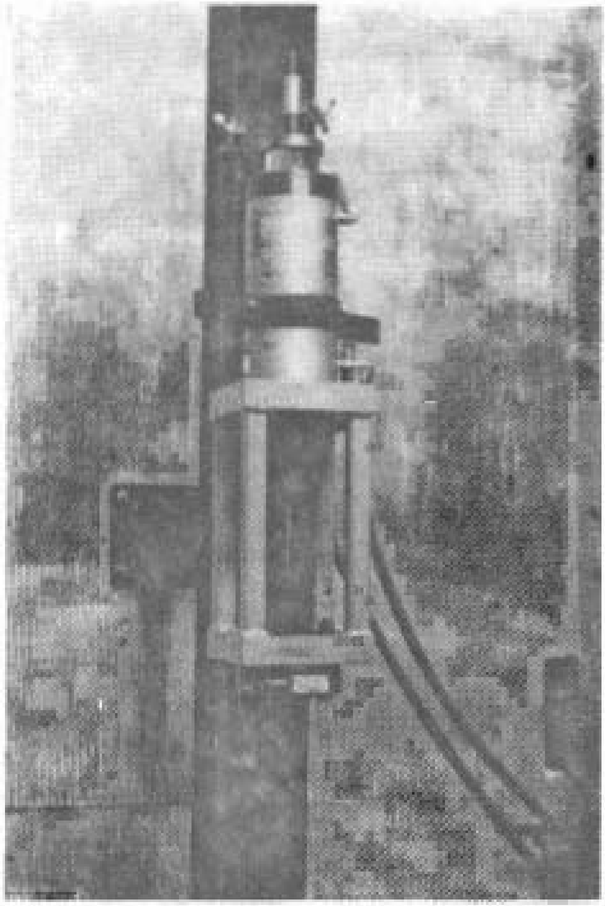
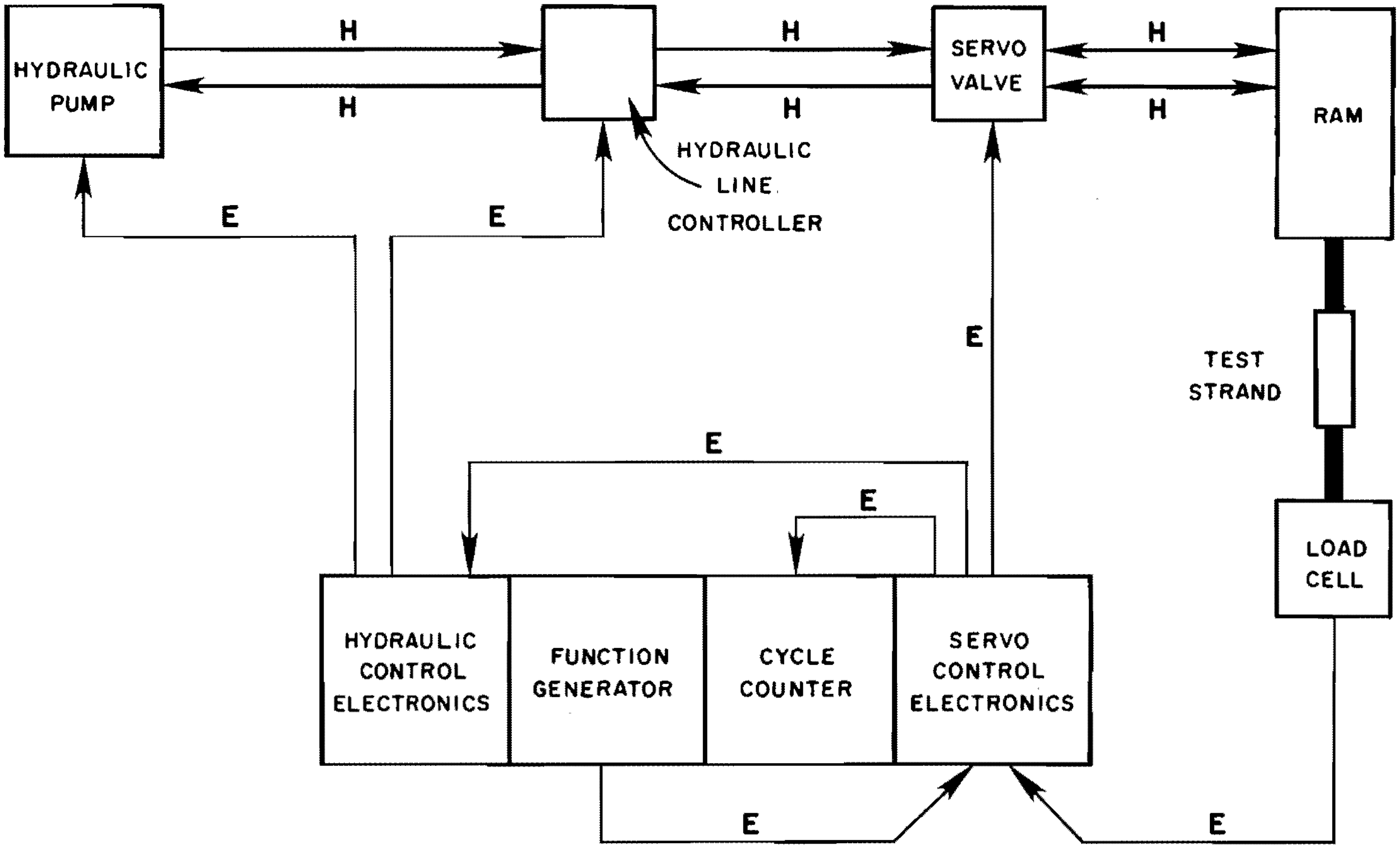


Figure 3-2: Fatigue Set-Up with Specimen Installed

The load control system used was a closed-loop hydraulic servo-controlled system. A block diagram for the system is shown in Fig. 3-3. The electronics were calibrated first with a National Bureau of Standards (NBS) traceable strain simulator substituted for the load cell. Then a 50 kip capacity load cell was mounted on the extension chair, and the extension chair-load cell combination was placed in a calibrated testing machine for proof load tests and a check of the electronic calibration. The servo controller itself was used to monitor the load cell during the proof tests. The particular load cell used was found to be slightly non-linear at the top end of its load range, but it was linear in the range of loads expected during the fatigue tests. The



H = Hydraulic interconnection

E = Electronic/electrical interconnection

Figure 3-3: Block Diagram: Strand Test Servo Control System electronics were readjusted slightly and several more load cycles were applied; the electronic readings and testing machine readings were observed to be consistent. Accuracy of the servo controller's load amplification electronics was determined to be within 1.5% of the smallest planned stress range. This percentage error was controlled by the accuracy in reading the load dial of the testing machine used for calibration.

Once the total system was functional and several tests had been run, a problem with the particular ram being used became evident. The ram had been intended primarily for use with static loading and thus had leather seals, which proved to have short lives under dynamic loading. When oil leakage became a problem, an identical ram was substituted for the leaking ram, and testing continued while new seals were placed in the leaking ram. During the high stress range tests for the initial brand comparison test phase, the rams were alternated twice. For the lower stress range tests, the extension chair was adapted to hold a 30-ton ram. This ram had polyurethane seals and exhibited no leakage throughout its use.

For the final phases of testing, two fatigue stand systems were available: the original stand with the 50 kip load cell and a second similar stand having a 100 kip load cell. Both systems used similar electronic servo control systems. The 50 kip stand was once more modified, this time so that it could use either of two rams: the 30 ton ram having polyurethane seals and a similar 100 ton ram, also with polyurethane seals. The 100 kip stand was used in conjunction with a second, identical 100 ton ram. Because the pressure in the hydraulic system was limited to a maximum of 3000 psi, the smaller ram was used for tests with lower stress levels, and the larger rams were used for tests with higher stress levels.

3.2 Gripping the Strand

In any system which is used for testing strands in fatigue, the method of gripping receives a lot of attention. There is a general requirement that the grip be designed to inhibit failures in the grip region. For the test system at hand, there were further requirements. The grip was restricted to short lengths near the ends of the specimens. Additionally, the grip had to be attached while the strand was in the test set-up, so the grip needed to be convenient and quick to install.

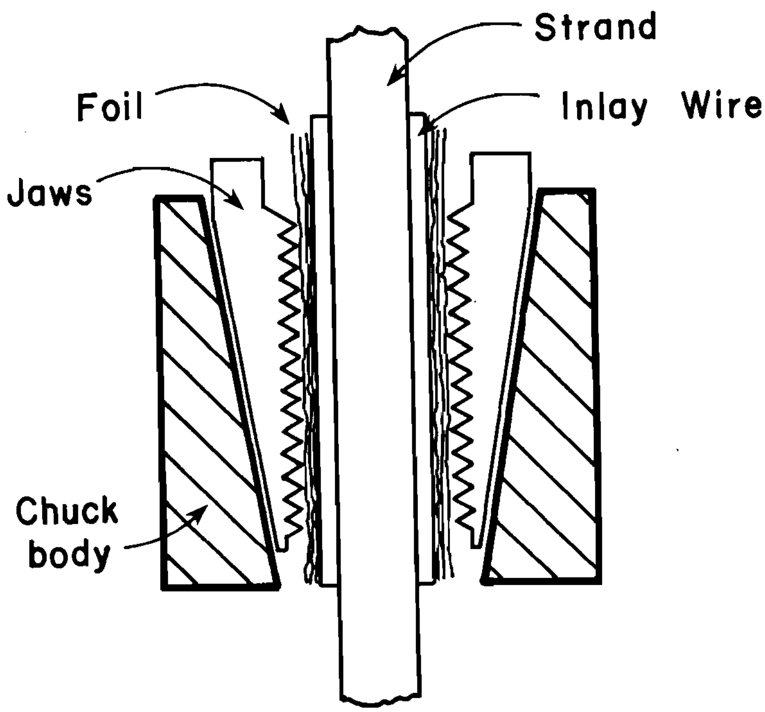


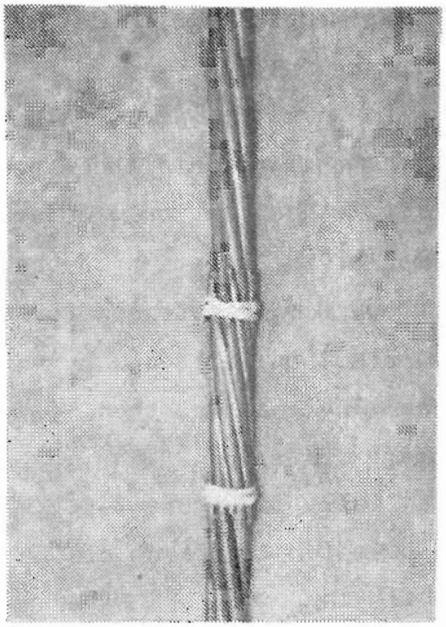
Figure 3-4: Section Through Foil-Protected Chuck

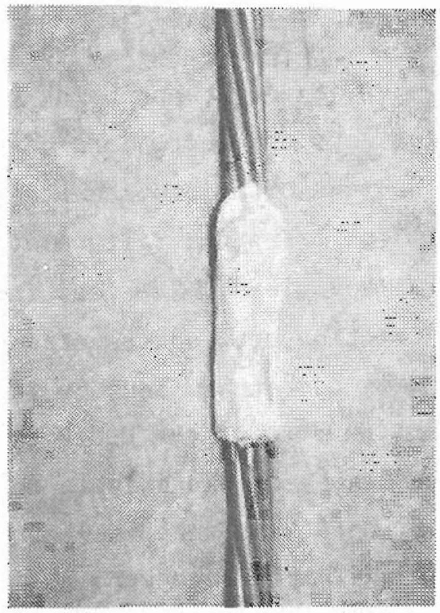
The grip method first used is shown in Figure 3-4. It is in principle similar to the gripping methods of Cullimore [10] and Edwards and Picard [12] in that it used aluminum to protect the strand from indentation by gripping jaws. The chucks used were multiple use chucks for 0.6 inch diameter strand. Oversize chucks were used because the inlay wires and aluminum foil used in the grip area effectively increase the diameter of the strand being gripped. The key item was the aluminum foil which kept the serrations of the jaws from biting into the strand. Should the jaws bite into the strand, a stress concentration occurs and there will be premature failure of the strand at the location of the indenting of the wires. The load from the strand was transferred to the jaws by friction between the strand and the aluminum foil, and by friction between the strand and the inlay wires. The load was then transferred to the body of the chuck by the wedging action of the jaws.

Assembly of the grip is shown sequentially in Figure 3-5. First, six soft iron wires were pre-formed to match the pitch of the strand to be gripped and were held temporarily in position in the "valleys" between the outer wires of the strand (Figure 3-5a). Next, the layers of aluminum foil were applied. Strips of foil were simply wrapped around the strand and inlay wires until enough layers had been accumulated, usually about 40 layers (Figure 3-5b). The foil thickness was 0.001 inch. The diameter of the inlay wires was 0.090 inch. Then the jaws of the chuck were positioned over the built-up layers of foil (Figure 3-5c), and the body of the chuck was slid into postion, performing its normal function of confining the jaws (Figure 3-5d).

This gripping method performed satisfactorily. At first, there were problems either with failures in the grip region due to biting, or else the jaws would not wedge in properly and the strand would slip suddenly at high loads. These problems were both found to be "fine tuning" problems which depended upon the number of layers of foil applied. Too many layers and the strand would slip, too few layers and the jaws would bite into the strand. After the proper number of layers was determined, the grip method was used without modification for all of the tests in the initial brand comparison phase, although strand slippage was still a problem at higher load levels.

For a similar series of tests conducted for a different sponsor [15], the gripping method was subsequently improved. The other


a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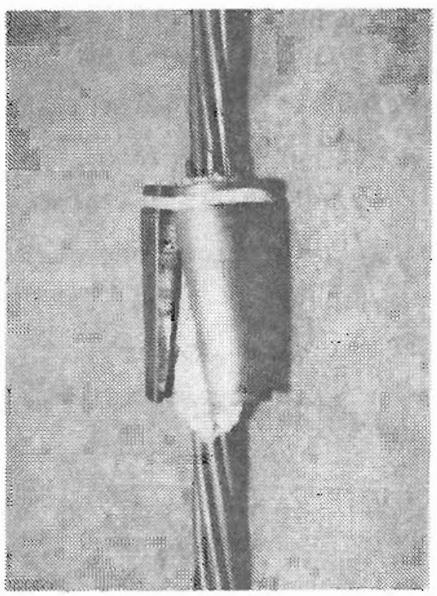
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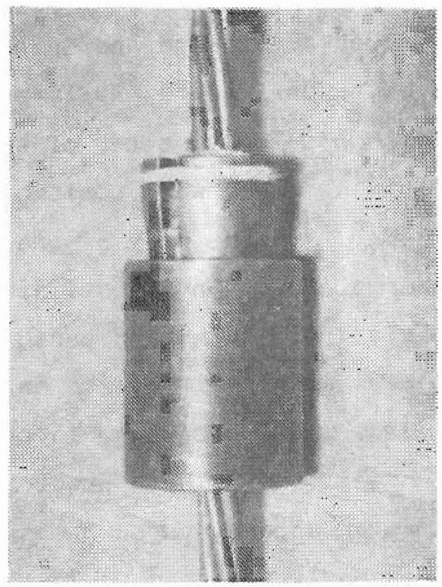
d

Figure 3-5: Attaching a Grip

series of tests used a larger diameter strand (0.6 inch) which slipped frequently. The slippage problem was solved by "double-chucking" the strand (Figure 3-6), an adaptation of a technique used by Cullimore [10]. The lower chuck or inner chuck (that is, the chuck bearing against the interface disc) was prepared with the inlay wires and aluminum foil. A chuck with a shorter body was used for this inner chuck so that the ends of the jaws protruded beyond the top of the body. Then a second multiple use chuck with unprotected jaws was slipped onto the strand and was placed into contact with the protruding jaw ends. Should the strand start to slip through the aluminum protected jaw, the standard chuck would force the protruding jaw ends of the short-bodied chuck into the chuck body, wedging the jaws in further. This wedging then transmitted the load to the protected chuck which evidently took most of the load again. This grip technique was used for all later tests, and the performance was good, with no failures due to grip biting, and no problems with slippage of strand under loads.

3.3 Installation of the Specimen

The process of installing a specimen and starting a test was straightforward. Replacing an expired specimen with a new one was done in as little as forty-five minutes. Most of the time was devoted to attaching the grips.

Strand specimens were cut to a length of about 72 inches. One grip was attached to the strand while it was outside of the fatigue stand. Next, an interface disc was slipped over the free end of the strand and brought down to the attached grip. Then the strand was put into the fatigue stand by threading the free end of the strand through the central openings of the set-up. The end with the attached grip and interface disc was held in place while the other interface disc and grip were installed. Because of the gripping method, the gage length varied from specimen to specimen, ranging from 48 to 55 inches.

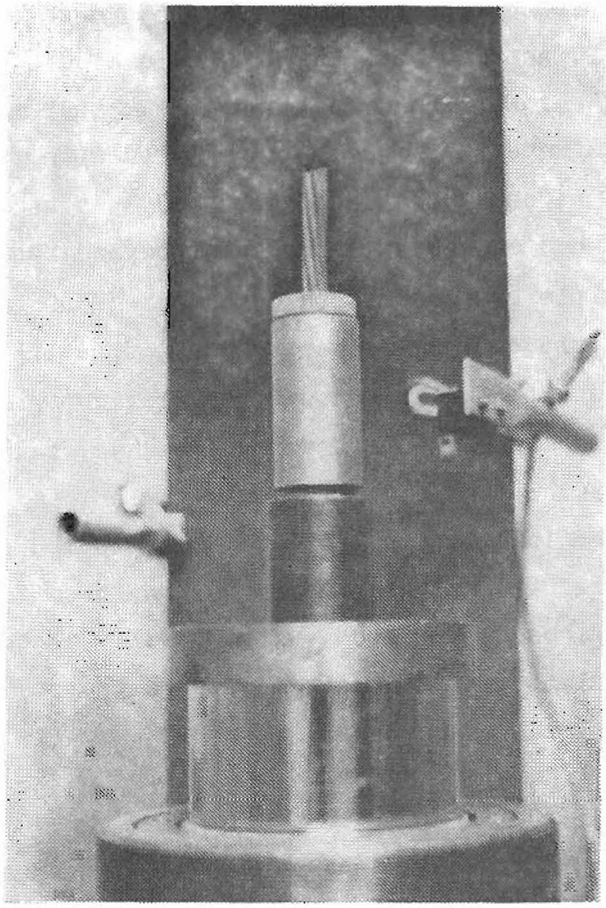

Figure 3-6: Double-Chuck Grip

3.4 Running a Test

Once both grips were installed, a low hydraulic pressure was applied to the system and the piston extended so that there was a slight load in the strand. At this point, the interface discs were checked for proper seating and alignment. When everything was correct, the load in the strand was increased slightly to start seating the grips. Then full hydraulic pressure was applied to the system. The load was increased to the desired mean level.

After the mean load level was reached, the cyclic portion of the load signal was imposed over the static signal. At an initial rate of 1 hertz, the amplitude of the imposed sine wave was increased from zero to the desired level. Then the frequency was increased to the desired value. The testing frequency depended upon several things: amplitude of the desired stress range, the particular ram being used, and the specimen response. The testing frequencies were between 3 and 12 hertz. Maximum and minimum loads were verified by electronic peak detection equipment. The load levels and testing frequencies are given in Chapter 4.

The servo control electronics was sensitive enough to detect the breaking of a wire in the specimen being fatigued, and was able to shut down the hydraulic system accordingly. The breaking of a wire represented a sudden change in the specimen's stiffness. This meant there was a sudden change in the load being detected by the load cell. The rapid change of the load generated a large error signal in the controlling electronics. This large error signal, in turn, triggered a shut down of the hydraulic pressure and stopped the counter keeping track of the number of cyclic load applications. Since this whole process was electronic, the system was halted during the cycle that the wire failed.

Chapter 4

TEST RESULTS

The strand fatigue tests reported in this chapter can be divided into two main groups: several short series of tests giving a relative comparison of strand samples from different manufacturers and then a longer series of tests on a sample from a coil of strand to be used in construction of girder specimens. It is natural to expect different samples of strand to have different results, but there are no recent data showing how much variation exists among various manufacturers. In addition, results from the tests on the sample of strand to be used in the girder specimens can be compared with the results of the tests of the various manufacturers' samples to see if the girder strand is unusually good, unusually poor, or average in terms of fatigue characteristics. Additional data for the girder strand were desired to correlate with the girder fatigue tests. Especially desirable are data in the low stress range, long life region (below 35 ksi stress range, beyond two millon cycles), because there is little of this type data in the literature. Additionally, most stress ranges seen in girders are in this low stress range region.

4.1 Relative Comparison Tests

Various prestressed concrete product manufacturers in the State of Texas who manufacture prestressed girders for the State Department of Highways and Public Transportation were asked to send a sample from any reel of strand being used in their prestressing yard, and to include the name of the strand's source and the mill test report, if available. The samples received represented six different manufacturers. The overall strand diameter, individual wire diameters, and pitch of the helix were measured. All samples were found to conform with ASTM Standard A416-74.

The initial six samples were designated by labels A through F. Specimens were cut from the strand samples and were tested at two different sets of stress levels. Stress levels and test results are presented in Table 4-1. The first set of stress levels, with the larger stress range, was chosen to give results with maximum lives less than 100,000 cycles. The second set of stress levels was chosen to give maximum lives less than one million cycles. The tests on these specimens were conducted during the fall of 1980. Sample G is a sample from the coil of strand to be used in making the girder specimens. Sample H is another sample of wire from the same manufacturer but made by a different process. The specimens from Samples G and H were tested during the spring of 1982.

Presented in Table 4-2 are the results of fatigue tests on 7/16 inch diameter, Grade 250 strand (Sample J). The sample is from a reel of strand used in the manufacture of AASHTO girder fatigue specimens. The girders are to be tested at The University of Texas as part of the prestressed concrete girder fatigue project. The strand fatigue tests of Sample J used the same stress ranges as Samples A through H, but were conducted at slightly lower stress levels because the strand was Grade 250.

There is the question of how many specimens to test: at least two are needed to get a mean and a standard deviation. To make a statement with high confidence about a measured property requires a larger number of data points. As the number of replicate specimens increases, the confidence associated with a statement about the relative difference between samples increases. The amount of testing and consequent time and cost also increases along with the confidence of the statements associated with the data.

Min. Stress:	162.0 ksi		81.0 ksi	
Max. Stress:	229.5 ksi		128.3 ksi	
Stress Range:	67.5 ksi		47.3 ksi	
	Life	Hz	Life	Hz
Sample A:	45,800	6	725,000	10
	65,200	6	190,400	10
	58,300	3	653,000	10
	72,900	6		
Sample B:	78,200	6	284,000	10
	120,000	6	607,000	10
	78,600	6	908,000	10
Sample C:	61,600	6	351,000	10
			270,000	9
			734,000	9
Sample D:			167,800	10
			163,700	10
Sample E:	44,100	6	591,000	10
			254,000	10
			342,000	10
Sample F:	41,100	3	270,000	10
	53,400	2.5	956,000	10
	79,600	6	199,100	10
	69,900	6		
Sample G:	67,700	5	2,623,000*	11/8**
	103,900	5	792,000	8
	88,100	5	434,000	12
			272,000	12
			821,000	
Sample H:	117,800	5	1,500,000	12
	74,800	5	593,000	8
	99,900	5	2,550,000*	8
			468,000	8

* Testing was halted before fatigue failure.
** First 1,115,000 cycles at 11 Hz, remainder at 8 Hz.

Table 4-1: Results: Relative Comparison Tests

Min. Stress:	147.5 ksi		73.2 ksi	
Max. Stress:	215.0 ksi		120.5 ksi	
Stress Range:	67.5 ksi		47.3 ksi	
	Life	Hz	Life	Hz
Sample J:	91,600	5	2,333,000*	12
	88,600	5	2,626,900	12
	92,100	5		

* Testing was halted before fatigue failure.

Table 4-2: Results: Tests on 7/16 Inch Strand

In order to investigate the influence of sample size upon the relative ranking of strand, the data from Tide and VanHorn [34] were examined to see if relative rankings would change if the sample size is decreased. Tide and VanHorn tested samples of strand from three manufacturers at ten different sets of stress levels. Test stress levels covered two different minimum stress levels and several different stress ranges. The data were divided into groups such that all data in a group were strand from one manufacturer which was tested at the same stress levels. The number of replicates in each group varied from five to eight. For the full set of data in each group, the mean log N value was found. To investigate the sample size effect, a second mean log N value for the first three replicates from each group was found. The results from the analyses are summarized in Table 4-3. The first column of the table identifies the various groups. The first number of the identifier is the minimum stress as a percent of minimum ultimate specified tensile strength, the stress convention used by Tide and Van-Horn. The second number is the stress range, also in percent of minimum specified ultimate strength. This is followed by a letter designating which manufacturer produced the strand tested in the group. The single digit number following the manufacturer code is the number of replicates in the group.

The last two columns of Table 4-3 give the rankings (by order of decreasing mean log N) of a given manufacturer in relation to the other

Group I. D.	Mean Log N			COV	Relative Rankings	
	All Repli- cates	First Three	Per- cent Change	(Per- cent) Data	All Replicates	First Three Replicates
40-20-A-6	5.341	5.327	-0.26	1.90	3	3
-B-5	5.432	5.508	+1.40	2.05	2	2
-C-7	5.445	5.612	+3.07	4.34	1	1
40-25-A-6	4.978	4.928	-1.00	1.38	3	3
-B-6	5.035	5.028	-0.14	1.30	2	2
-C-6	5.101	5.030	-1.39	2.91	1	1
40-30-A-6	4.814	4.837	+0.48	1.43	3	3
-B-6	4.852	4.842	-0.21	0.79	2	2
-C-6	4.860	4.858	-0.04	1.93	1	1
60-16-A-7	5.530	5.633	+1.86	3.70	3	1*
-B-8	5.620	5.516	-1.85	2.97	1	2*
-C-5	5.532	5.494	-0.69	1.72	2	3*
60-20-A-6	5.222	5.239	+0.33	2.60	2	1*
-B-6	5.172	5.079	-1.80	3.70	3	3
-C-6	5.340	5.221	-2.23	4.09	1	2*
60-25-A-6	4.937	4.918	-0.38	0.62	2	2
-B-6	4.907	4.918	+0.22	2.22	3	2*
-C-6	5.050	5.094	+0.87	2.81	1	1

* Ranking changed by reduction of sample size.

Table 4-3: Analysis of Tide and VanHorn Data manufacturers tested at the same stress levels. The first rankings were assigned using the mean log N values based on all replicates from a manufacturer. The second column of rankings was assigned using mean log N values based on the first three replicates. For the lower minimum stress level, none of the rankings differ and the maximum percent difference in the mean log fatigue life value is 3.1%. For the higher minimum stress level, six of the nine rankings differ, but the maximum percent difference in the mean log fatigue life is 1.9%. Another observation is that where relatively large changes in the mean log N values occurred due to sample size differences, the coefficient of variation calculated from all the specimens was also relatively large.

The above analysis indicates that three valid failure points are sufficient to characterize mean log fatigue values. For the relative comparison tests, a valid failure was defined as a fatigue failure occurring in the free length of the strand clearly away from the grip area. With the earlier relative comparison tests (Samples A through F), the single-chuck grip was used. At the high load levels there were instances of grip slippage; specimens from some samples simply could not be gripped, while specimens from other samples posed no problems at all. Samples A, B, and F were determined to be low-relaxation strand (this, however, had not been noted on the samples' mill test reports), while Samples C, D, E, and G were determined to be conventional strand. The slippage problem was divided in a similar manner. The samples which were low-relaxation had fewer problems with gripping at the high load levels as compared to conventional strand. No physical reason was immediately evident explaining why the low-relaxation strand would slip less than conventional strand. For the later relative comparison tests (Samples G and H), the double-chuck grip was used, eliminating the slippage problem.

Some specimens exhibited simultaneous failures of two wires: one failure in the free length of the strand and a second failure in the vicinity of the grip. The part of the strand near the grip was inspected for causes of premature failure, such as biting of the chuck's jaws, etc. If there was no evidence of premature failure, the specimen was accepted as a valid failure. Any specimen which failed only in the grip region was not considered to be a valid failure.

During the initial comparison among manufacturer tests, the piston, interface disc, and top grip (acting together) would rotate approximately one revolution during the first minute or so of cyclic loading, indicating that the strand was untwisting. Concern was expressed about the effect the untwisting could have on test results. The untwisting could relax stresses in the outer (helical) wires of the strand, giving possibly unconservative results. Additionally, the load in the center wire could increase, meaning that center wire failures could occur more often.

To judge the effect of this untwisting, the results of some of the relative comparison tests were compared with published data. The published data chosen for comparison were those of Tide and VanHorn because the strand they reported on was also 1/2 inch, 270 ksi strand. A multivariate regression analysis using the least squares method [24] produced the following mathematical model for Tide and VanHorn's data:

$$\text{Log } N = 11.33 - 3.45 \text{ Log } S_r$$

The correlation coefficient was 0.922, the standard error of estimate (estimated standard deviation) was 0.1723, and the sample size was 156. Figure 4-1 shows the mean line of this model along with tolerance limits (mean life model plus or minus 2.17 times the standard error) such that it is 95% probable that 95% of the distribution is within the limits. The data points shown are those of Samples A through F, inclusive, of Table 4-1. These data points mostly fall within the tolerance limits. The higher stress range data points show somewhat lesser lives than the model of the Tide and VanHorn data indicates for that stress range. Only one center wire fatigue failure was observed in all of the early relative comparison tests. Any effects of the untwisting appear insignificant or non-existent in comparison with the relatively large scatter inherent in fatigue test results.

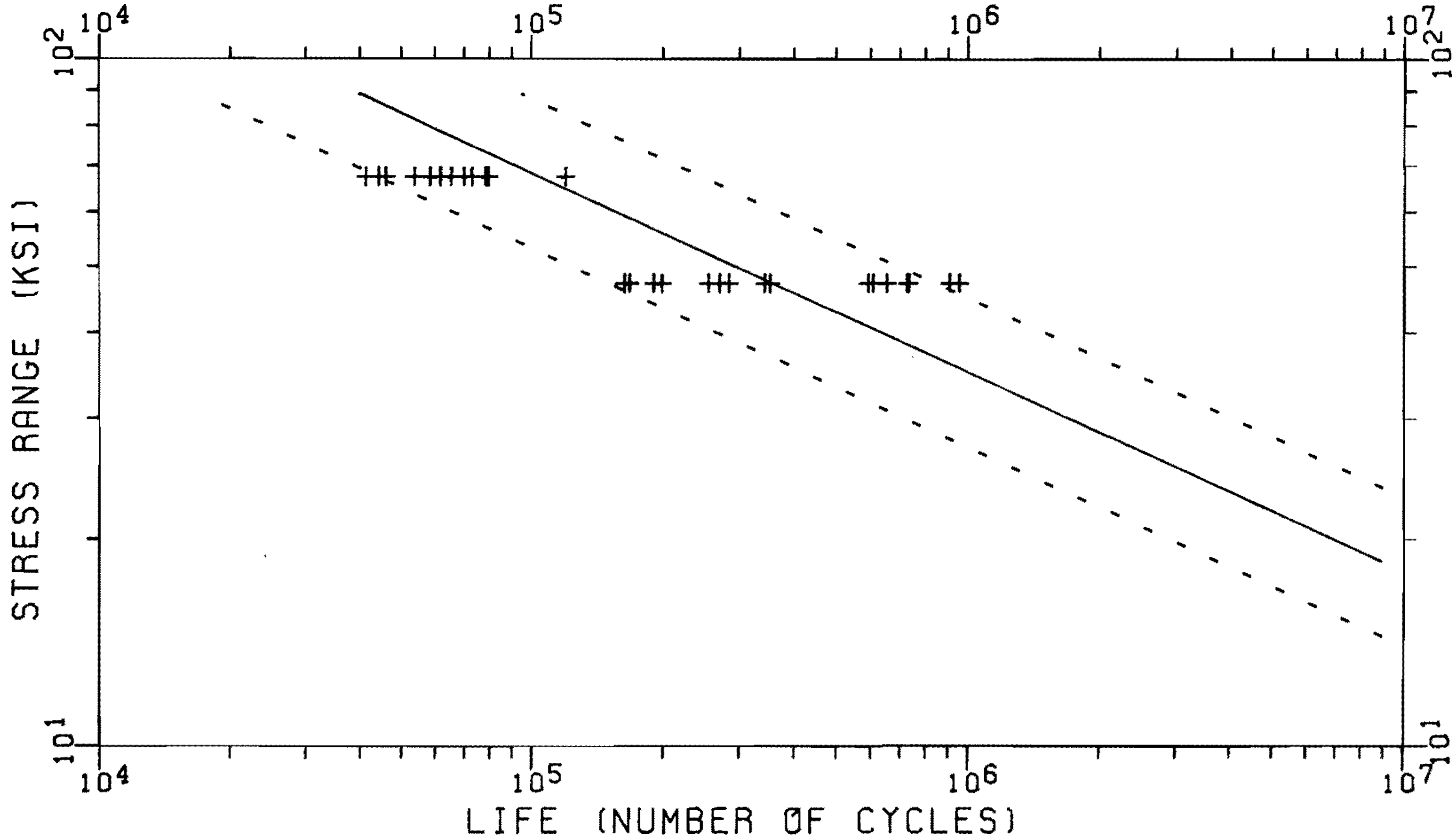

Figure 4-1: Results of Earlier Relative Comparison Tests

Analysis results of the relative comparison test data are presented in Table 4-4. Figure 4-2 compares graphically the average lives of Table 4-4 along with the original data points from Table 4-1. Evident is a significant variation from manufacturer to manufacturer.

Sample	Mean Log N	Corre-sponding Life	Standard Deviation of Log N
Stress Range = 47.3 ksi			
H	5.873	747,000	0.267
B	5.731	539,000	0.257
G	5.721	526,000	0.229
A	5.652	448,000	0.323
C	5.614	411,000	0.225
E	5.570	372,000	0.1859
F	5.570	372,000	0.361
D	5.219	165,700	---
Stress Range = 67.5 ksi			
H	4.982	95,800	0.0999
J	4.958	90,800	0.0091
B	4.956	90,400	0.1067
G	4.931	85,300	0.0938
A	4.776	59,700	0.0863
F	4.772	59,100	0.1276

Table 4-4: Analysis of Relative Comparison Tests

The purpose of the relative comparison tests is to evaluate the strand to be used in construction of the test girder specimens (Sample G) in relation to strand in general use. This comparison should look not only at the mean lives, but also at the minimum lives observed in the samples. The minimum life is significant in that the minimum life can be considered the life at which the structure using the strand starts to degrade.

In terms of mean lives, the girder strand (Sample G) has lives among the longest at both the high stress range and the low stress range. In terms of the observed minimum life, Sample G exhibits a

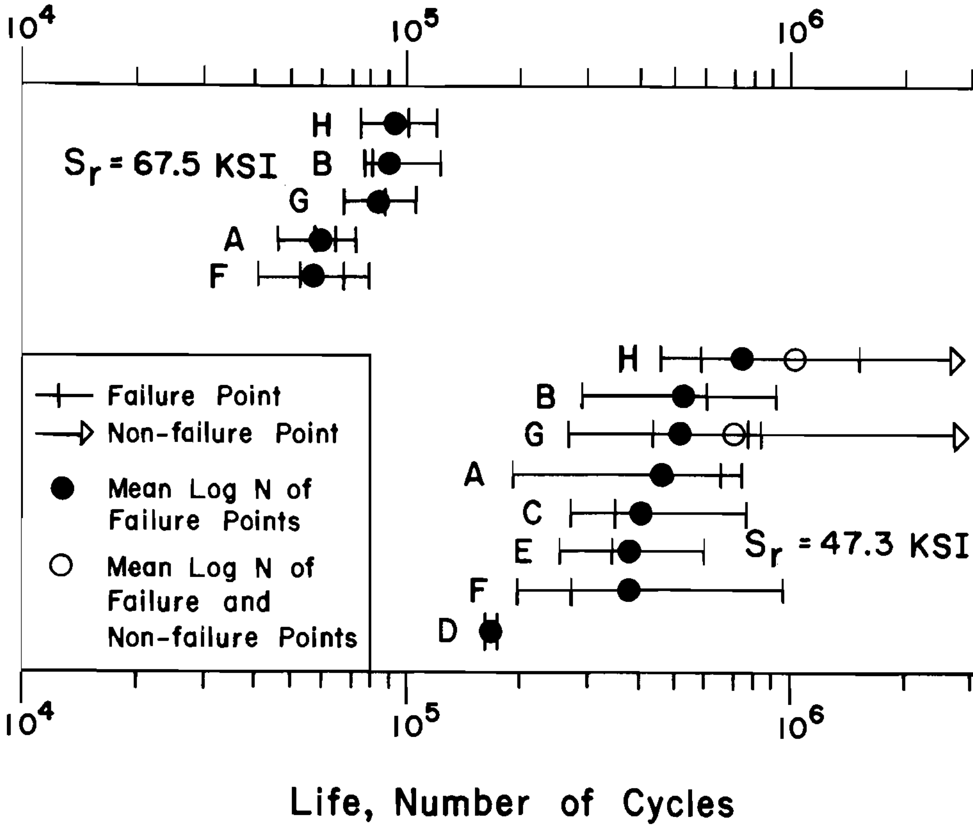

Figure 4-2: Average Lives

difference in the performance at the two stress ranges. At the higher stress range, its observed minimum life is among the longest. But at the lower stress range, the observed minimum life of Sample G falls in the middle of the range of the minimum values. Overall, the fatigue performance of Sample G can be considered above average, but not the best.

Of note is that Samples E, G, and H were made by the same manufacturer, with Samples E and G made by the same process. Even within one manufacturer, there is a significant variation in fatigue performance of the same product. It must be kept in mind that some of this variation is due to the scatter inherent in all fatigue data.

4.2 Beam Strand Tests

Additional tests were run on the strand to be used in the construction of the test girders (Sample G). These tests involved both short life and long life tests. Unless they failed, specimens were allowed to run out to ten million cycles before being removed. A minimum of three replicates was tested at each set of stress levels. Stress levels and test results are presented in Table 4-5.

In many of the long life, low stress range tests, the failure occurred in the region where the chuck was used to grip the specimen. Each of the grip region failures was examined for possible indentation of the strand by the jaws of the chuck. No evidence of indenting was found on any of the strands. Consequently, this type of grip region failure may be inherent to the gripping technique and may be caused by one or all of the following mechanisms:

- The compressive forces from the grip's wedging action increased the fretting between the individual wires of the strand and also between the strand wires and the grip's inlay wires.

- The load was not evenly distributed among the wires where the strand enters the grip. The wire which failed in fatigue had been overloaded.

- The failure was a true wire fatigue failure which happened to occur in the grip region.

To quantify the fatigue characteristics of the girder strand, multivariate regression analyses using the least squares method [24]

Minimum Stress (ksi)	Maximum Stress (ksi)	Stress Range (ksi)	Life (Number of Cycles)	Frequency (Hz)
162.0	209.3	47.3	299,000	8
			302,000	8
			583,000**	8
			1,218,000**	8
162.0	202.5	40.5	763,000	10
			312,000	10
			1,257,000	10
162.0	195.8	33.8	3,870,000**	11
			1,513,000	11
			10,230,000*	11
			1,383,000**	11
108.0	148.5	40.5	1,122,000	10
			963,000**	10
			2,910,000**	10
108.0	141.8	33.8	6,080,000**	15
			10,610,000**	15
			6,030,000**	15

* Denotes specimen for which testing was halted before fatigue failure occurred.

** Denotes specimen in which the fatigue failure occurred in the grip region.

Table 4-5: Results: Tests on the Girder Strand were run. The data base included the data listed in Table 4-5 plus the data for Sample G listed in Table 4-1. Two parallel sets of analyses were run: one involving all failure points and the other involving only the failure points which occurred outside of the grip region. In both cases, non-failure points ("runouts") were excluded. Reasons for excluding non-failure data from the regression analyses are given in Section 5.1 of Chapter 5.

For the analyses which included grip region failures, the following two mean fatigue life models were found:

$$\text{Log } N = 16.11 - 5.34 \text{ Log } S_r - 0.686 \text{ Log } S_{min}$$

$$\text{Log } N = 14.88 - 5.48 \text{ Log } S_r$$

The correlation coefficients were 0.897 and 0.887, respectively. The standard errors of estimate were 0.278 and 0.283, respectively. In using these results, it must be kept in mind that the grip region failures may not represent the true fatigue behavior of the strand. However, the grip region failures do represent conservative estimates of fatigue lives of the strand.

The analyses which excluded the grip region failures gave the following models:

$$\text{Log } N = 13.51 - 4.16 \text{ Log } S_r - 0.446 \text{ Log } S_{min}$$

$$\text{Log } N = 12.67 - 4.23 \text{ Log } S_r$$

The correlation coefficients were 0.924 and 0.914, respectively, and the standard errors of estimate were 0.1869 and 0.1886, respectively. These data and the resulting models represent fatigue behavior of the strand only. However, the models must once again be used with caution. The majority of the data points have a minimum stress with 162.0 ksi. The resulting models can be used with strong confidence only where the minimum stress is near 162.0 ksi, and the stress range is within the bounds defined by the stress ranges of the specimens tested.

The data of Table 4-5 have been plotted in Figure 4-3 along with three mathematical models representing only strand fatigue failures,

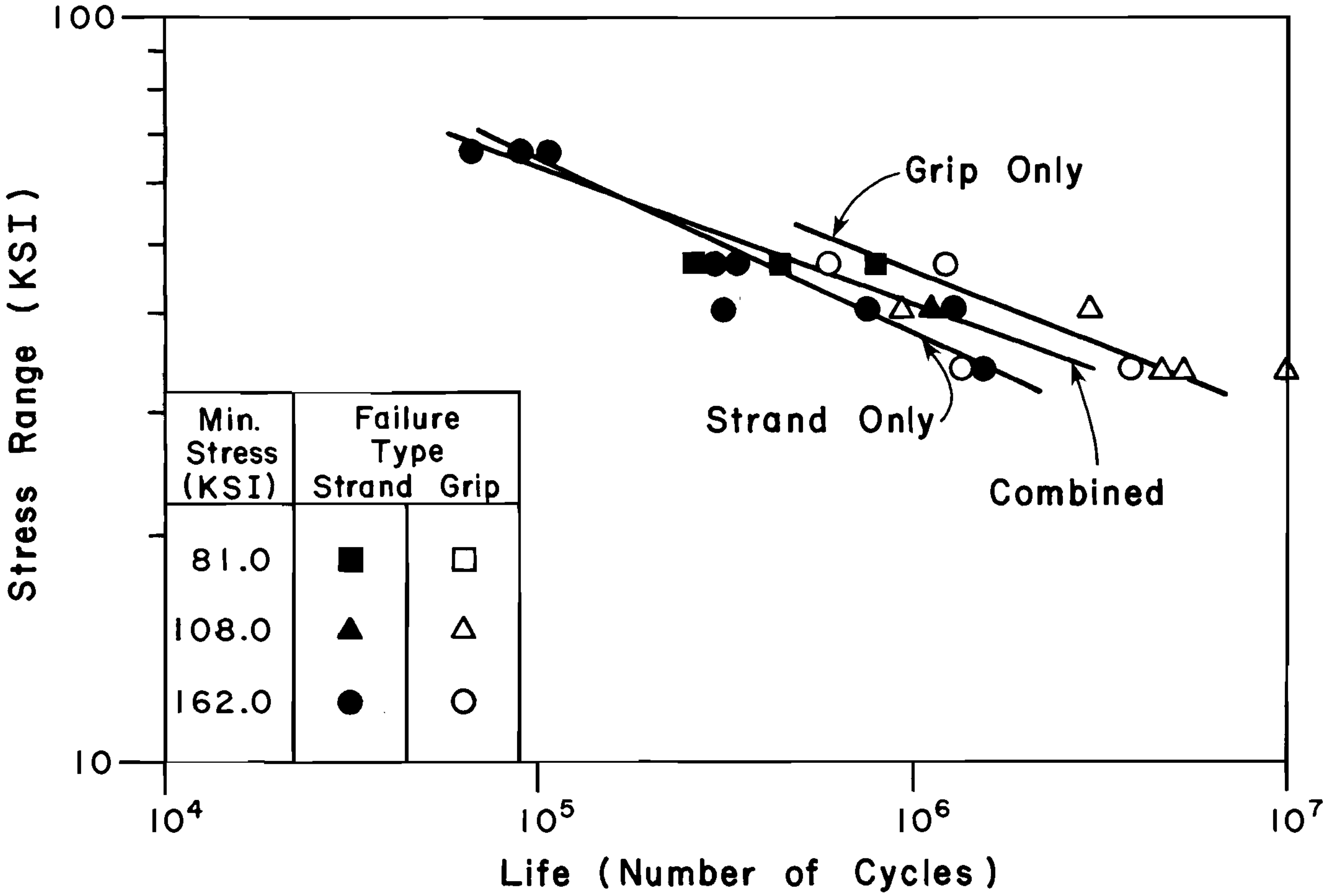

Figure 4-3: Girder Strand Failure Data

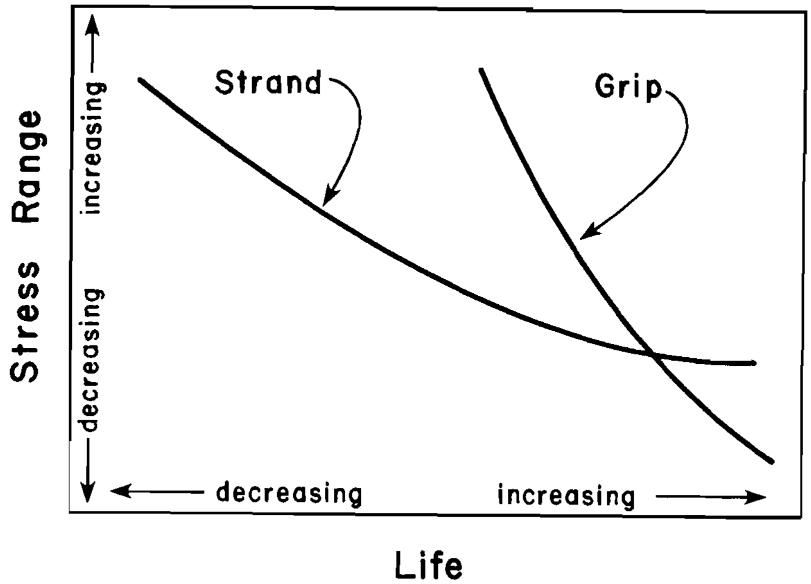

Figure 4-4: Generalized Strand and Grip Fatigue Models

only grip region fatigue failures, and combined strand and grip region fatigue failures. The grip fatigue failures for the most part have occurred at lives greater than strand fatigue failures. This suggests that (for the particular grip used in this study) at long lives, the grip region is more critical in fatigue than the free length of the strand.

This idea is shown qualitatively in Figure 4-4. For the shorter life, higher stress range region, the strand fatigue curve lies below the grip region fatigue curve, meaning that the failures will occur in the strand. In the long life region, the grip region fatigue curve lies below the strand curve, meaning that the failures will occur in the grip region. A mixture of strand and grip region failures occurring at the same test stress levels suggests that those tests are near the intersection of the strand curve and grip region curve.

It should also be kept in mind that the curves' intersection region is also the same general region where a break in the slope of the

Log N - Log S_r curve could occur. This break could be a change in the slope of the curve to the horizontal because the fatigue limit has been reached. Or it could be a slight flattening of the slope, as suggested by Hilmes [19].

Because of the problem of grip failures during low stress range, long life tests, it was impossible to determine a fatigue limit for the strand. The preliminary regression analyses indicate that minimum stress has a significant effect. This will be further discussed in the next chapter.

Chapter 5

ANALYSIS AND DISCUSSION OF STRAND FATIGUE BEHAVIOR

With any fatigue-related study, gathering information is only a part of the task. To achieve meaningful quantitative and qualitative results, the data must be interpreted using statistical methods. Then the results of the statistical analyses must themselves be interpreted and transformed into information which is meaningful to the design engineer.

5.1 Analysis of Strand Fatigue Data

The method used to find the mathematical models presented in this section was a multivariate regression analysis by the least squares method, as described by Natrella [24]. The set of data analyzed contained all of the failure points listed in Appendix A (excluding Hilmes and Cullimore), the failure data points listed in Table 4-1, and the failure data points listed in Table 4-5 (excluding grip failures). The data from Sample J, the 7/16 inch diameter strand used in the AASHTO test girders, also were excluded from the analyses.

In all cases, non-failure points ("runouts") were excluded. Non-failure points tend to be clustered at certain lives (e.g., two million cycles and four million cycles). With fatigue data, it is important to know both the fatigue lives and the nature of the distribution of the failures. Runouts do not correctly represent the distribution of failure data to the regression analysis procedures, so if they were included the regression results would not be fully representative of fatigue behavior. For the instance where simply a mean life at a specific stress range is desired, including non-failure data might be appropriate, depending upon the circumstances. But for the purposes of the regression analyses in this chapter the importance of the distribution of the data is recognized, so non-failure points are excluded. In any event, exclusion of non-failure data is conservative.

The models used in the regression analyses are presented in Table 5-1. The constants B_i are determined by regression analysis. Table 5-2 defines the data sets used in the regression analyses. Also listed in Table 5-2 are the number of data points for each data set (the sample size) and the stress domain of the data set. The models are the most accurate when used inside their data sets' domains. Table 5-3 presents the results of the various regression analyses. The first column of the table identifies the regression model. The letter corresponds to the data base as listed in Table 5-2 and the digit following the letter corresponds to the general model as given in Table 5-1.

It has been established previously that strand fatigue lives are log-normally distributed [19, 34, 37] and that the relationship between log of the fatigue life (Log N) and the log of the stress range (Log S_r) is linear [19]. It was decided to investigate what effect minimum stress (S_{min}) has on the fatigue life. Regressions A-1 through A-3 of Table 5-3 were found using the full data base (data set A). They indicate that, in regard to estimating mean Log N values, there is a definite minimum stress effect. Regressions A-2 and A-3 indicate that the data correlate equally well with Log S_{min} as with S_{min}. Regressions similar to regressions A-2 and A-3 which used mean stress or maximum stress instead of minimum stress also gave similar correlations and standard errors. It was decided to adopt as a convention the use of minimum stress rather than mean or maximum stress because minimum stress tends be used more often in the area of prestressed concrete than the other two stresses.

To further investigate the effect of minimum stress, two special regressions were developed using selected information from the data

Model No.	General Model
1	$\text{Log } N = B_1 + B_2 \text{ Log } S_r$
2	$\text{Log } N = B_1 + B_2 \text{ Log } S_r + B_3 \text{ Log } S_{min}$
3	$\text{Log } N = B_1 + B_2 \text{ Log } S_r + B_3 S_{min}$

Table 5-1: General Models

Data Set	Description of Data in the Set	Sample Size	Stress Domain of the Data (Stresses in ksi)
A	All Collected Data	391	$75 \leq S_{min} \leq 165$, $22 \leq S_r \leq 81$
B	105 ksi $\leq S_{min} \leq$ 110 ksi	127	$105 \leq S_{min} \leq 110$, $32 \leq S_r \leq 81$
C	158 ksi $\leq S_{min} \leq$ 165 ksi	164	$158 \leq S_{min} \leq 165$, $32 \leq S_r \leq 69$
D	7/16 inch diam.	81	$105 \leq S_{min} \leq 160$, $22 \leq S_r \leq 81$
E	1/2 inch (12.7 mm) diam.	268	$81 \leq S_{min} \leq 165$, $32 \leq S_r \leq 81$
F	0.6 inch (15.2 mm) diam.	26	$50 \leq S_{min} \leq 97$, $26 \leq S_r \leq 69$

Table 5-2: Data Sets and Stress Domains

Regression I. D.	Mean Fatigue Life Regression Model (Stresses in ksi)	Correl. Coeff.	Std. Error	K Factor
A-1	$\text{Log } N = 11.45 - 3.50 \text{ Log } S_r$	0.865	0.228	2.11
A-2	$\text{Log } N = 13.54 - 3.56 \text{ Log } S_r - 0.947 \text{ Log } S_{min}$	0.899	0.200	2.11
A-3	$\text{Log } N = 12.06 - 3.59 \text{ Log } S_r - 0.00355\, S_{min}$	0.900	0.199	2.11
B-1	$\text{Log } N = 11.82 - 3.66 \text{ Log } S_r$	0.950	0.142	2.24
C-1	$\text{Log } N = 11.49 - 3.59 \text{ Log } S_r$	0.904	0.180	2.20
D-1	$\text{Log } N = 10.39 - 2.91 \text{ Log } S_r$	0.812	0.271	--
D-2	$\text{Log } N = 16.07 - 3.56 \text{ Log } S_r - 2.14 \text{ Log } S_{min}$	0.875	0.225	--
E-1	$\text{Log } N = 11.74 - 3.68 \text{ Log } S_r$	0.894	0.194	--
E-2	$\text{Log } N = 13.48 - 3.66 \text{ Log } S_r - 0.837 \text{ Log } S_{min}$	0.918	0.173	--
F-1	$\text{Log } N = 12.51 - 4.01 \text{ Log } S_r$	0.899	0.261	--
F-2	$\text{Log } N = 15.02 - 3.84 \text{ Log } S_r - 1.51 \text{ Log } S_{min}$	0.917	0.240	--

Note: See Table 5-2 for the stress domains of the models listed above.

Table 5-3: Mean Fatigue Life Regression Results base. In one case, only data points with minimum stresses between 105 ksi and 110 ksi were used (data set B); in the other case the data points had minimum stresses between 158 ksi and 165 ksi (data set C).

Table 5-4 shows what stress ranges the various regression results predict for a mean fatigue life of two million cycles. This has been done for two different minimum stresses. Considering the predicted stress ranges from regression results A-2 through C-1, minimum stress is shown to be significant. Between the two minimum stress levels, the average stress ranges differ by 3.9 ksi, or about 14% of the smallest predicted stress range. Note that the regressions all predict about the same stress ranges. This indicates that the same minimum stress effect is shown in regression models based on all of the available data (data set A) as is shown in regression models based on data grouped by minimum stress (data sets B and C). Any of regressions A-2 through C-1 represent the mean fatigue life equally well when used within the data sets' stress domains.

The predicted mean life stress ranges of Table 5-4 for data sets D, E, and F (7/16, 1/2, and 0.6 inch diameter strand, respectively) indicate that there is a variation in the fatigue behavior of different strand sizes. Note that the variation is not consistent with different types of general models. The stress ranges predicted from regressions D-1, E-1 and F-1 indicate that 0.6 inch strand has the highest fatigue strength for a two million cycle mean life. But the stress ranges predicted from regressions D-2, E-2, and F-2 indicate that 0.6 inch strand has the lowest fatigue strength.

These inconsistencies are probably due to limitations in the data sets. There are fewer data points for the 7/16 inch strand (data set D) compared to 1/2 inch strand (data set E). The limited data set also does not have the same diversity of minimum stress levels as the 1/2 inch strand data set (see Table 5-2). Note that for 0.6 inch strand (data set F), the number of data points is quite small and the stress domain also lacks diversity of minimum stress. Until more complete data are available, distinctions by size of strand are not warranted.

Regression I. D.	Predicted Stress Range (ksi) S_{min} = 105 ksi	S_{min} = 160 ksi
A-1	29.6	29.6
A-2	31.3	28.0
A-3	31.6	27.9
B-1	32.2	--
C-1	--	27.9
D-1	25.4	25.4
D-2	33.8	26.3
E-1	30.1	30.1
E-2	31.6	28.7
F-1	35.3	35.3
F-2	29.9	25.3

Table 5-4: Two Million Cycle Mean Life Stress Ranges

5.2 Development of a Design Relationship

Rather than being directly concerned with mean fatigue life estimates, the designer wants to know what to do to minimize the chance of fatigue failure. There are several statistical approaches to developing the needed information, the regression results of Table 5-5 representing one approach. The original regression results are listed in Table 5-3. The results in Table 5-5 represent the one-sided tolerance limit where it is 95% probable that at least 97.5% of the distribution will be above the limit. The tolerance limits are a function of both the standard error of estimate (the estimated standard deviation) and the number of data points analyzed [26]. The relationship between the lower limit regression results and the mean life models is:

(Lower Limit Model) =
(Mean Life Model) - K x (Standard Error).

The K factors used are listed in the last column of Table 5-3.

Again, it is convenient to look at what stress ranges the models predict will cause a fatigue life of two million cycles. Table 5-6 shows these ranges, at two different minimum stress levels, for the models of Table 5-5. Of note is the approximate agreement of regressions A-2L, A-3L, and B-1L at the lower minimum stress level, and the close agreement of regressions A-1L, A-2L, A-3L, and C-1L at the higher minimum stress level. Still evident is a significant effect of minimum stress, the difference between the average predicted stress ranges of the two minimum stress levels being 3.4 ksi, or about 16% of the smallest predicted stress range.

For the purposes of design, lower limit regression model A-1L of Table 5-5 would be the most appropriate to use. Although it was previously stated that minimum stress was significant, it is desirable that design equations be kept straightforward. Also, design guides should be properly conservative. Modified regression model A-1L best fits these requirements. Figure 5-1 shows model A-1L along with all the failure points upon which it is based.

5.3 Strand Length and Fatigue Life

The information in the data base comes from test specimens of varying gage lengths (35 to 54 inches). It is possible that the recommended design relationship (Model A-1L) could be applicable only within a certain range of lengths. Thus, the question of the effect of length needs to be resolved.

Edwards and Picard [12] tested specimens of three different lengths (255, 570, and 890 mm or 10.0, 22.4, and 35.0 inches) at four different stress ranges. Figure 5-2 shows a plot of the reported data. The mean Log N values do decrease with increasing length, but the effect

Regression I. D.	Lower Tolerance Limit Model (Stresses in ksi)
A-1L	$\text{Log } N = 10.97 - 3.50 \text{ Log } S_r$
A-2L	$\text{Log } N = 13.12 - 3.56 \text{ Log } S_r - 0.947 \text{ Log } S_{min}$
A-3L	$\text{Log } N = 11.64 - 3.59 \text{ Log } S_r - 0.00355 \; S_{min}$
B-1L	$\text{Log } N = 11.50 - 3.66 \text{ Log } S_r$
C-1L	$\text{Log } N = 11.09 - 3.59 \text{ Log } S_r$

Note: See Table 5-2 for the domains of the models listed above.

Table 5-5: Lower Tolerance Limit Fatigue Life Models

Regression I. D.	Predicted Stress Range (ksi) S_{min} = 105 ksi	S_{min} = 160 ksi
A-1L	21.6	21.6
A-2L	23.9	21.3
A-3L	24.2	21.3
B-1L	26.3	--
C-1L	--	21.6

Table 5-6: Two Million Cycle Lower Limit Stress Ranges

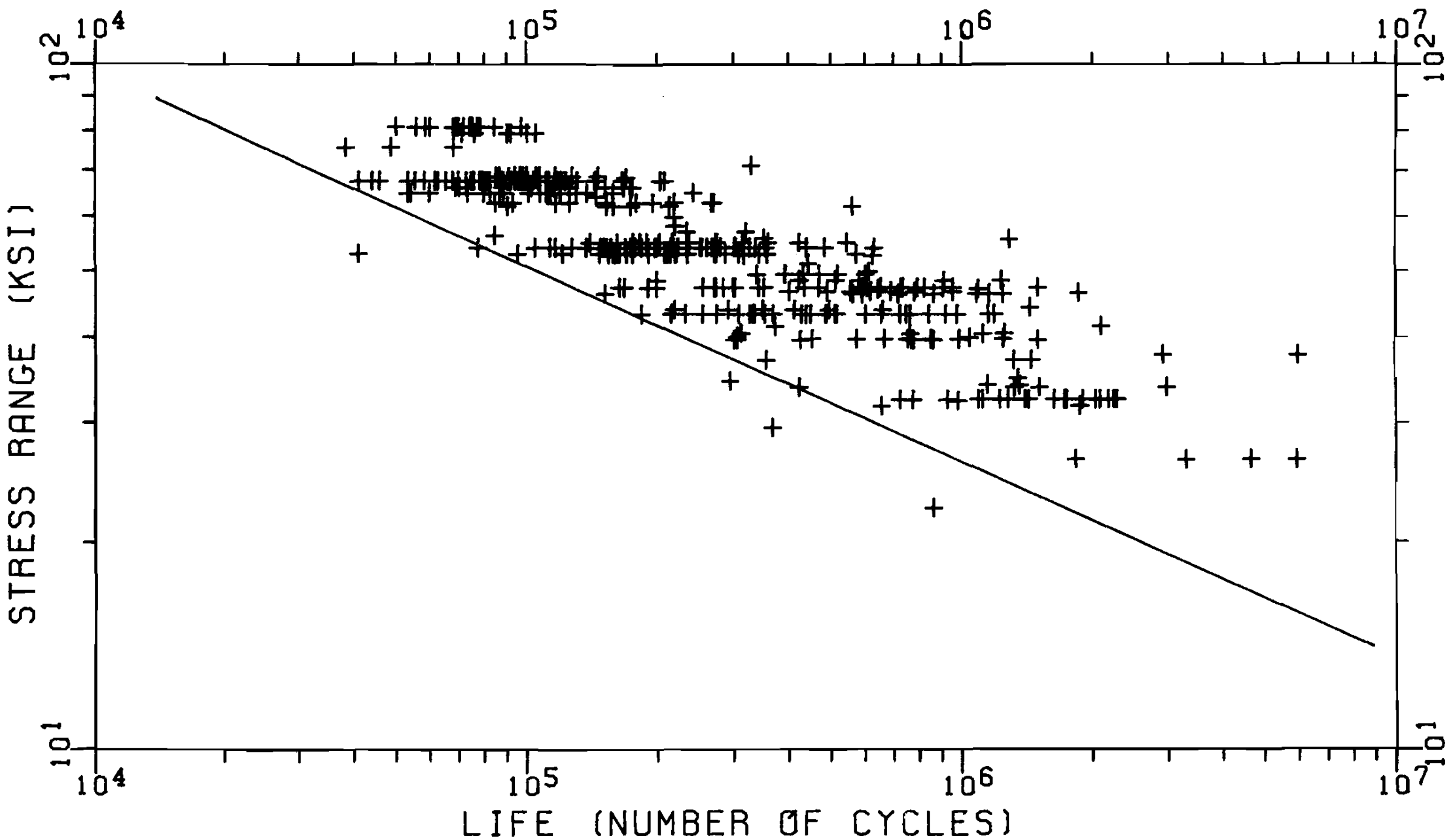

Figure 5-1: Recommended Design Model and Its Data

is less pronounced at longer lengths. For the two highest stress ranges, the mean Log N values at lengths of 22.4 and 35.0 inches are nearly the same. The appearance of the data in general suggests that with further increases in length (beyond 35 inches) the mean Log N values will not change much for any given stress range.

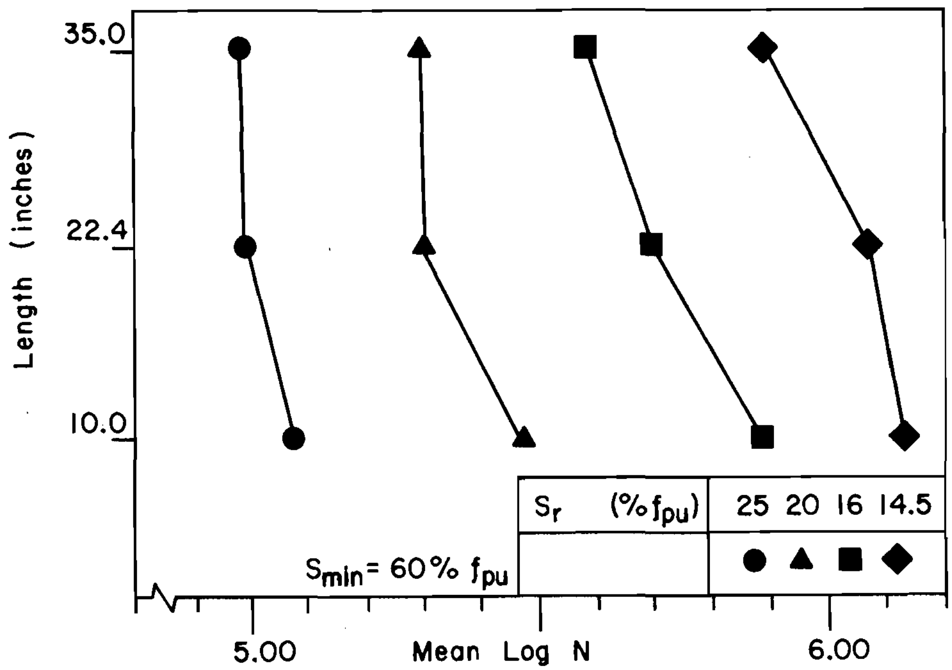

Figure 5-2: Length Effect Data

The recommended design model is based on a probability of survival of 97.5%, whereas Edwards and Picard's data are mean life values (50% survival). It could be that the observation of the stabilizing of lives with increasing length may not apply to low probability of failure data, but this does not appear to be the case. Birkenmaier and Narayanan [8] report prestressing wire fatigue tests which indicate that the length effect is diminished at low probabilities of failure. Considering both the Edwards and Picard data and the observation of Birkenmaier and Narayanan, the recommended design model appears valid for lengths of strand usually encountered in design.

5.4 A Fatigue Limit for Prestressing Strand

It is important to address the issue of a fatigue limit. Early researchers have extrapolated their data to find values for fatigue limits [36]. Other researchers have suggested that there is instead a slight flattening of the Log N-Log S_r curve at long lives [19]. Recently, it has been expressed that there seems to be no fatigue limit for strand [18].

Figure 5-3 shows the available failure and non-failure data at stress ranges of less than 35.0 ksi along with Model A-1L. There are six recorded strand fatigue failures at stress ranges of less than 30.0 ksi [15, 21, 36]. The same references also report 21 non-failure data points for stress ranges of less than 30.0 ksi. The lowest reported stress range causing a fatigue failure is 22.5 ksi [21]. Using the available data as a guide, a reasonable fatigue limit appears to be 20.0 ksi, also shown in Figure 5-3. It must be kept in mind that this limit is based on extrapolation of the available data. Such a fatigue limit needs to be incorporated into an overall philosophy which considers the number and magnitude of stress cycles.

5.5 Code Provisions and Committee Recommendations

Code provisions and published committee recommendations are the usual source of information for the designer. Table 5-7 compares some recommendations and provisions with the suggested design equation A-1L of Table 5-5:

$$\text{Log } N = 11.0 - 3.5 \text{ Log } S_r.$$

Category A and Category B are from the AASHTO Specifications [1]. Values are given for both redundant and nonredundant load path structures and are based on fatigue tests of structural steel beams and girders. Figure 5-4 shows that regression A-1L falls midway between and approximately parallel to the Category A and Category B recommendations for redundant load path structures.

For strand used in prestressed concrete, ACI Committee 215 [18] recommends that the stress range not exceed 0.10 f_{pu} for uncracked

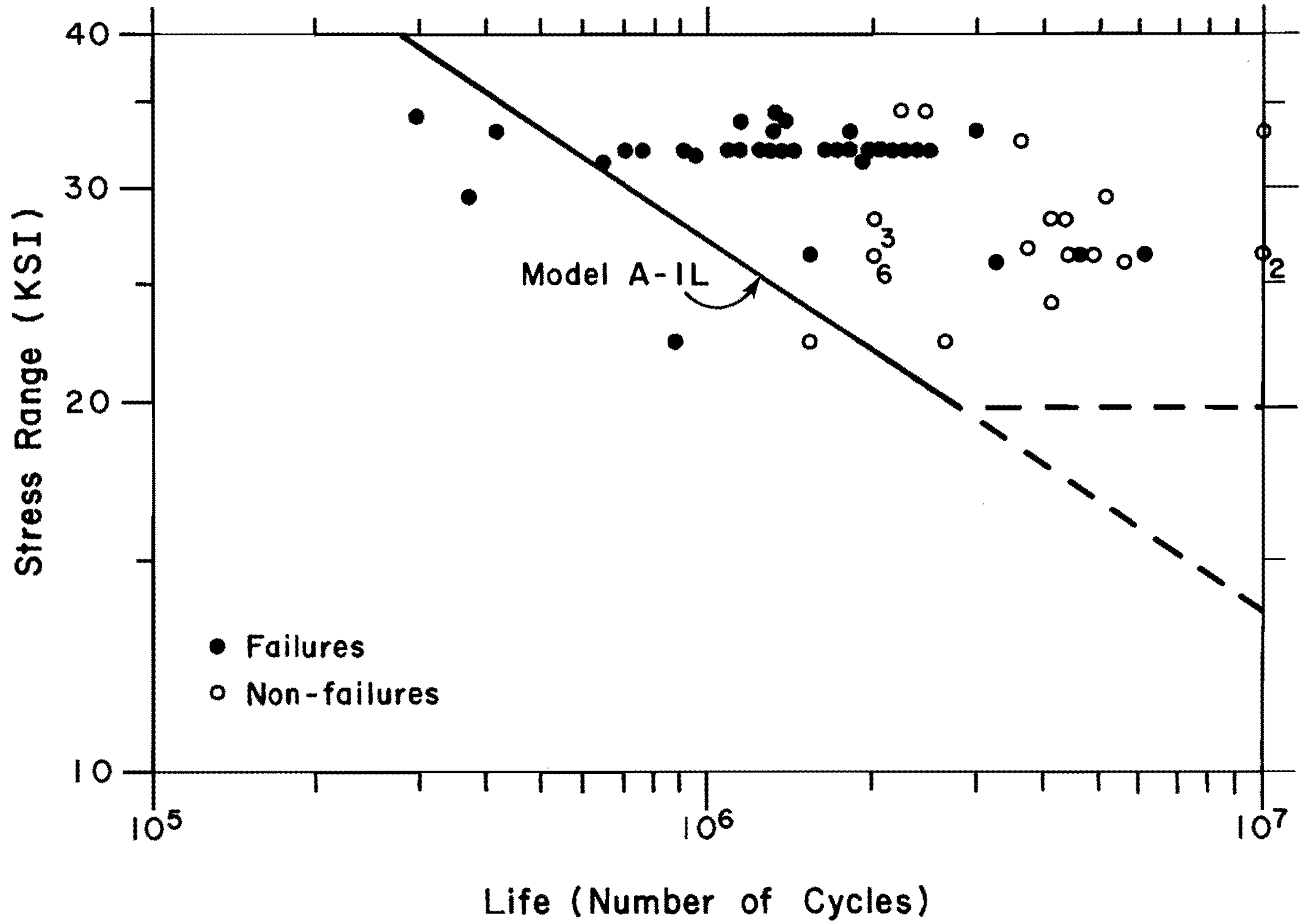

Figure 5-3: Low Stress Range Data

	Allowable Stress Range (ksi)			
	For 100,000 cycles	For 500,000 cycles	For 2,000,000 cycles	For Over 2,000,000 cycles
Model A-1L	50	32	22	20
AASHTO Category A (redundant)	60	36	24	24
AASHTO Category B (redundant)	45	27.5	18	16
AASHTO Category A (nonredundant)	36	24	24	24
AASHTO Category B (nonredundant)	27.5	18	16	16
Committee 215, GR 250 (1)	25*	25*	25*	25*
Committee 215, GR 270 (1)	27*	27*	27*	27*
Committee 215, GR 250 (2)	10*	10*	10*	10*
Committee 215, GR 270 (2)	10.8*	10.8*	10.8*	10.8*

*Committee 215 does not differentiate between number of cycles in its design recommendations.

AASHTO Stress Cycles [Table 1.7.2B]

Main (Longitudinal) Load Carrying Members

Type of Road	Case	ADTT*	Truck Loading	Lane Loading†
Freeways, Expressways, Major Highways and Streets	I	2500 or more	2,000,000**	500,000
	II	less than 2500	500,000	100,000
Other Highways and Streets not included in Case I or II	III		100,000	100,000

*Average Daily Truck Traffic (one direction).
†Longitudinal members should also be checked for truck loading.
**Members shall also be investigated for "over 2 million" stress cycles produced by placing a single truck on the bridge distributed to the girders as designated in Article 1.3.1(B) for one traffic lane loading.

Table 5-7: Comparison with Code Provisions and Committee Recommendations

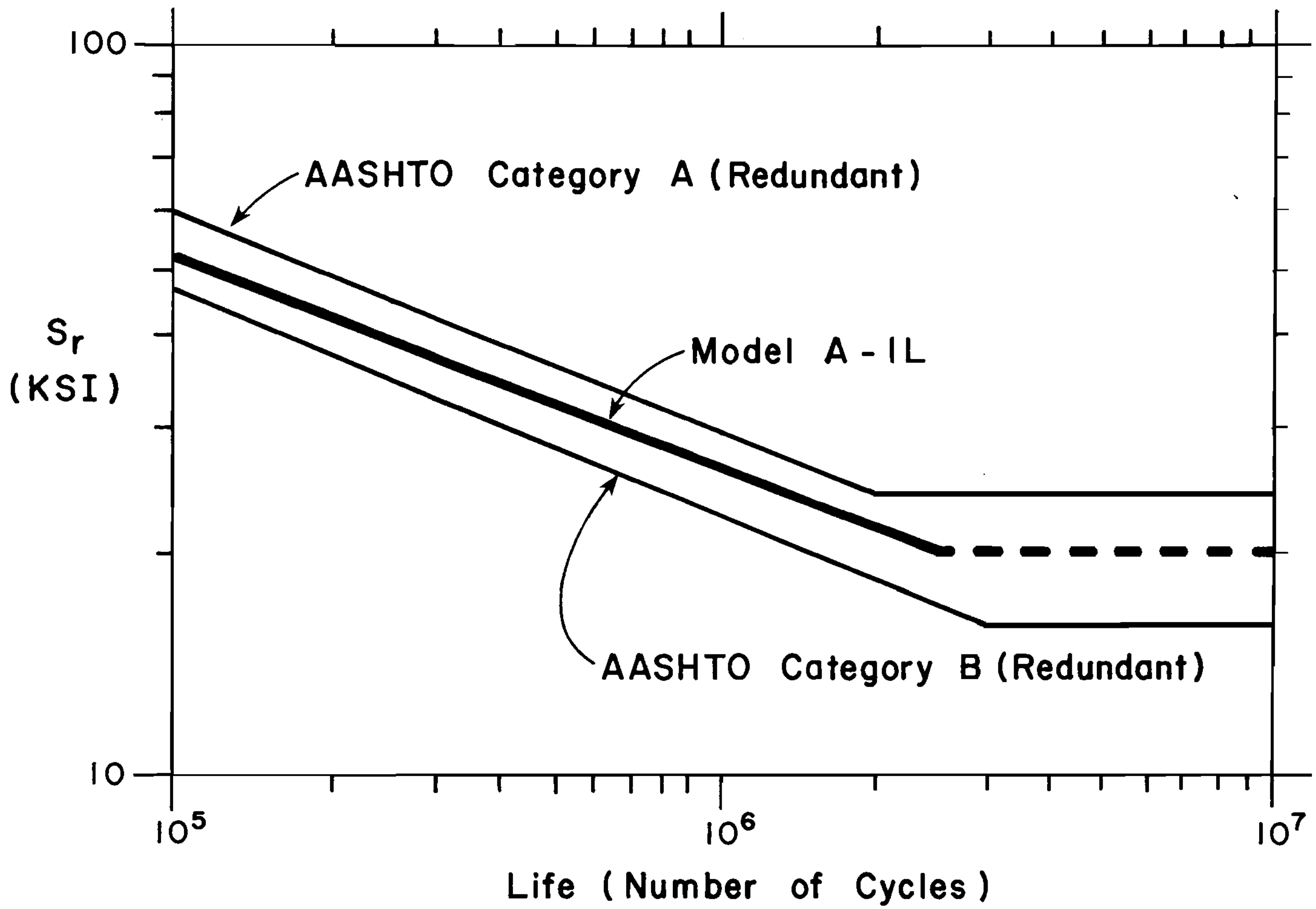

Figure 5-4: Comparison with Code Provisions

sections or 0.04 f_{pu} for cracked sections. Reported elsewhere in the literature are results of several constant load cycle fatigue tests of beams and girders [20, 25, 27, 28, 29, 30, 35]. Figure 5-5 compares these beam and girder results with regression A-1L and the Committee 215 recommendations. The data are plotted at lives and stress ranges as reported by the various authors. In all cases the specimens were cracked before fatigue loading or cracking developed during the early stages of fatigue loading. There appears to be no correlation between the beam and girder results and regression A-1L. Note also that there are eight girder and beam test results which fall below the lowest Committee 215 recommendations.

The principal uncertainty with the data plotted in Figure 5-5 is the reported stress ranges. There was little consistency in the methods used by the various authors to determine the stress ranges in the strand. The analysis of strand stresses at a cracked section is the current weak link in interpreting prestressed concrete fatigue data. Until the procedures for analysis of stresses at a cracked section are refined, large scatter of the data, as observed in Figure 5-5, can be expected.

5.6 Considerations in Design for Fatigue

One of the prerequisites in a proper design for fatigue is that an accurate estimate of the stress range be made. Once an estimation of the stress range has been found, then the relationship to the fatigue threshold can be evaluated. If the stress range is over the threshold, then fatigue should be considered in the design process. The following paragraphs briefly discuss the evaluation of the threshold and some other fatigue design considerations for two common uses of prestressing strand where fatigue is likely.

5.6.1 Stay Cables and Suspension Hangers. Application of the fatigue information developed in this chapter to stay cables and

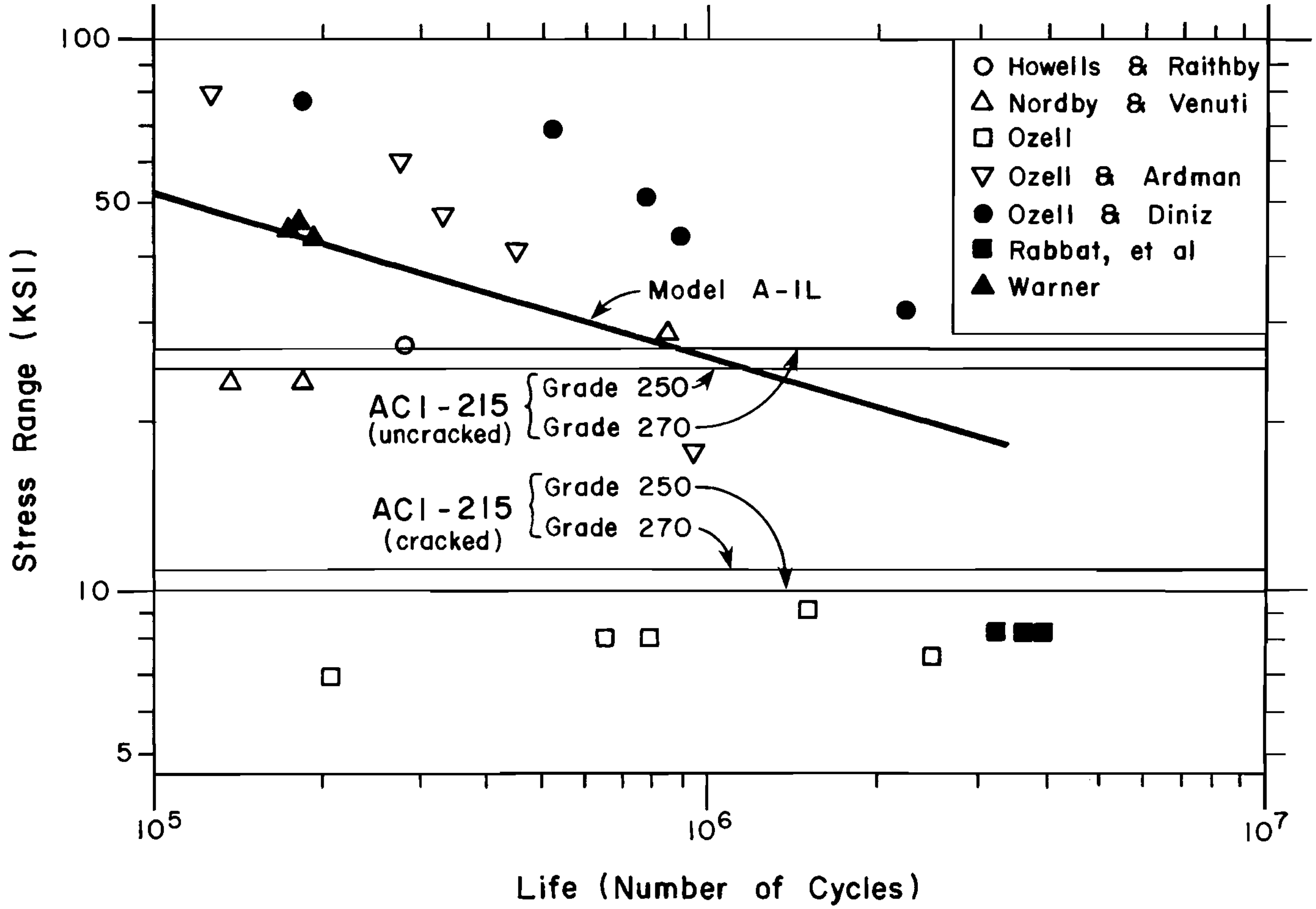

Figure 5-5: Comparison with Cracked Beam and Cracked Girder Tests

suspension hangers is most appropriate. The type of loading seen by the stays and hangers is identical to the type of loading applied to the specimens which generated the fatigue data used in this chapter's analyses.

Analysis for stresses in stay cables and suspension hangers is fairly straightforward and reliable. However, when the stays and hangers are used to support bridge structures, the problem arises in establishing what is the credible fatigue load to consider. Discussion of this problem is beyond the scope of this paper, but it must be noted that the selection of a credible load is very important in the fatigue design of a bridge structure.

At the present time, the prudent yet flexible solution is to base design of redundant stay cables and suspension hangers on the values given for AASHTO Category B for redundant load path structures, as shown in Fig. 5.4 and Table 5-7. If the member is nonredundant, then the lower Category B values for nonredundant load path structures shown in Table 5-7 should be used. This approach ties the design of such members to the general AASHTO approach and allows some variation in design according to expected traffic frequency and loading type. This overall approach will need further development as more test data become available.

It must be kept in mind that while the recommended model is based on tests of strand from many different sources, the model represents lower bound fatigue behavior of those samples tested. Strand used in the stays or hangers for a specific bridge usually comes from the same manufacturer but may be from many coils and different manufactured lengths of strand. It is most likely that the design model will be a lower bound representation of the strand used, but if the strand has unusually poor fatigue characteristics due to manufacturing problems, the design model may not be sufficiently conservative and the stays or hangers may fail unexpectedly early. In other cases, the designer may wish to base design on higher stress ranges than given by the lower bound model.

A solution to these situations is to require testing of samples of the strand to be used in the stays or hangers. At least one sample should be obtained from each manufactured length of strand actually used to construct the stays or hangers. The tests should investigate both the fatigue life at the maximum expected stress range and also fatigue life at the assumed threshold stress range. The tests should be conducted at the highest expected minimum stress and the tests should not be considered run out until ten million cycles have been reached. The test specimens should be of the longest practical length, but not less than 4 ft. From each sample obtained, at least three specimens should be tested at both the high and low stress ranges. The results of these tests would indicate if the strand is of a consistently poor quality.

It must be cautioned that fatigue considerations should not be limited to just the strand used in the stays or hangers. Often the anchorages or socketing device can induce a stress concentration, causing the strand to fail at the socket or anchor earlier than expected. There is also the possibility that the anchorage device itself can fail in fatigue. If the stays are bent over a saddle, there is again the chance for stress concentrations in the strand and the possibility of early failures. All of these factors need to be considered in addition to the basic fatigue behavior of the component strand.

5.6.2 Pretensioned Concrete Girders. Fatigue considerations for pretensioned girders must be divided into two cases: cracked girders and uncracked girders. It is difficult to relate fatigue of strand as an isolated element to fatigue of strand in concrete at a cracked section because of the problems in analyzing for stresses at a cracked section. The recommended design model and fatigue limit cannot be used for fatigue of strand at cracked sections.

But if the girder remains uncracked, fatigue of strand in an uncracked girder can be related to fatigue of strand as an isolated element when certain assumptions are made. One assumption is that the estimate of the stress range seen by the strand in the uncracked girder is reliable. It is also assumed that in uncracked sections, lateral forces on the strand are negligible.

If these assumptions hold true, then strand fatigue in an uncracked section is similar to fatigue of strand as an isolated element. The recommended AASHTO Category B limits for redundant load path structures are a conservative application of the design model and should be directly applicable to uncracked pretensioned girders.

The design model can be considered as being a widely representative lower bound of the strand used in pretensioned girders. With the typical practices used in the production of pretensioned concrete components, strand from a number of different reels and possible different strand manufacturers appears in the final product. The design model is based on tests of strand from a number of different strand manufacturers. Thus, the design model reasonably accounts for possible variation of strand fatigue behavior from manufacturer to manufacturer. The further conservatism introduced by the selection of the slightly lower AASHTO Category B values provides further margins of safety to recognize the limits in the data base.

Again, the designer must be cautioned that these recommendations do not apply to cracked sections. Any investigation of fatigue in a pretensioned component has to include determining whether or not the section cracks. Only if the section remains uncracked can the above recommendations be applied.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From the strand tests reported herein and from a large number of previous tests reported in the literature, a large data base containing information about fatigue tests on strand as an isolated element has been built. Analysis of the information suggests that minimum stress does have an influence on the fatigue life of the strand, but that the influence is not great enough to warrant including minimum stress in design equations. From this data base the following lower bound relationship was developed:

$$\text{Log } N = 11.0 - 3.5 \text{ Log } S_r$$

where S_r is the stress range in ksi units and N is the number of fatigue cycles. A fatigue limit stress of 20 ksi appears reasonable. It must be emphasized that the equation represents the fatigue behavior of strand as an isolated element. It was developed from the strand fatigue failure points in the data base previously mentioned. It is 95% probable that 97.5% of the failure points fall above this line. The failure points had minimum stresses from 75 ksi to 165 ksi, and stress ranges from 22 ksi to 81 ksi.

Currently, there exist no code provisions or material standards dealing directly with fatigue of prestressing strand. Of the existing code provisions for fatigue of structural steel, the AASHTO Category B for redundant structures is the closest match (in a conservative manner) to the relationship recommended in the previous paragraph, and is recommended for fatigue design of prestressing strand where the stress range can be accurately estimated, such as with cable stays or uncracked prestressed concrete sections.

Tests conducted on samples of strand representing various manufacturers indicate significant variation among manufacturers. A similar variation was observed in the fatigue performance for two samples of the same product produced by the same manufacturer.

Tests were conducted on a sample from strand which will be used in construction of girder fatigue specimens. The results indicate that the strand has fatigue performance somewhat better than that of the "average" strand. After completion of the girder fatigue testing, it is hoped that a relationship between the strand test results and the girder test results can be developed.

The fatigue tests on the girder strand sample also gave rise to another observation. It was noted that, for the particular grip being used, the fatigue curves for strand in air and strand in the grip region were different. In the long life, low stress range region, the grip region fatigue curve dominated.

6.2 Recommendations for Further Research

Areas for future research can be divided into two general areas: fatigue behavior of strand as an isolated element and fatigue behavior of strand in application environments. Concerning the first category, there is still a lack of test results in the low stress range, long life region. Hindering the research is the development of a grip which is both fatigue resistant at these low stress ranges and convenient to use. There is also a strong need for research specifically designed to investigate the length effect at lengths typically encountered in design (lengths beyond three feet). Further research could also investigate the nature of the minimum stress effect and see if it is consistent across various stress ranges.

Prestressed concrete fatigue research should be directed towards explaining the differences observed in fatigue of strand as an isolated element and fatigue of strand in beams and girders. Areas to investigate include methods of determining the stress in the strands, the effects of cracked sections, the effects of bond degradation, and the effects of lateral forces between the strand and the concrete. Cable stay research would be concerned with strand fatigue in grips or sockets, fatigue behavior of bundled strands, length effects, and effects of eccentricities introduced due to lateral forces and to alignment tolerances or errors.

Appendix A

TABLES OF DATA

Group Number	Absolute Stresses (ksi)			Indexed Stresses (fraction of f_{conv})		
	min.	max.	range	min.	max.	range
Nuwaysir						
101	139.0	166.8	27.8	.556	.667	.111
102	139.0	176.0	37.0	.556	.704	.148
103	139.0	185.3	46.3	.556	.741	.185
104	139.0	194.7	55.8	.556	.779	.223
Lane and Ekberg						
151	132.2	172.3	40.0	.529	.689	.160
152	136.2	170.0	33.8	.545	.680	.135
153	136.2	177.8	41.5	.545	.711	.166
154	136.2	182.5	46.3	.545	.730	.185
155	136.2	192.5	56.3	.545	.770	.225
156	163.0	187.5	24.5	.652	.750	.098
157	163.0	189.7	26.8	.652	.759	.107
158	163.0	192.5	29.5	.652	.770	.118
159	163.0	195.2	32.3	.652	.781	.129
160	163.0	197.5	34.5	.652	.790	.138
161	163.0	200.0	37.0	.652	.800	.148
162	175.0	197.5	22.5	.700	.790	.090
Slutter and Ekberg						
201	140.0	174.0	34.0			

Table A-1: Stress Levels

Group Number	Absolute Stresses (ksi)			Indexed Stresses (fraction of f_{conv})		
	min.	max.	range	min.	max.	range
Fisher and Viest						
251	135.2	183.6	48.4			
252	135.2	197.3	62.1			
253	135.2	210.9	75.7			
254	162.5	197.3	34.8			
255	162.5	210.9	48.4			
256	162.5	224.6	62.1			
Warner and Hulsbos						
301	105.8	145.4	39.7	.400	.550	.150
302	105.8	152.0	46.3	.400	.575	.175
303	105.8	158.6	52.9	.400	.600	.200
304	105.8	171.9	66.1	.400	.650	.250
305	105.8	185.1	79.3	.400	.700	.300
306	105.8	198.3	92.5	.400	.750	.350
307	105.8	211.5	105.8	.400	.800	.400
308	158.6	185.1	26.4	.600	.700	.100
309	158.6	190.4	31.7	.600	.720	.120
310	158.6	191.7	33.0	.600	.725	.125
311	158.6	198.3	39.7	.600	.750	.150
312	158.6	211.5	52.9	.600	.800	.200
313	158.6	224.7	66.1	.600	.850	.250
Hilmes						
351	128.5	161.7	33.2			
352	128.5	164.5	36.0			
353	128.5	170.0	41.5			
354	128.5	175.5	47.0			
355	128.5	178.3	49.8			
Tide and VanHorn						
401	108.0	140.4	32.4	.400	.520	.120
402	108.0	140.4	32.4	.400	.520	.120
403	108.0	140.4	32.4	.400	.520	.120
411	108.0	151.2	43.2	.400	.560	.160
412	108.0	151.2	43.2	.400	.560	.160
413	108.0	151.2	43.2	.400	.560	.160

Table A-1 (Continued)

Group Number	Absolute Stresses (ksi) min.	max.	range	Indexed Stresses (fraction of f_{conv}) min.	max.	range
Tide and VanHorn (Continued)						
421	108.0	162.0	54.0	.400	.600	.200
422	108.0	162.0	54.0	.400	.600	.200
423	108.0	162.0	54.0	.400	.600	.200
431	108.0	175.5	67.5	.400	.650	.250
432	108.0	175.5	67.5	.400	.650	.250
433	108.0	175.5	67.5	.400	.650	.250
441	108.0	189.0	81.0	.400	.700	.300
442	108.0	189.0	81.0	.400	.700	.300
443	108.0	189.0	81.0	.400	.700	.300
451	151.2	216.0	64.8	.560	.800	.240
452	151.2	216.0	64.8	.560	.800	.240
453	151.2	216.0	64.8	.560	.800	.240
454	151.2	216.0	64.8	.560	.800	.240
455	151.2	216.0	64.8	.560	.800	.240
461	162.0	194.4	32.4	.600	.720	.120
462	162.0	194.4	32.4	.600	.720	.120
463	162.0	194.4	32.4	.600	.720	.120
471	162.0	205.2	43.2	.600	.760	.160
472	162.0	205.2	43.2	.600	.760	.160
473	162.0	205.2	43.2	.600	.760	.160
481	162.0	216.0	54.0	.600	.800	.200
482	162.0	216.0	54.0	.600	.800	.200
483	162.0	216.0	54.0	.600	.800	.200
491	162.0	229.5	67.5	.600	.850	.250
492	162.0	229.5	67.5	.600	.850	.250
493	162.0	229.5	67.5	.600	.850	.250
Cullimore						
501	72.4	103.6	31.2			
502	66.6	109.3	42.7			
503	63.6	112.4	48.8			
504	60.5	115.5	55.0			
505	57.6	118.3	60.7			
506	54.6	121.4	66.9			

Table A-1 (Continued)

Group Number	Absolute Stresses (ksi)			Indexed Stresses (fraction of f_{conv})		
	min.	max.	range	min.	max.	range
Edwards and Picard						
551	109.7	156.4	46.6	.400	.570	.170
552	109.7	159.1	49.4	.400	.580	.180
553	109.7	164.6	54.9	.400	.600	.200
554	109.7	178.3	68.6	.400	.650	.250
555	164.6	204.4	39.8	.600	.745	.145
556	164.6	208.5	43.9	.600	.760	.160
557	164.6	219.4	54.9	.600	.800	.200
558	164.6	233.2	68.6	.600	.850	.250
Muller and Zeller						
701	96.7	140.8	44.1			
702	95.3	140.8	45.5			
703	93.9	140.8	46.9			
704	91.0	140.8	49.8			
705	89.6	140.8	51.2			
706	88.2	140.8	52.6			
707	86.8	140.8	54.1			
708	85.4	140.8	55.5			
709	83.9	140.8	56.9			
711	98.2	140.8	42.7			
712	96.7	140.8	44.1			
713	93.9	140.8	46.9			
714	88.2	140.8	52.6			
715	83.9	140.8	56.9			
716	81.1	140.8	59.7			
717	76.8	140.8	64.0			
718	72.6	140.8	68.3			
719	69.7	140.8	71.1			

Table A-1 (Continued)

Group Number	Absolute Stresses (ksi)			Indexed Stresses (fraction of f_{conv})		
	min.	max.	range	min.	max.	range
Storebaelt Bridge Tests						
751	50.8	88.5	37.7			
752	50.8	97.2	46.4			
753	50.8	108.8	58.0			
Frank and Hsu						
801	78.2	106.6	28.4			
802	73.0	99.5	26.5			
803	73.0	99.5	26.5			
811	75.3	138.0	62.7			
812	75.3	138.0	62.7			
813	75.3	138.0	62.7			

Table A-1 (Concluded)

Group	Lives		
Nuwaysir			
101	5155500. *		
102	1317200.	2082000. *	1446500.
	1469000. *		
103	861000.		
104	352100.		
Lane and Ekberg			
151	304700.	1041100.	
152	1326100.	422000.	2967600.
153	2101200.	373200.	
154	151500.		
155	84400.		
156	4107100. *		
157	3733500. *		
158	368400.		
159	980200.		
160	294200.		
161	356400.		
162	1564500. *	864000.	2962800. *
Slutter and Ekberg			
201	1147000.	1360000.	

Note: Asterisk indicates non-failure point.

Table A-2: Lives of Individual Data Points

Group		Lives	
Fisher and Viest			
251	1236000.	909200.	579000.
252	560700.	152700.	174000.
253	68100.	48700.	38200.
254	1351400.	2190000. *	2489300. *
255	512800.	422000.	199100.
256	213400.	90600.	159000.
Warner and Hulsbos			
301	3282500. *	5375000. *	
302	1246000.	1159600.	1082000.
	561000.	591000.	715000.
303	287400.	308400.	344100.
	274000.	573000.	359000.
304	175500.	152600.	168000.
	116000.	126000.	174000.
305	90400.	92000.	105200.
	100400.	71000.	76000.
306	36500.	54000.	
307	37800.		
308	3306000.	5440600. *	
309	652800.	1873500.	
310	3630200. *		

Note: Asterisk indicates non-failure point.

Table A-2 (Continued)

Group	Lives		
Warner and Hulsbos (Continued)			
311	425500.	304800.	777000.
	863000.	768500.	300600.
	1500000.		
312	234400.	211000.	160000.
	170600.	121000.	159000.
	222000.	95500.	155000.
	235800.	271800.	191300.
	176000.	162400.	208400.
	214500.	147600.	40900.
	164500.	220600.	
313	103000.	70000.	88300.
	73000.	88500.	68600.
Hilmes			
351	3342000. *	2030000. *	2600000. *
	2006000. *	2765000. *	2623000. *
	2116000. *	2743000. *	2463000. *
	2547000. *	2077000. *	
352	1580000.	2359000.	2403000.
	1608000.	3881000. *	2141000.
	4131000. *	4098000. *	4424000. *
353	466000.	489000.	2101000.
	483000.	394000.	2736000. *
	2680000. *		
354	335000.	798000.	320000.
	1660000.	893000.	2174000.
	2712000. *	2390000. *	
355	1726000.	2008000. *	791000.
	246000.	2502000. *	2080000. *
	2020000. *	290000.	54000.
	93000.	85000.	42000.

Note: Asterisk indicates non-failure point.

Table A-2 (Continued)

Group	Lives		
Tide and VanHorn			
401	2241000.	2282000.	772500.
402	928000.	2185000.	1281300.
403	1747000.	1427000.	1901000.
411	721700.	723000.	1154000.
412	763000.	428000.	600400.
413	1189900.	976600.	919000.
	745100.		
421	156400.	281100.	218000.
	252400.	261200.	176300.
422	338000.	303000.	326800.
	184400.	235500.	
423	630000.	223700.	484900.
	137700.	301900.	272200.
	169200.		
431	99200.	75800.	80900.
	112600.	101000.	107100.
432	131100.	96700.	95900.
	91800.	120500.	120100.
433	123500.	80600.	123300.
	96400.	166700.	204000.
441	71700.	67800.	77200.
	69400.	50000.	58500.
442	74300.	75200.	60000.
	74200.	69800.	74800.
443	97500.	68800.	55800.
	58500.	78400.	84400.

Table A-2 (Continued)

Group		Lives	
Tide and VanHorn (Continued)			
451	158700.	242500.	130500.
452	54100.	79900.	53400.
	73300.	107900.	111600.
453	112500.	138100.	119900.
454	59800.	87200.	82800.
455	88900.	114000.	101500.
461	1405500.	1635000.	1091000.
462	1115900.	722000.	1224900.
463	1728600.	2031900.	2083800.
471	439100.	842900.	215200.
	326400.	232100.	254200.
	334800.		
472	183900.	517200.	370000.
	353700.	487400.	512500.
	653800.	449000.	
473	332100.	333600.	273400.
	307600.	489300.	
481	190700.	148400.	267900.
	104600.	151000.	178500.
482	174000.	77500.	127800.
	254400.	215700.	113500.
483	199500.	116900.	197900.
	439300.	152700.	356400.
491	78500.	81700.	88600.
	87800.	87200.	96300.

Table A-2 (Continued)

Group	Lives		
Tide and VanHorn (Continued)			
492	92300.	62500.	98300.
	55300.	90700.	97600.
493	208600.	94400.	97000.
	111200.	82300.	114300.
Cullimore			
501	9340000. *	4570000. *	5440000. *
	4870000. *	4750000. *	6620000.
	4200000.		
502	11160000. *	3070000.	2120000.
	5660000. *	5370000. *	10230000. *
	1370000.		
503	1230000.	2560000.	4370000.
	706000.	8020000.	1140000. *
504	1200000.	670000.	814000.
	539000.	314000.	4990000.
	6510000. *		
505	382000.	821000.	3160000.
	347000.	354000.	
506	412000.	1330000.	283000.
	142000.	429000.	
Edwards and Picard			
551	416000. +	496400. +	558600. +
	619000. +	686000. +	772000. +
	921200. +		
552	347000. +	395400. +	432700. +
	469800. +	514200. +	585800. +

Note: Asterisk indicates non-failure point, plus indicates replacement point.

Table A-2 (Continued)

Group	Lives		
Edwards and Picard (Continued)			
553	191300. +	238900. +	277200. +
	315400. +	358800. +	416300. +
	519900. +		
554	87400. +	98900. +	107600. +
	116300. +	126600. +	143200. +
555	473500. +	581700. +	667600. +
	752400. +	848000. +	973200. +
	1195700. +		
556	230100. +	295600. +	351400. +
	411600. +	489300. +	628500. +
557	144300. +	163400. +	177200. +
	189800. +	202500. +	216900. +
	235200. +	266400. +	
558	87400. +	91400. +	94200. +
	96900. +	99900. +	104500. +
Muller and Zeller			
701	2000000. *		
702	2000000. *	2000000. *	2000000. *
703	1095000.		
704	612000.		
705	443000.		
706	2000000. *	625000.	
707	2000000. *	303000.	
708	1293000.		

Note: Asterisk indicates non-failure point,
plus indicates reconstructed point.

Table A-2 (Continued)

Group	Lives		
Muller and Zeller (Continued)			
709	320000.		
711	2000000. *	2000000. *	2000000. *
712	1439000.		
713	644000.		
714	317000.		
715	2000000. *	234000.	
716	2000000. *	219000.	
717	2000000. *	145000.	
718	170000.		
719	330000.		
Storebaelt Bridge Tests			
751	6010000.	2910000.	
752	1860000.	10000000. *	
753	220000.		

Note: Asterisk indicates non-failure point

Table A-2 (Continued)

Group	Lives		
Frank and Hsu			
801	4030000. *	4250000. *	2000000. *
	2000000. *	2000000. *	
802	10000000. *	4550000. *	4860000. *
	2000000. *	2000000. *	1835000.
	2000000. *		
803	4670000.	10000000. *	5950000.
	2000000. *	2000000. *	2000000. *
811	93300.	125840.	219340.
	153280.	84850.	
812	117100.	267170.	270000.
813	195780.	179200.	153330.

Note: Asterisk indicates non-failure point

Table A-2 (Concluded)

Appendix B

ORDER STATISTICS

B.1 Introduction to Order Statistics

For even a minimal confidence level, most statistical methods require a relatively large number of data points (a large sample size). Reemsnyder [31] presents a method using order statistics "that permits the estimation of the CFD [cumulative frequency distribution] from relatively small sample sizes." The key point of the method is that when the observations ("statistics") of the sample population ". . .are arranged in order of increasing magnitude, the cumulative distribution frequency at each statistic may be estimated as a function of the rank or order of that statistic."

Reemsnyder continues and describes the theory of order statistics as follows:

> A population (for example, a particular grade of steel) consists of a large number m of individuals (tensile specimens). A value x_j (property) is assigned to each individual and is regarded as an observed point of the one-dimensional random variable Y (for example, tensile strength) where j is the order number of these values ordered from least to greatest or
>
> $$x_1 < x_2 < . . . < x_j < . . . < x_m.$$
>
> The probability of drawing an individual with a value Y equal to or less than x_j is
>
> $$P(Y \leq x_j) = F(x) = u_j$$
>
> where u_j is a relative order number
>
> $$u_j = j/m$$
>
> and is the cumulative frequency distribution of Y, F(x).

The function F(x) may be estimated by drawing a sample of size n from the population and arranging the individuals in order of increasing value

$$x_{1n} < x_{2n} < \ldots < x_{in} < \ldots < x_{nn}$$

The distribution function of the sample, u_{in} is called the "ith order statistic" and is identical to the population distribution function u_j. Since neither function is known, they must be estimated by

$$u_i = P_i + e$$

where P_i, the "plotting position," is a quantity uniquely determined by i (the order number of the sample) and n (the sample size) and e is the sampling error.

Reemsnyder mentions several different formulas for determining the plotting position. The most general form presented is:

$$P_i = (i - a)/(n - a - b + 1) \text{ where } 0 \leq a,\ b \leq 1$$

This formula is attributed to Bloom [9].

B.2 Reconstruction of Data Points

Order statistics can be used in a "reverse" manner. Given the mean, standard deviation, and sample size, the values of the original observations can be estimated. The following example illustrates the method used to produce the data of Edwards and Picard [12], as mentioned in Section 2.1.10 of Chapter 2.

This example will show how the data of group 558 in Appendix A was reconstructed. Edwards and Picard [12] reported that for one set of specimens tested, the sample size was 6, the mean value of log N ($\overline{\log N}$) was 4.98026, and the standard deviation of log N ($s_{\log N}$) was 0.03036. Proceeding from left to right in Table B-1, the first step is to assign the order numbers, i. The last order number is equal to the sample size. Next, the plotting position P_i is found. For the example in the table, the plotting position formula mentioned in the previous section was used, with a = b = 0.528. This value was selected for a and

i	P_i	x	log N	life
1	0.0794	-1.409	4.938	86600
2	0.248	-0.682	4.960	91100
3	0.416	-0.212	4.974	94200
4	0.584	0.212	4.987	97000
5	0.752	0.682	5.001	100200
6	0.921	1.409	5.023	105500

Table B-1: Example of Reconstructed Data

b because it gave results with means and standard deviations in close agreement (within 0.8%) with the original means and deviations given by Edwards and Picard. The formula gives the plotting position in terms of probability. The next step is to convert from the probability value to the corresponding standard deviation, x, of the standard normal probability distribution. This was done using a computer routine based on a polynomial approximation given in a mathematical handbook [3]. The next step is to find log N by evaluating the equation

$$\log N = \overline{\log N} + (x)(s_{\log N})$$

for the various values of x. The corresponding life is found by raising 10 to the power log N ($10^{\log N}$).

Although this method certainly cannot reproduce the exact data points which were generated in the original experiments, it does give a set of points with the same mean and standard deviation.

B.3 Graphic Evaluation of Data

Order statistics can be used to graphically investigate how well data fits an expected distribution. Again, the procedure will be illustrated by an example. The data used in the example are a replicate group from Warner and Hulsbos [37] with $s_{min} = 0.40\ f_{pu}$ and $s_r = 0.30\ f_{pu}$ (Group 305 in Appendix A).

i	life (N)	P_i
1	71000	0.0794
2	76000	0.248
3	90400	0.416
4	92000	0.584
5	100400	0.752
6	105200	0.9206

Table B-2: Data for Plot Example

---

	log N	N	P
Plus two	4.812	64800	0.9772
Mean	4.946	88300	0.5000
Minus two	5.080	120300	0.0228

Table B-3: Points on the Mean Line

The first step is to arrange the data in order of increasing lives and to assign order numbers (Table B-2, the first two columns). Then, a plotting position formula is chosen and the plotting position is computed. The values for a and b used here are the same as used in the previous example. The points are then plotted (Fig. B-1), with life on the abscissa (log scale) and with plotting position on the ordinate (probability scale).

Next, the information needed to construct the mean line is determined. Since fatigue life is log-normally distributed, the mean log N and the standard deviation of log N are found (respectively, 4.946 and 0.06713 for the data of Table B-2). The lives at mean log N and at plus and minus two standard deviations from the mean log N are found (the first two columns of Table B-3). These points are assigned a plotting position, P, based on their standard normal distribution. The mean

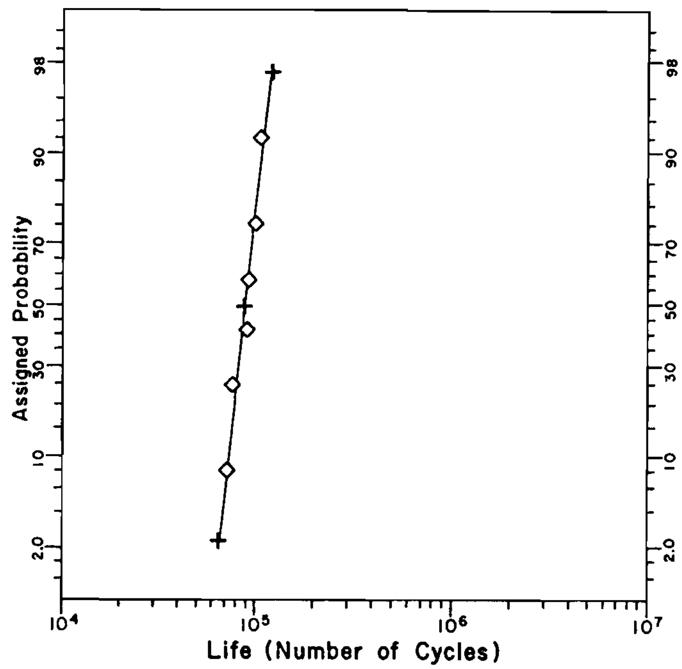

Figure B-1: Example Plot

value is plotted at the 50% position; plus two deviations is at 97.72%; and minus two deviations is at 2.28%. These points are plotted and, since the points are co-linear, a line can be drawn through the three points (Fig B-1).

The line represents the ideal distribution for the points. If the data points were exactly log-normally distributed, they would fall on the line. In general, the closer all of the data points are to the line, the closer the data follow a log-normal distribution.

Appendix C

STATIC TESTS

For three specimens each of Samples G and H, static tests to ultimate strength were performed. Table C-1 presents the results of the tests. Figures C-1 and C-2 show typical stress-strain curves obtained from the static tests.

Specimen	Ultimate Load (kips)	Ulitmate Stress* (ksi)
G-St1 **	40.9	267
G-St2 **	41.4	271
G-St3 **	41.0	268
J-St1	29.3	271
J-St2 **	29.1	270
J-St3 **	29.2	270

* Stresses are based on nominal areas of 0.153 $in.^2$ for Sample G (1/2 inch, Grade 270) and on 0.108 $in.^2$ for Sample J (7/16 inch, Grade 250).

** Failure occurred in the grip region.

Table C-1: Results of Static Ultimate Tests

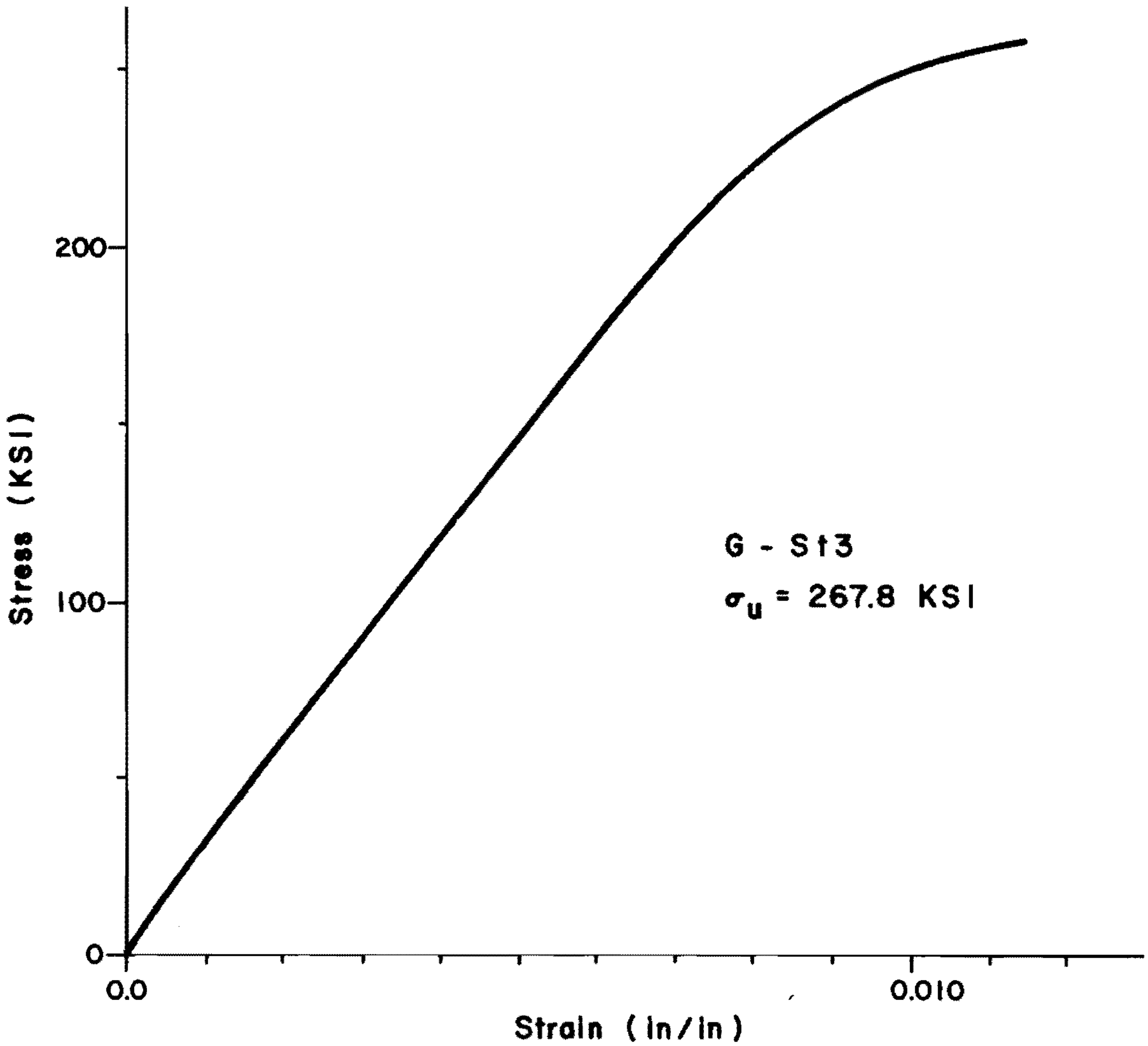

Figure C-1: Stress-Strain Curve for Specimen G-St3

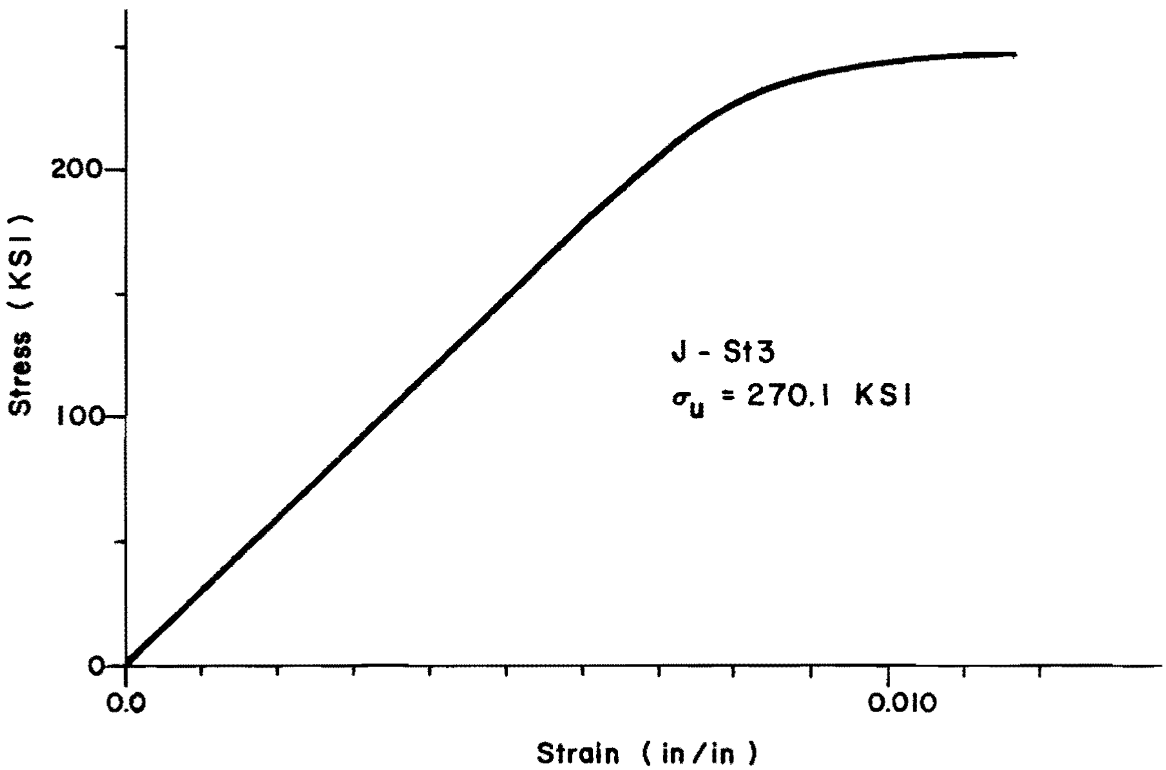

Figure C-2: Stress-Strain Curve for Specimen J-St3

Appendix D

CHEMICAL ANALYSES

The chemistry of the strands included in the testing program are given in Table D-1. The chemical analysis was performed by an independent laboratory from samples cut from the test specimens. The first letter of the chemistry sample corresponds to the letter code given to the strand sample in the fatigue tests. The second letter denotes whether the sample was from an outer wire, the letter "O," or the center wire, the letter "C."

The percent copper of the samples appears to be significant with respect to the fatigue performance of the strand. Strand D, which had the poorest fatigue performance, also had a high copper content relative to the other strands. The center wire of Strand J also had a high copper content. The fatigue failures of strand sample J were predominantly in the center wire.

Sample	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al
A-0	0.81	0.74	0.017	0.010	0.24	0.02	0.04	<0.01	0.04	0.025
A-C	0.82	0.72	0.018	0.006	0.22	0.02	0.04	<0.01	0.02	0.028
B-0	0.78	0.73	0.014	0.008	0.20	0.02	0.02	<0.01	0.01	<0.005
B-C	0.77	0.77	0.020	0.010	0.21	<0.01	0.02	<0.01	0.01	0.025
C-0	0.82	0.88	<0.005	0.010	0.28	0.03	0.06	<0.01	0.05	0.026
C-C	0.82	0.89	0.006	0.012	0.30	0.03	0.06	<0.01	0.06	0.064
D-0	0.77	0.80	0.014	0.012	0.19	0.08	0.04	<0.01	0.10	0.022
D-C	0.77	0.83	0.014	0.022	0.21	0.08	0.06	<0.01	0.19	0.023
E-0	0.82	0.78	0.010	<0.005	0.18	<0.01	0.03	<0.01	0.01	0.029
E-C	0.83	0.74	0.013	0.010	0.20	0.03	0.01	<0.01	0.04	0.057
F-0	0.77	0.81	0.013	0.011	0.23	0.02	0.06	<0.01	0.03	<0.005
F-C	0.74	0.81	0.010	<0.005	0.20	<0.01	0.02	<0.01	0.01	0.023
G-0	0.83	0.88	0.015	0.005	0.21	<0.01	0.04	0.01	0.02	0.037
H-0	0.84	0.86	0.019	0.006	0.24	<0.01	0.06	0.01	0.02	0.040
J-0	0.77	0.63	0.017	0.019	0.23	0.02	0.09	0.01	0.08	0.031
J-C	0.81	0.78	0.021	0.013	0.24	0.04	0.06	0.01	0.13	0.015

Table D-1: Chemical Analysis of Strand Samples

References

[1] Standard Specifications for Highway Bridges. 12th edition, American Association of State Highway and Transportation Officials, 1977.

[2] Abeles, P. W. "Static and Fatigue Tests on Partially Prestressed Concrete Constructions." Journal of the American Concrete Institute, 26(4):361-376, December, 1954.

[3] Ambrowitz and Stegun. Handbook of Mathematical Functions. National Bureau of Standards, 1968.

[4] ACI Committee 215. "Consideration for Design of Concrete Structures Subjected to Fatigue Loading." Journal of the American Concrete Institute, 71(3):97-121, March, 1974.

[5] ACI Committee 318. Building Code Requirements for Reinforced Concrete (ACI 318-77). American Concrete Institute, 1977.

[6] American Society for Testing and Materials. "Standard Specification for Uncoated Seven-Wire Stress-Relieved Strand for Prestressed Concrete (A 416-80)." In 1981 Annual Book of ASTM Standards, American Society for Testing and Materials, 1981.

[7] Baus, R., and Brenneisen, A. "The Fatigue Strength of Prestressing Steel." In Steel for Prestressing, pages 95-117. Federation Internationale de la Precontrainte, 1969. Madrid Symposium, 6 and 7 June, 1968.

[8] Birkenmaier, M., and Narayanan, R. "Fatigue Resistance of Large High Tensile Steel Stay Tendons." In Fatigue of Steel and Concrete Structures, pages 663-672. International Association of Bridge and Structural Engineers, 1982.

[9] Bloom, G. Statistical Estimates and Transformed Beta-Variables. John Wiley and Sons, Inc., 1958.

[10] Cullimore, M. S. G. "The Fatigue Strength of High Tensile Steel Wire Cable Subjected to Stress Fluctuations of Small Amplitude." In Publications, pages 49-56. International Association of Bridge and Structural Engineers, 1972.

[11] Dykers, S. R., and Frank, K. H. Test of Luling Hybrid Socketed Cable Stays. Technical Report, Phil M. Ferguson Structural Engineering Laboratory, The University of Texas at Austin, September, 1980.

[12] Edwards, A. D., and Picard, A. "Fatigue Characteristics of Prestressing Strand." Proceedings, Institution of Civil Engineers, 53(Part 2):325-336, September, 1972.

[13] Fisher, J. W., and Viest, I. M. "Fatigue Tests of Bridge Materials of the AASHO Road Test." In Special Report No. 66, pages 132-147. Highway Research Board, 1961.

[14] Frank, K. H., Breen, J. E., and Campbell, M. A. Creep, Ultimate Strength and Fatigue Tests of Two Stay Cables with Hybrid Epoxy Steel Sockets. Test Report, Civil Engineering Structures Research Laboratory, The University of Texas at Austin, June, 1976.

[15] Frank, K. H. and Hsu, C. K. Fatigue and Static Tests of Three Samples of 0.60 Inch Diameter Seven Wire Prestressing Strand. Technical Report, Phil M. Ferguson Structural Engineering Laboratory, The University of Texas at Austin, December, 1981.

[16] Frank, K. H. Letter from Prof. K. H. Frank, Phil M. Ferguson Structural Engineering Laboratory, The University of Texas at Austin, Austin, Texas, to Ing. Gustavo del Rio, Director General de Servicios Tecnicos, Secretaria de Asentamientos Humanos y Orbas Publicas, Mexico D. F., Mexico. February 16, 1982.

[17] Hanson, J. M., Hulsbos, C. L., and VanHorn, D. A. "Fatigue Tests of Prestressed Concrete I-Beams." Journal of the Structural Division, ASCE, 96(ST11):2443-2464, November, 1970.

[18] Hawkins, N. M., and Shah, S. P. "American Concrete Institute Considerations for Fatigue." In Fatigue of Steel and Concrete Structures, pages 41-50. International Association of Bridge and Structural Engineers, 1982.

[19] Hilmes, J. B. "Statistical Analysis of the Fatigue Characteristics of Underreinforced Prestressed Concrete Flexural Members." PhD thesis, Iowa State University of Science and Technology, 1965. Civil Engineering.

[20] Howels, H., and Raithby, K. D. Static and Repeated Loading Tests on Lightweight Prestressed Concrete Beams. TRRL Laboratory Report 804, Transportation and Research Laboratory, 1977. Crowthorne, Berkeshire, U. K.

[21] Lane, R. E., and Ekberg, C. E. Repeated Load Tests on 7-Wire Prestressing Strands. Prestressed Concrete Bridge Members, Progress Report 21, Fritz Engineering Laboratory, Lehigh University, January, 1959.

[22] Lin, T. Y., and Burns, N. H. Design of Prestressed Concrete Structures. John Wiley and Sons, 1981.

[23] Muller, F., and Zeller, W. Zulassungsprufungen and Spanndrahtlitzen T 12,4 mm, St 160/180 und T 15,2 mm, St 160/180; heir: Dauerschwingversuche. Prufungsbreicht, Institut fur Beton und Stahlbeton, Universitat Karlsruhe, August, 1975.

[24] Natrella, M. G. Experimental Statistics. National Bureau of Standards, 1966.

[25] Nordby, G. M., and Venuti, W. J. "Fatigue and Static Tests of Steel Strand Prestressed Beams of Expanded Shale Concrete and Conventional Concrete." Journal of the American Concrete Institute, 29(2):141-160, August, 1957.

[26] Odeh, R. E., and Owen, D. B. Tables for Normal Tolerance Limits, Sampling Plans, and Screening. Marcel Dekker, Inc., New York City, 1981.

[27] Ozell, A. M. "Fatigue Life of Prestressed Concrete I-Beams with Depressed Strands." In Fourth Congress, pages 128-135. Federation Internationale de la Precontrainte, 1962.

[28] Ozell, A. M., and Ardman, E. "Fatigue Tests of Pre-Tensioned Prestressed Beams." Journal of the American Concrete Institute, 28(4):413-424, October, 1956.

[29] Ozell, A. M., and Diniz, J. F. "Fatigue Tests of Prestressed Concrete Beams Pretensioned with 1/2 Inch Strands." Prestressed Concrete Institute Journal, 3:79-88, June, 1958.

[30] Rabbat, B. G., Karr, P. H., Russel, H. G., and Bruce, N. G., Jr. Fatigue Tests of Full-Size Prestressed Girders. Research Report 113, Portland Cement Association, June, 1978.

[31] Reemsnyder, H. S. Estimation of Cumulative Frequency Distributions by Order Statistics for Sample Sizes 1 to 100. Technical Report, Homer Research Laboratories, Bethlehem Steel Corporation, November, 1967.

[32] Storebaeltgruppen. The Great Belt Bridge. Fatigue Tests with Cable Models: 1st Series of Tests. Technical Report, Structural Research Laboratory, Technical University of Denmark, August, 1979. Research requested by Statsbroen Store Baelt.

[33] Slutter, R. G., and Ekberg, C. E. "Static and Fatigue Tests on Prestressed Concrete Railway Slabs." In Proceedings, pages 1-50. American Railway Engineering Associaton, 1959.

[34] Tide, R. H. R., and VanHorn, D. A. A Statistical Study of the Static and Fatigue Properties of High Strength Prestressing Strand. Report 309.2, Fritz Engineering Laboratory, Lehigh University, June, 1966.

[35] Warner, R. F. "Probable Fatigue Life of Prestressed Concrete Flexural Members". PhD thesis, Lehigh University, September, 1961.

[36] Warner, R. F., and Hulsbos, C. L. "Fatigue Properties of Prestressing Strand." Prestressed Concrete Institute Journal, 11(1):32-52, February, 1966.

[37] Warner, R. F., and Hulsbos, C. L. "Probable Fatigue Life of Prestressed Concrete Beams." Prestressed Concrete Institute Journal, 11(2):16-39, April, 1966.