AVRADCOM
Report No. TR 80-F-9

LEVEL II

AD

12

# MANUFACTURING METHODS AND TECHNOLOGY (MANTECH) PROGRAM

# SERVICE LIFE DETERMINATION FOR THE UH-60A (UTTAS) HELICOPTER ELASTOMERIC BEARINGS

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FINAL REPORT

April 1980

Contract No. DAAG46-78-C-0030



United States Army
AVIATION RESEARCH AND DEVELOPMENT COMMAND

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| | |
|---|---|
| 1. REPORT NUMBER: AVRADCOM TR80-F-9 | 2. GOVT ACCESSION NO.: AD-A091 756 |
| 3. RECIPIENT'S CATALOG NUMBER: | |
| 4. TITLE (and Subtitle): Service Life Determination for the UH-60A (Uttas) Helicopter Elastomeric Bearings | 5. TYPE OF REPORT & PERIOD COVERED: Final Report Aug 1978 to Apr 1980 |
| | 6. PERFORMING ORG. REPORT NUMBER: APE79-021 |
| 7. AUTHOR(s): Ernest P. Gaudette | 8. CONTRACT OR GRANT NUMBER(s): DAAG46-78-C-0030 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS: Lord Kinematics, 1635 W. 12th St., Erie, Pa. 16512 | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: D/A Proj.: 1757095; AMCMS Code: 1498-94.5 57095 (YYS) |
| 11. CONTROLLING OFFICE NAME AND ADDRESS: Army Aviation Research & Development Command, St. Louis, Missouri 63166 | 12. REPORT DATE: Apr 1980 |
| | 13. NUMBER OF PAGES: |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Army Materials & Mechanics Research Center, Watertown, MA 02172 | 15. SECURITY CLASS. (of this report): Unclassified |
| | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A |

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited

(18) USAAVRADC-11, AMMRC
(17) TR-80-F-9, TR-80-25

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES
AMMRC TR80-25
N.H.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

| | | |
|---|---|---|
| UH-60A Helicopter | Elastomers | Predictions |
| Helicopters | Bearing | Blackhawk |
| Fatigue | Life Expectancy | |

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
A method for predicting the endurance life of the elastomeric bearings on the UTTAS helicopter rotor is presented. The critical layers, based on elastomer strain, are determined analytically for these two bearings. Representative standard laboratory test specimens, bonded with the specified elastomers are subjected to the same static and typical dynamic strains, and tested to failure. Two resulting S-N curves are reported, one for each of the two rotor elastomeric bearings. A short verification of Miner's cumulative damage theory is also conducted and reported.

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# FOREWORD

This project was accomplished as part of the U. S. Army Aviation Research and Development Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army Material. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U. S. Army Aviation Research and Development Command, ATTN: DRSAV-EXT, P.O. Box 209, St. Louis, MO 63166.

The work described in this report was accomplished under a contract let and monitored by the U. S. Army Materials and Mechanics Research Center (DAAG46-78-C-0030).

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## OBJECTIVE

The contract, of which this is the final report, had the objective of developing a method to predict the service life of the Sikorsky Aircraft UTTAS Helicopter elastomeric bearings. The report describes a method for predicting the service life of both the UTTAS spherical and thrust bearings in a manner that will effect cost savings and improve accuracy when compared to previously used methods. The prediction technique involves an analytical evaluation of the bearing to determine the critical elastomer and metal shim layer in terms of stress and strain. These values of stress and strain are compared to laboratory generated S-N data, which for the case of the metal shim is obtained from a source such as MIL-HDBK-5C, and for the elastomer the S-N data is obtained from laboratory test specimens. The test program reported here gives a method for obtaining the specimen S-N data for a bearing critical elastomer layer and relating it to a minimum life for a specific bearing.

# INTRODUCTION

## Scope

The work performed under this contract was to develop an improved service fatigue life prediction technique for the Sikorsky UTTAS Elastomeric Bearings and to predict the service life of the bearings. The two Lord bearings designed for installation into the UTTAS main rotor system are LB4-1034-2-1 and LB5-1034-1-1. In each bearing the most critical elastomer layer, in terms of strain, was determined by finite element analysis and the strains calculated for this layer imposed on a standard Lord Kinematics' test specimen. The indicated edge shear strain determined from the finite element analysis was reproduced on the test specimen by a steady compression load, while the dynamic torsional shear strain applied to the specimen was the variable with which the specific S-N curve for the critical layer was developed. Using the S-N curve and the Sikorsky load-motion spectrum, SES701059, a predicted service life of the bearings can be determined. A test to verify Miner's Cumulative Damage Theory, using two test specimens and a spectrum of conditions selected from SES701059, was also performed. The prediction method is documented so that engineering and technical personnel who are not elastomeric bearing specialists can predict elastomeric bearing service life.

It is our belief that reduction of test cost is the area in which the prediction method will have its greatest impact. Laboratory test specimens and existing test machines have been used to the greatest extent possible to minimize cost. Lord Kinematics feels that the potential for increased accuracy is high. However it must be recognized that many of the factors which influence the comparison of laboratory tests of any type to actual service could not be evaluated within the scope of the test program. Among these factors are the realism of load/motion conditions, environmental effects, type of service exposure, and the influence of manufacturing quality.

The prediction method is directly analogous to the methods utilized to predict service life of a metallic part. That is, the structure is analyzed to determine the peak fatigue stress level; S-N material data and Miner's Cumulative Damage Theory are utilized to predict service life. Increased accuracy is provided in the method prediction by actually testing laboratory specimens to verify the analysis.

## Qualifying Assumptions

Prior to a detailed discussion of the prediction method, a discussion of the basic problem of predicting elastomeric bearing service lives is presented, along with the assumptions used to maintain the work within the defined scope.

Prediction of elastomeric bearing service life is a complex problem in which many of the influences on service life cannot be defined for the bearing designer. In addition, several factors which influence service fatigue life cannot be considered in a program of the scope defined by the contract. Therefore, assumptions are necessary in developing any method for predicting life.

## Realism of Load/Motion Conditions

The accuracy of any mathematical analysis is directly influenced by the accuracy of the numerical values used as input. This, of course, assumes that the formulae utilized are accurate and based on sound principles. If the formula used to determine fatigue life is a linear relationship between strain and life, then the "error" in service life prediction will be the same percentage error as that between specified service conditions and actual service conditions. However, if the relationship is not linear, as is the case here, then the "error" may be magnified by the calculation.

It must also be recognized that the type of usage in service can vary and also influence test results. A helicopter used in peace time troop transport could conceivably be a less severe load/motion environment compared to the same helicopter in a combat environment.

Application of the method described herein is based on the assumption that the specified load and motion conditions are truly representative of service conditions.

Manufacturing Considerations

Accurate prediction of elastomeric bearing service life is dependent on manufacturing considerations for which additional assumptions and requirements must be stated. The materials and processes utilized in the manufacture of the test samples must be essentially identical to those used for the full size elastomeric bearing. The elastomers and adhesive systems must be identical from test sample to full size bearing. Material fatigue data must be obtained on the elastomers and adhesive system specific to the bearing manufacturer, and such data are not of general use in predicting the fatigue life of bearings from another source.

All test specimens used in this program were fabricated using the same elastomer and metal processes as on the actual bearings. Consistent quality of elastomeric bearings is necessary for accurate service life prediction. The elastomeric bearing in service must be truly representative of that which was analyzed or tested in the laboratory.

Environmental Considerations

The test procedure does not include environmental testing, primarily because of the complexity that would result. It has been proven in laboratory testing of Lord Kinematics' bearings using Lord elastomers, adhesives, and processes, that reasonably applied environments typical of helicopter service exposure have a

minimal effect on the service life. This was proven in laboratory tests of Lord P/N LM-726-1 elastomeric pitch change bearing for the Bell Model 540 Rotor and the Lord P/N LM-730-2 centering bearing for the Sikorsky CH53-D Rotor Head. It must be assumed that the environmental exposure in service will be typical of that represented by previous laboratory tests and will not be unrealistically severe.

## Geometry Effects

The stress or strain on an elastomeric bearing in service can result from a number of different load conditions. As an example, the spherical bearing in the UTTAS Rotor System is subjected to both radial and axial (centrifugal) loading as well as motion in the cocking (flapping and lead-lag) and pitch change directions. In the prediction method it is assumed that the state of stress/strain in the critical layer of the bearing can be duplicated in the laboratory test specimen by the properly selected combination of axial compression load and shear motion. It is the belief of Lord Kinematics that the above assumption is valid. Lord Kinematics feels that elastomeric bearings of all geometries can be analyzed to determine stress/strain conditions which, in turn, can be modeled by simple laboratory test specimens.

## Determination of Critical Layer

Lord Kinematics utilizes a proprietary blend of natural rubber in elastomeric bearings, which is available in several distinct shear moduli. A particular bearing design may incorporate up to 15 different versions of the same basic elastomer, differing in shear moduli.

In the analysis which determines the critical layer of the elastomeric bearing with respect to stress/strain levels, it is assumed that the fatigue life of various elastomers with different various shear moduli is not a variable. Lord Kinematics believes that this is a valid assumption based on previous experience with Lord elastomers in fatigue.

## Failure Definition

The traditional and primary definition of failure at Lord Kinematics for laboratory tests of both full size elastomeric bearings and laboratory samples has been a specified decrease in shear spring rate in a particular direction. The mode of failure of properly designed and manufactured elastomeric bearings is a gradual "wearing out" in which the elastomer is abraded out of the sections, resulting in a gradual decrease in spring rate. Recent tests have used a 10% to 30% decrease in shear spring rate as a failure criterion, and the resulting life has been viewed as the lower limit where the mean minus three sigma point would fall for metal fatigue curves. This definition of failure when applied to a specimen provides a convenient, easily measured criterion. However, it ignores other failure modes which can occur in service such as shim cracking or loss of stability. It must therefore be assumed that the full size elastomeric bearing has been designed so that the mode of failure will be a gradual loss of spring rate duplicating the mode of failure of the lab specimens. This should be a valid assumption for elastomeric bearings designed by Lord Kinematics.

## Validity of the Method

The prediction method of calculating the service life of an elastomeric bearing is based on sound engineering and scientific principles. In this method, it is assumed that Miner's Cumulative Damage Theory is applicable to the fatigue of elastomer in a manner analogous to metal fatigue. Based on previous experience, Lord Kinematics believe this to be a valid assumption.

## Limitations of the Method

The prediction method is valid for bearings of any configuration provided that the compression loading is essentially steady state in nature. This is true of the Sikorsky UTTAS bearings since the cyclic centrifugal (compression) load is a

small percentage (5-10%) of the normal centrifugal force, and based on Lord Kinematics experience, its effect can be safely ignored. Lord Kinematics considers the theory supporting the prediction method valid for any configuration or mode of loading. However, the number of test samples and the detailed test procedure would of necessity be modified to evaluate the effects of alternating compression. It must be pointed out that the data presented in this report is only valid for the bearings under consideration and cannot be used to predict the life of any other elastomeric bearing. There are a number of parameters inherent in the elastomer, such as base material, blending ingredients, cure system and adhesive, which will influence the prediction results.

Data Scatter

It has been assumed that minimal scatter will occur, minimizing the number of data point replications which are necessary. This assumption was made in order to minimize test cost. Lord Kinematics' experience with similar tests, both laboratory specimens and actual elastomeric bearings, indicates that this is a valid assumption.

Low Cycle Fatigue (Ground-Air-Ground) Inputs

The prediction method assumes that the primary mode of elastomeric bearing failure in service will be due to high cycle shear fatigue. Failure under low cycle repeated loading due to Ground-Air-Ground (G-A-G) loading, instabilities under maximum load conditions, or other modes of failure are considered beyond the scope of the contract. It is assumed that adequate consideration has been given to these possible failure modes and that an evaluation either empirical or by tests of actual bearings has been made. This is a valid assumption for the Sikorsky UTTAS bearings designed and manufactured by Lord Kinematics.

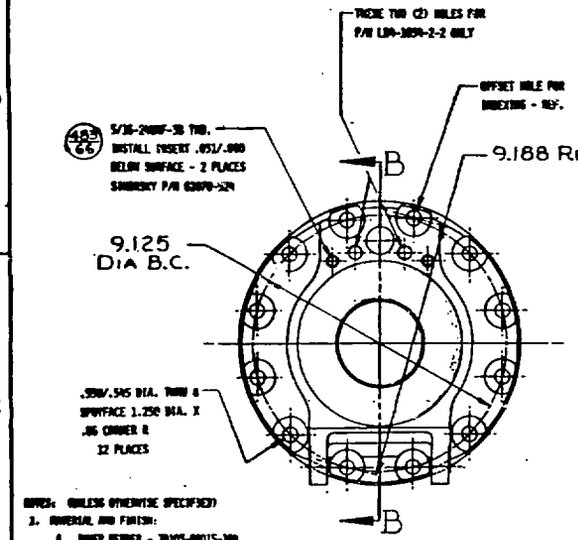
# PREDICTION METHOD

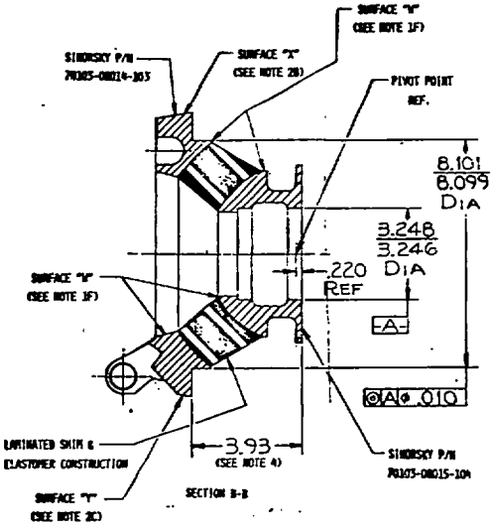
## Introduction

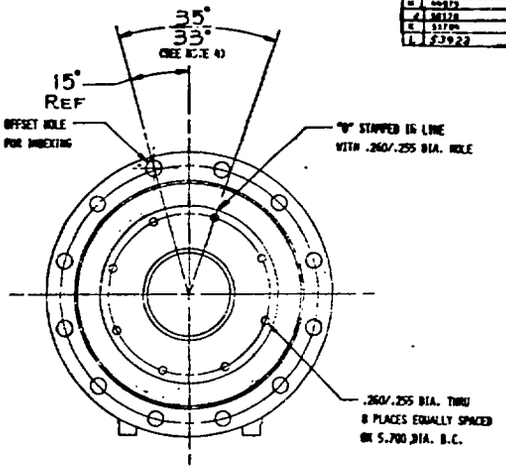
The Lord Kinematics approach to calculating the fatigue life of the Sikorsky UTTAS elastomeric bearings utilizes the same philosophy as metal fatigue analysis. The method is structured to enable engineering and technical personnel who are not specialists with this technology to predict service lives. It will require analytical ability, materials data, and the validity of the assumptions previously stated.

## Modelling of the Elastomeric Bearings

The elastomeric bearings for which a predicted service life is to be obtained was first modeled for a finite element computer analysis. The modeling consisted of defining the bearing geometry as closely as possible and specifying the material properties for the elastomer layers, metal shims, and attachment features. Figures 1 and 2 are the engineering drawing and finite element model respectively of Lord P/N LB4-1034-2-1, while Figures 3 and 4 are the engineering drawing and finite element model respectively of Lord P/N LB5-1034-1-1. The finite element models shown in Figures 2 and 4 are deformed grids; that is, they reflect the behavior of the bearing after imposition of an axial deflection. This deflection in the bearing causes the elastomer layers to bulge and produce a shear strain at the edge of each layer. The deflection in the bearing can be converted to a corresponding load which produced the deflection and the load compared as a ratio to the actual axial load through the bearing. In this manner the actual strains and stresses in the bearing can be evaluated.




NOTES: UNLESS OTHERWISE SPECIFIED)

1. MATERIAL AND FINISH:
   - A. INNER MEMBER - 70105-08015-104
     7075-T73 ALUM. ALLOY PER QQ-A-367 - 100% FLUORESCENT PENETRANT INSPECT PER MIL-I-6866 - ANODIZED PER MIL-A-8625C. TYPE II. CLASS 1 (STAINS DUE TO BONDING PERMISSIBLE)
   - B. OUTER MEMBER - 70105-08014-103
     6AL-4V TITANIUM ALLOY PER SIKORSKY SPEC. SS8945 AND 70105-08014, SHT. 3. NOTE 6 - 100% FLUORESCENT PENETRANT INSPECT PER MIL-I-6866 - (CR) SHOT PEEN PER SIKORSKY SPEC. SS8766. EXCEPT THREADED HOLES. INTENSITY 0.005-.008A USING #70 STEEL SHOT.
   - C. SHIMS - .040 THICK (TOTAL NUMBER 17) - 17-7PH STAINLESS STEEL PER MIL-S-25043 OR AMS 5528. HEAT TREATED TO (Rc 40 TO Rc 46). 100% FLUORESCENT PENETRANT INSPECTED PER MIL-I-6866.
   - D. ELASTOMER - NATURAL RUBBER ASTM D2000-5A4[ ]A13B13C20F19K13L34
   - E. MACHINED SURFACES 125 MICROINCHES MAX., EXCEPT 250 MICROINCHES MAX. ON DRILLED HOLES.
   - F. CEMENT AND ELASTOMER FLASH PERMITTED ON SURFACES MARKED "W"; ALL OTHER SURFACES TO BE FREE OF ELASTOMER AND CEMENT.
2. IDENTIFICATION:
   - A. MAJOR METAL PARTS ARE TRACEABLE TO CHEMICAL AND MECHANICAL PROPERTIES THROUGH INDIVIDUAL SERIAL NUMBERS. VERIFICATION OF -173 TEMPER BY ELECTRICAL CONDUCTIVITY TEST.
   - B. "LORD KINEMATICS ERIE PA USA 70105 REF. P/N LBA-3054-2-CL CURE DATE(CC)-(CC). PATENT NUMBER 3,679,197 INK STAMPED AND CLEAR COATED ON SURFACE "X".
   - C. 70105-SB7001-[ ] REV. R. SERIAL NUMBER B[ ]-[ ] AND INSPECTION STAMPS IMPRESSION STAMPED PER SS8766 ON SURFACE "Y". (VIBROSCRIBING OPTIONAL).
3. DESIGN PARAMETERS:
   - A. RADIAL CALCULATED STATIC SPRING RATES @ 75° ± 10°F.
     AXIAL SPRING RATES MAY VARY ±25% FROM NOMINAL VALUES FOR DESIGN PURPOSES ONLY FOR PRODUCTION)

| | | RADIAL LOAD | |
|---|---|---|---|
| | | "F" LB. | 72.680 LBS. |
| RADIAL | LB./IN.) | 1,362,630 | 1,362,630 |
| AXIAL | LB./IN.) | 500.295 | 607.213 |
| TORSIONAL | (IN.-LB./DEG.) | 766 | 706 |
| ROCKING | (IN.-LB./DEG.) | 1,385 | 1,385 |

   - B. LOAD AND MOTION SPECTRUM UTILIZED FOR DESIGN CALCULATIONS. LOADS PER SIKORSKY SPEC. SES701059 REVISION A, DATED 6/4/77. MOTIONS PER THE FOLLOWING TABLE:

| CASE NO. | CYCLES | PITCH STATIC ± FREQUENCY (CPS.) | ROCK-LOAD STATIC ± FREQUENCY (CPS.) | PLUNGE STATIC ± FREQUENCY | PACK QTY |
|---|---|---|---|---|---|
| 1 | 3,000 | 0.35 ± 0.35 | -2.1 ± 2.1 | -0.42 ± 0.2 | 200 |
| 2 | 1,000 | 1.57 ± 0.35 | 4.1 ± | -1.45 ± 0.1 | |
| 3 | 1,000 | 1.23 ± 0.35 | 3.1 ± | -1.7 ± 2.0 | |
| 4 | 1,000 | 1.0 ± 0.35 | -1.4 ± 2 | -4.1 ± 2.00 | |
| 5 | 1,000 | 1.57 ± 0.35 | 2.8 ± | -4.2 ± 2.5 | |
| 6 | 1,000 | 1.35 ± 0.35 | 2.8 ± | -3.9 ± 2.5 | |
| 7 | 1,000 | 1.35 ± 0.35 | 2 ± | -4.3 ± 2.50 | |
| 8 | 1,000 | 0.9 ± 0.35 | 2.3 ± | -4.00 ± 2.7 | |
| 9 | 1,000 | 1.57 ± 0.35 | 4.0 ± | -3.9 ± 2.5 | |
| 10 | 6,000 | 1.57 ± 0.40 | -0.2 ± | -4.1 ± 2.00 | |
| 11 | 10,000 | 0.9 ± 0.00 | 1.3 ± | -4.4 ± 2.9 | |
| 12 | 3,000 | 1.35 ± 0.35 | 2.3 ± | -4.2 ± 2.50 | |
| 13 | 1,000 | 1.57 ± 0.40 | 2.5 ± | -3.95 ± 2.6 | |
| 14 | 6,500 | 1.0 ± 0.40 | 0.2 ± | -4.1 ± 2.00 | |
| 15 | 5,000 | 0.57 ± 0.70 | -0.5 ± | -4.45 ± 2.45 | |
| 16 | 5,000 | 0.57 ± 0.00 | -2.5 ± | -4.25 ± 2.1 | |
| 17 | 4,000 | 0.70 ± 0.35 | -0.7 ± | -4.5 ± 2.30 | |
| 18 | 2,000 | 0.57 ± 1.00 | -2.1 ± | -3.7 ± 2.4 | |
| 19 | 0.05 | 1.35 ± 0.57 | -1.0 ± | -2.62 ± 3.00 | |
| 20 | 2.5M | 0.57 ± 1.35 | -4 ± | -4 ± 3.52 | |
| 21 | 0.000 | 0.57 ± 0.00 | 0 ± | -4.05 ± 3.5 | |
| 22 | 1,000 | 1.70 ± 0.35 | 3.5M ± | -4 ± 3.00 | |
| 23 | 3,000 | 0.57 ± 0.77 | 1.7 ± | -4 ± 3.7 | |
| 24 | 11,000 | 0.00 ± 0.35 | 3.2 ± | -3.5 ± 3.0 | |
| 25 | 6,000 | 0.57 ± 1.00 | -0.9 ± | -4.3 ± 3.7 | |
| 26 | 2.5? | 0.6 ± 1.57 | 0 ± | -0.6 ± 0.5 | |
| 27 | 0.000 | 0.57 ± 1.35 | -2.0 ± | -3.3 ± 4.0 | |
| 28 | 2,000 | 0.57 ± 1.35 | -0.2 ± | -2.67 ± 3.0 | |
| 29 | 0.500 | 0.35 ± 1.35 | -0.2 ± | -2.57 ± 5.5 | |
| 30 | 0.000 | 0.57 ± 1.35 | -0.6 ± | -3.35 ± 6.0 | |
| 31 | 0.000 | 0.57 ± 1.35 | -0.9 ± | -3.34 ± 7.0 | |
| 32 | 0.000 | 0.57 ± 1.57 | -1.1 ± | -4.35 ± 8.0 | |
| 33 | 0.000 | 0.57 ± 1.70 | -2.0 ± | -4.00 ± 9.0 | |
| 34 | 0.000 | 0.57 ± 1.57 | -2.7 ± | -4.00 ± 10.0 | |
| 35 | 1,000 | 0.57 ± 1.71 | -2.2 ± | -4.35 ± 12.0 | |
| 36 | 0.000 | 0.57 ± 1.57 | -2.2 ± 2.5 | -4.35 ± 12.0 | 200 |

   - C. DESIGN LIFE PER SIKORSKY SPECIFICATION SES701059, REV. A, DATED 6/4/77.
4. DIMENSIONS TO BE DETERMINED PRIOR TO ANY LOAD-DEFLECTION TESTS.
5. PARTS TO BE INDIVIDUALLY PACKAGED WITH "70105 SB7001-[ ] LORD KINEMATICS ERIE, PA USA REF P/N LBA-3054-2-CL S/N AND DATE OF CURE TO APPEAR ON THE SHIPPING CARTON.
6. BEARING SHALL NOT BE FLUSHED WITH OR IMMERSED IN KEROSENE OR PETROLEUM DISTILLATES OF ANY KIND. WHEN MAGNETIC PARTICLE INSPECTION IS REQUIRED, WATER TYPE SUSPENSION SUCH AS MIL. 24A FLUORESCENT PARTICLE CONCENTRATE, AND WAC WATER CONDITIONER SHALL BE USED.
7. THE DRAWING HAS BEEN REVIEWED FOR CRITICAL CHARACTERISTICS (CR).
8. LORD Q.A. PLAN QCP-8075-001 APPLIES.



| | | |
|---|---|---|
| LBA-3054-2-2 | 70105-SB7001-[ ]R8 | REV. "R" |
| LBA-3054-2-1 | 70105-SB7001-[ ]R6 | REV. "R" |
| LORD P/N | SIKORSKY P/N | REV. LETTER |

LBA-3054-2-2
LBA-3054-2-1
PART NO.

LORD Lord Kinematics
ELASTOMERIC BEARING, BONDED

SIZE D | LBA-3034-2

1 C.C.

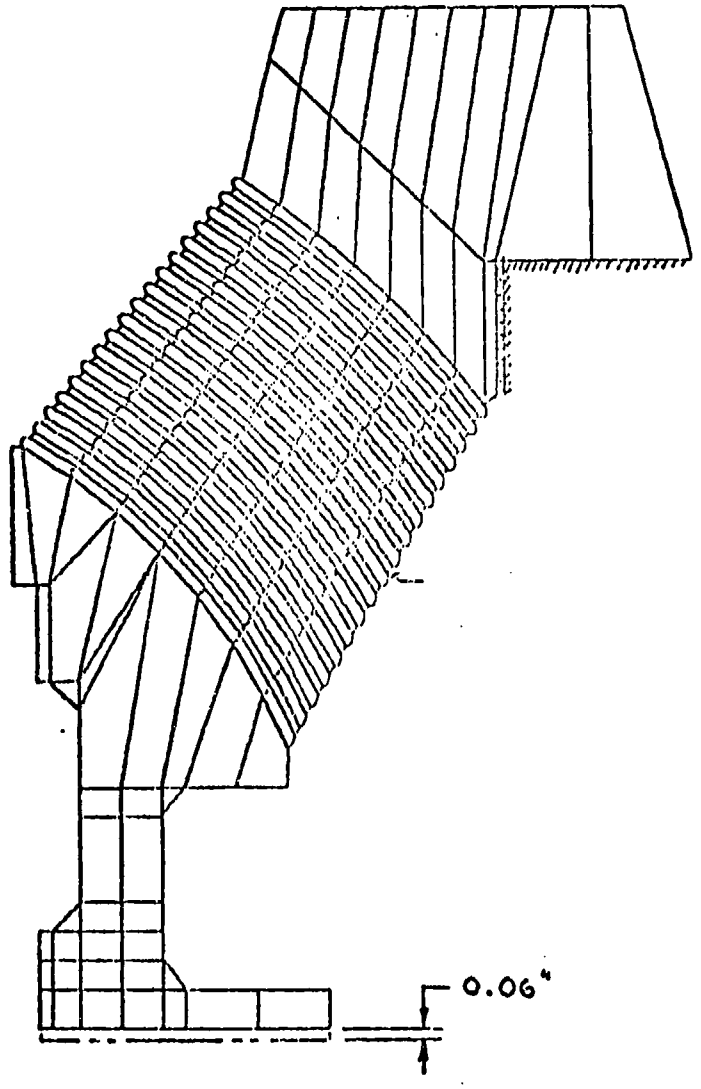
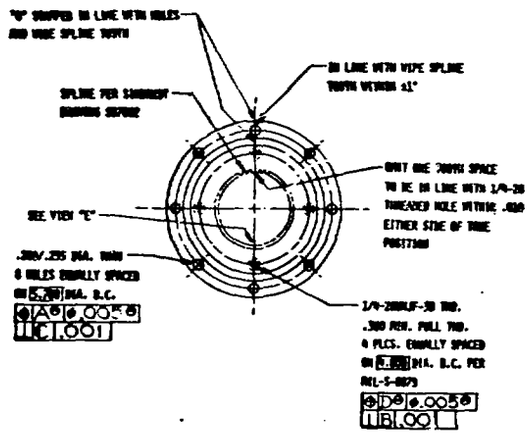
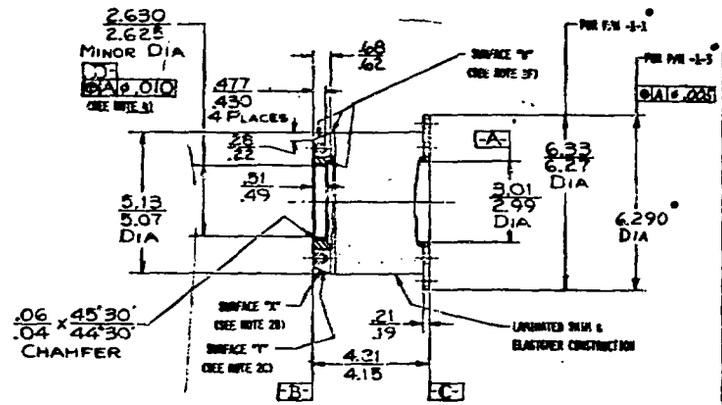



Figure 2. LB4-1034-2-1 Deformed Grid




**SPLINE DATA**

30° INVOLUTE SIDE BEARING

| | |
|---|---|
| DIAMETRAL PITCH | 24/48 |
| NO. OF TEETH | 64 |
| PITCH DIAMETER | 2.6667 |
| BASE CIRCLE DIAMETER | 2.3094 |
| CHORDAL TOOTH SPACE (EFFECTIVE) | .0664/.0654 |
| CIRCULAR TOOTH SPACE (DIMENSIONAL) | .0685/.0675 |
| DIMENSIONS BETWEEN TWO .0720 DIA. PINS — BASED ON DIMENSIONAL TOOTH SPACE | 2.9689/2.9627 |
| MAJOR DIAMETER | 2.7507/2.7417 |
| MINOR DIAMETER | 2.6388/2.6258 |
| MIN. T.I.F. DIAMETER | 2.7083 |
| MAX. ACCUMULATED SPACED SPACING ERROR BETWEEN ANY TWO TEETH | .0015 |
| MAX. TOOTH TO TOOTH SPACING ERROR | .0009 |
| MAX. LEAD ERROR (TOTAL) | .0002 |
| MAX. INVOLUTE PROFILE ERROR AT T.I.F. +.0004 -.0006 AT T.I.P. +.0004 -.0006 | |
| MIN. FILLET RADIUS | .029 |

NOTE: GO GAUGE TO BE MADE MIN. EFFECTIVE TOOTH SPACE WIDTH. NO GO GAUGE TO BE MADE TO MAX. DIMENSIONAL TOOTH SPACE WIDTH.
ABOVE DATA BEFORE PLATING OR PROTECTIVE FINISH.

NOTES: UNLESS OTHERWISE SPECIFIED)

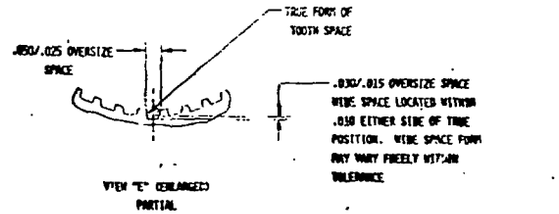
1. MATERIAL AND FINISH:
   - A. PLATED RUBBER - 7075-T73 ALUM. ALLOY PER QQ-A-367, QQ-A-225/9, OR QQ-A-250/12 - 3000 FLUORESCENT PENETRANT INSPECT PER MIL-I-6866 - ANODIZED PER MIL-A-8625C, TYPE II, CLASS 1 (STAINS DUE TO DYEING PERMISSIBLE)
   - B. SPLINED RUBBER - 6AL-4V (ANNEALED) TITANIUM ALLOY MIL-T-9046, TYPE 3, COMP. C OR MIL-T-9047 TYPE 3 COMP. A OR FORGING PER SIKORSKY SPEC. SS-8445 - 3000 FLUORESCENT PENETRANT INSPECT PER MIL-I-6866 (X) SHOT PEEN PER SIKORSKY SPEC. SS8766, EXCEPT THREADED HOLES. INTENSITY 0.012 (EXCEPT SPLINE). INTENSITY SPLINE ONLY .008A. USING STEEL SHOT.
   - C. SHIM - .051 THICK (NOMINAL BARRIER SI) 301 1/4 HARD STAINLESS STEEL PER MIL-S-5059. 100% FLUORESCENT PENETRANT INSPECTED PER MIL-I-6866.
   - D. ELASTOMER - NATURAL RUBBER ASTM D2000-5AA[illegible]
   - E. MACHINED SURFACES 125 MICROINCHES R[illegible]. EXCEPT 250 MICROINCHES MAX. ON DRILLED HOLES.
   - F. CEMENT AND ELASTOMER FLASH PERMITTED ON SURFACES MARKED "F" ALL OTHER SURFACES TO BE FREE OF ELASTOMER AND CEMENT.
2. IDENTIFICATION:
   - A. ALUM METAL PARTS ARE TRACEABLE TO CHEMICAL AND MECHANICAL PROPERTIES THROUGH INDIVIDUAL SERIAL NUMBERS. VERIFICATION OF -T73 TEMPER BY ELECTRICAL CONDUCTIVITY TEST.
   - B. "LORD KINEMATICS ERIE PA USA 76095 P/N. P/N L05-3034-1-[ ] CURE DATE[illegible] PARTS 5292711. 4040690" INK STAMPED [illegible] CLEAR COATED ON SURFACE "E".
   - C. P[illegible]-[ ] REV. N. SERIAL NUMBER [ ]-[ ] AND INSPECTION STAMPS IMPRESSION STAMPED PER SS8758 ON SURFACE "F". (VIBROCRISTING OPTIONAL).
3. DESIGN PARAMETERS:
   - A. NOMINAL CALCULATED STATIC SPRING RATE @ 75° ± 10°F. (ACTUAL SPRING RATES MAY VARY ±15% FROM NOMINAL VALUES PUR DESIGN PURPOSES. ADJ[illegible] FOR PRODUCTION)

| | | |
|---|---|---|
| RADIAL | (LB./IN.) | 700.000 |
| TORSIONAL | (IN.-LB./DEG.) | 118 |

   - B. LOAD AND MOTION SPECTRUM UTILIZED FOR DESIGN CALCULATIONS: LOADS PER SIKORSKY SPEC. SES701059 REV. A, DATED 4/4/77. MOTIONS PER THE FOLLOWING TABLE:

| COND. | PERCENT OCCURRENCE | PITCH STATIC ± VIBRATORY (DEG.) | FREQ. CPH |
|---|---|---|---|
| 1 | 10.3314 | 9.042 ± 1.914 | 258 |
| 2 | 7.5754 | 10.266 ± 3.045 | |
| 3 | 11.2244 | 4.611 ± 3.8889 | |
| 4 | 21.7905 | 13.92 ± 9.611 | |
| 5 | 19.2937 | 7.308 ± 5.665 | |
| 6 | 21.451 | 13.398 ± 6.96 | |
| 7 | 7.3962 | 13.55 ± 7.917 | |
| 8 | 0.8975 | 14.268 ± 8.787 | |
| 9 | .033 | 13.79 ± 9.483 | |
| 10 | 0.0069 | 14.264 ± 17.578 | 258 |

   - C. DESIGN LIFE PER SIKORSKY SPECIFICATION SES701059 REV. A, DATED 4/4/77.
4. DIMENSIONS TO BE DETERMINED PRIOR TO ANY LOAD-DEFLECTION TESTS.
5. PARTS TO BE INDIVIDUALLY PACKAGED WITH "76286-587002-[ ] LORD KINEMATICS ERIE, PA USA REF. P/N L05-3034-1-[ ] S/N AND DATE OF CURE TO APPEAR ON THE SHIPPING CARTON.
6. BEARING SHALL NOT BE FLOODED WITH OR EXPOSED IN NAVSOL OR PETROLEUM DISTILLATES OF ANY KIND. UNDER MAGNETIC PARTICLE INSPECTION IS REQUIRED. WATER TYPE SUSPENSION SUCH AS MIL. 148 FLUORESCENT PARTICLE CONCENTRATE. AND USA WATER CONDITIONER SHALL BE USED.
7. THE DRAWING HAS BEEN REVIEWED FOR CRITICAL CHARACTERISTICS (CC).
8. LORD D.A. PLAN DCP-0173-001 APPLIES.




| L05-3034-1-3 | 76286-587002-046 | REV. "F" |
|---|---|---|
| | | |
| L05-3034-1-1 | 76286-587002-046 | REV. "F" |
| LORD P/N | SIKORSKY P/N | REV. LETTER |

SPECIAL TOLERANCE:
.XX DECIMALS ± .015
.XXX DECIMALS ± .005
FRACTIONS ± 1/32
ANGLES ± 2°

L05-3034-1-3
L05-3034-1-1
PART NO.

LORD Ford Kinematics Erie, Pa 16512

ELASTOMERIC BEARING

D | L05-3034-1

- 17 -

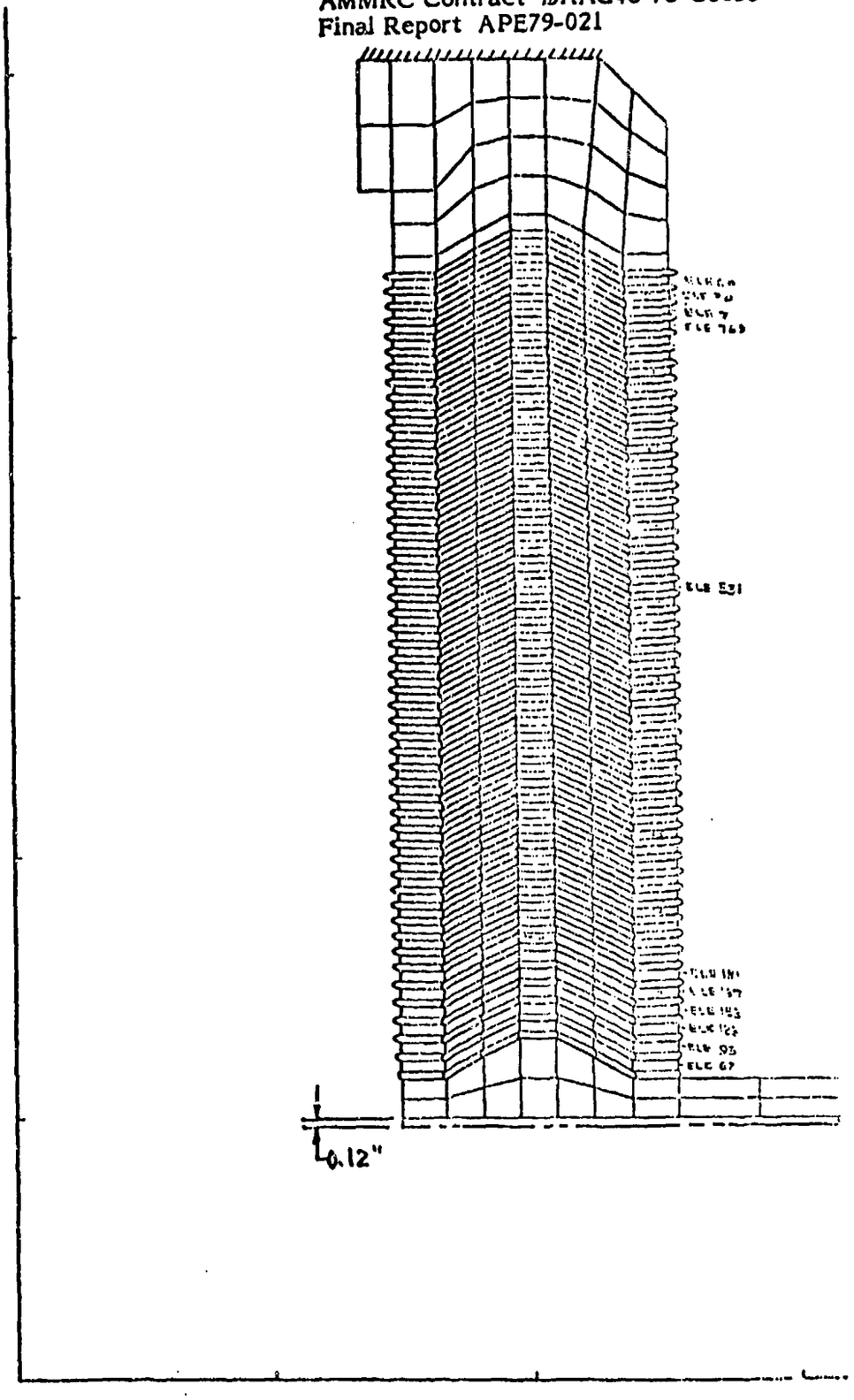



Figure 4. LORD LDS-1034-1-1 WITH AXIAL LOAD

The axial load through both UTTAS bearings is a result of the centrifugal blade loading in the helicopter. This load is assumed to be steady, as mentioned in the introduction, and the edge shear strain which this steady load produces will be reproduced on the test specimen.

Finite Element Analysis

A Lord computer program entitled "SARLAS" was utilized to perform the finite element analysis of the subject bearings. This computer program is a derivative of the program "TEXGAP" which was developed at the University of Texas by Professors E. B. Becker and R. S. Dunham. The computer program "TEXGAP" is not available from Lord Kinematics. It is distributed and is available only from Professor E. B. Becker at the University of Texas. The program was financed by the U. S. Air Force through United Technology. These programs are capable of analyzing a complex structure of metals, composites, and rubber-like materials without the simplifying assumptions of rigid metals (shims) or simple and regular geometries as in the closed form solutions. The unique characateristic of these programs is the ability to analyze materials with a shear modulus many orders of magnitude less than the bulk modulus. This is commonly spoken of in terms of "incompressible" or nearly incompressible materials (Poisson's Ratio = 0.499995). The computer program "SARLAS" is proprietary to Lord Kinematics and consists of "TEXGAP" with revisions to input and output format to facilitate usage and interpretation of results.

In summary, "TEXGAP" was used to determine the level of strain in each elastomer layer. The critical layer was then determined in terms of direct and indirect shear strain. "TEXGAP" was also used to determine the level of stress in each metallic shim, and using available metal S-N data (i.e., MIL-HDBK-5) a fatigue analysis of the shim was performed.

Selection of Critical Layer

A. Lord P/N LB4-1034-2-1

The critical layer in terms of elastomeric edge shear strain was selected using the "SARLAS" analysis. The highest calculated value occurred in the 17th layer from the spherical center at the inside diameter.

B. Lord P/N LB5-1034-1-1

The critical layer of this bearing in terms of elastomeric edge shear strain was also selected using the "SARLAS" analysis. The highest calculated value occurred in the 1st layer from the small end plate at the outside diameter.

Metal Shim Fatigue Analysis

The metal shim fatigue analysis was performed on the bearings for Sikorsky.

The analytical approach employed in the shim stress analysis utilized a combination of finite element analysis, strain gage data and parametric analysis. The bearings were analyzed using SARLAS in the axial loading mode.

A listing of the maximum and minimum stresses and strains (by material) and their locations in the bearings was obtained. The shims where the maximum hoop stress and the maximum combined stress were reported were then used for the detailed analysis and comparison with available data. The change in hoop stress, due to a flap (cocking) input to a spherical thrust bearing is linear and is affected mainly by axial loading while cocking. A parametric analysis utilizing strain gage data from previous testing of similar bearings in conjunction with the SARLAS analysis was used to obtain the predicted level of alternating stress with cocking angle.

The fatigue life of the thrust bearing shims is dependent primarily on the Ground-Air-Ground axial loading with little or no change due to the torsional (pitch) input. Strain gage analysis of similar thrust bearings indicate an acceptable level of of correlation with SARLAS finite element analysis; therefore, the calculated SARLAS value was used.

The results of the spherical shim analysis are presented on a Working Stress Diagram for $10^8$ cycles derived from Sikorsky data, to demonstrate shim life acceptability (Figure 5). The results of the thrust shim analysis is presented on a mean -3 $\sigma$S-N curve to demonstrate shim life acceptability (Figure 6), also derived from Sikorsky data.

Critical Elastomer Layer Modeling

The laboratory test specimen selected was a bonded right circular cylinder ("disk") configuration. Figure 7 is a drawing of the specimen, TL-367-1-4, as used in the test. The bonded specimens had the identical elastomer and adhesive system as the critical layer in the respective bearings. A finite element analysis was conducted on the laboratory test specimen for each of the two critical layer elastomers. A deflection of .005 inch was imposed on the test specimen model which was then translated into an equivalent load and in an induced edge shear strain. The calculated edge shear strain was scaled to give the required loading necessary to produce the critical edge shear strain on the test specimen. Figures 8 and 9 are computer drawings of the deformed shape of the test specimen. It was only necessary to model one quarter of the test specimen to obtain the required information, due to its symmetrical shape. Table 1 presents the common physical parameters between the actual bearings and their respective test specimens.

CONSTANT LIFE DIAGRAM(1)
WORKING STRESS LEVELS
$10^8$ CYCLES

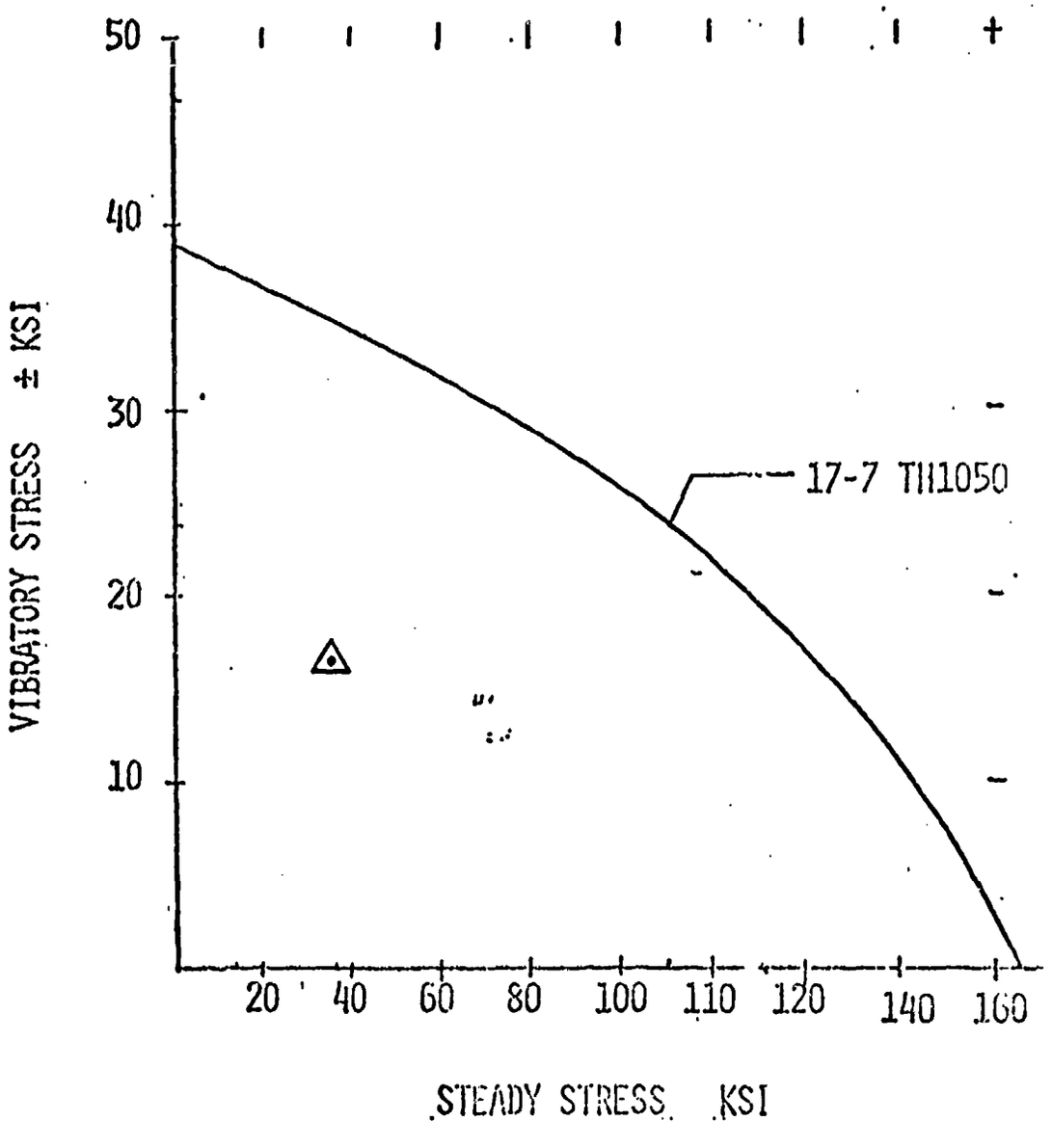



Figure 5. LB4-1034-2-1 Metal Shim
Fatigue Constant Life Diagram

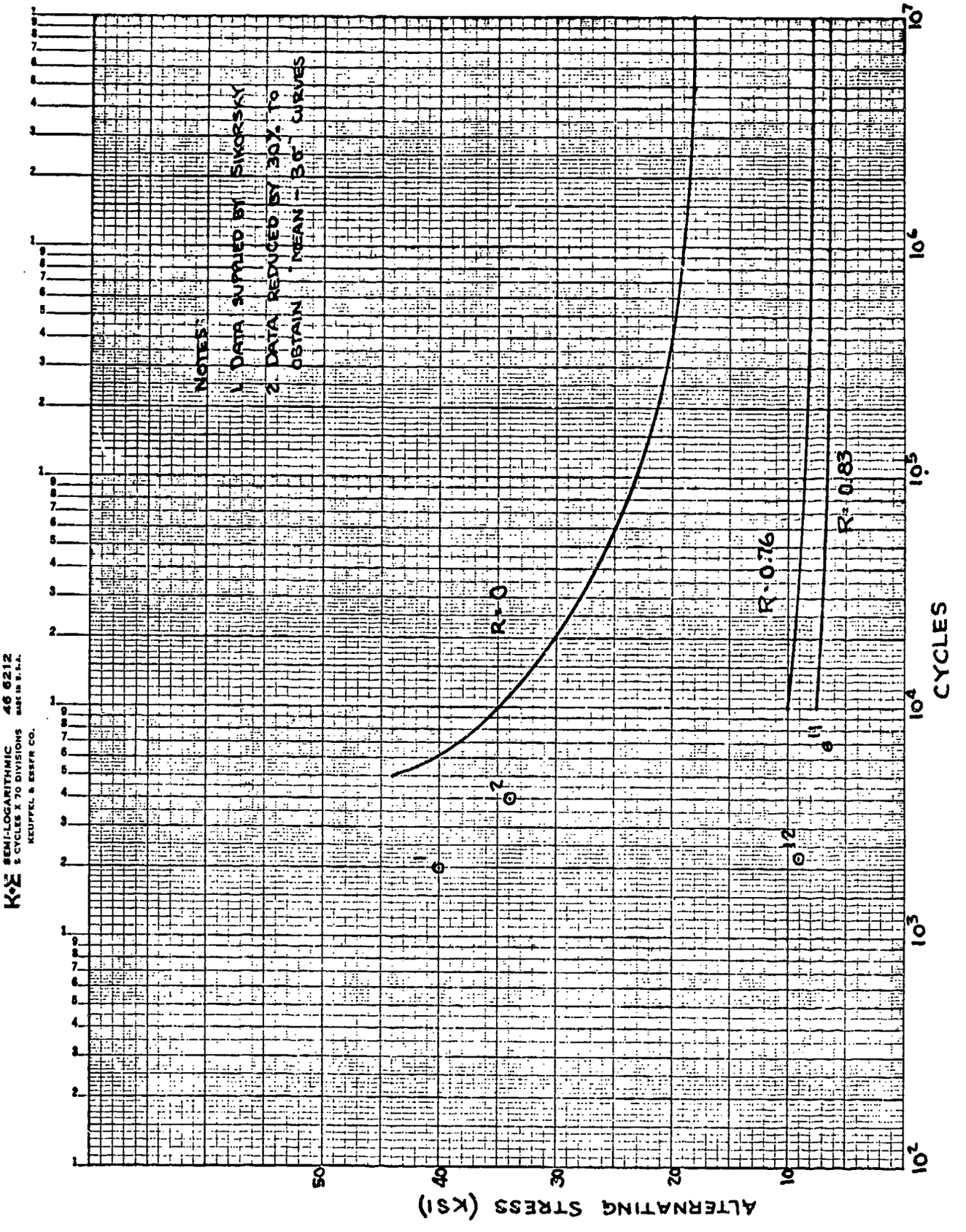
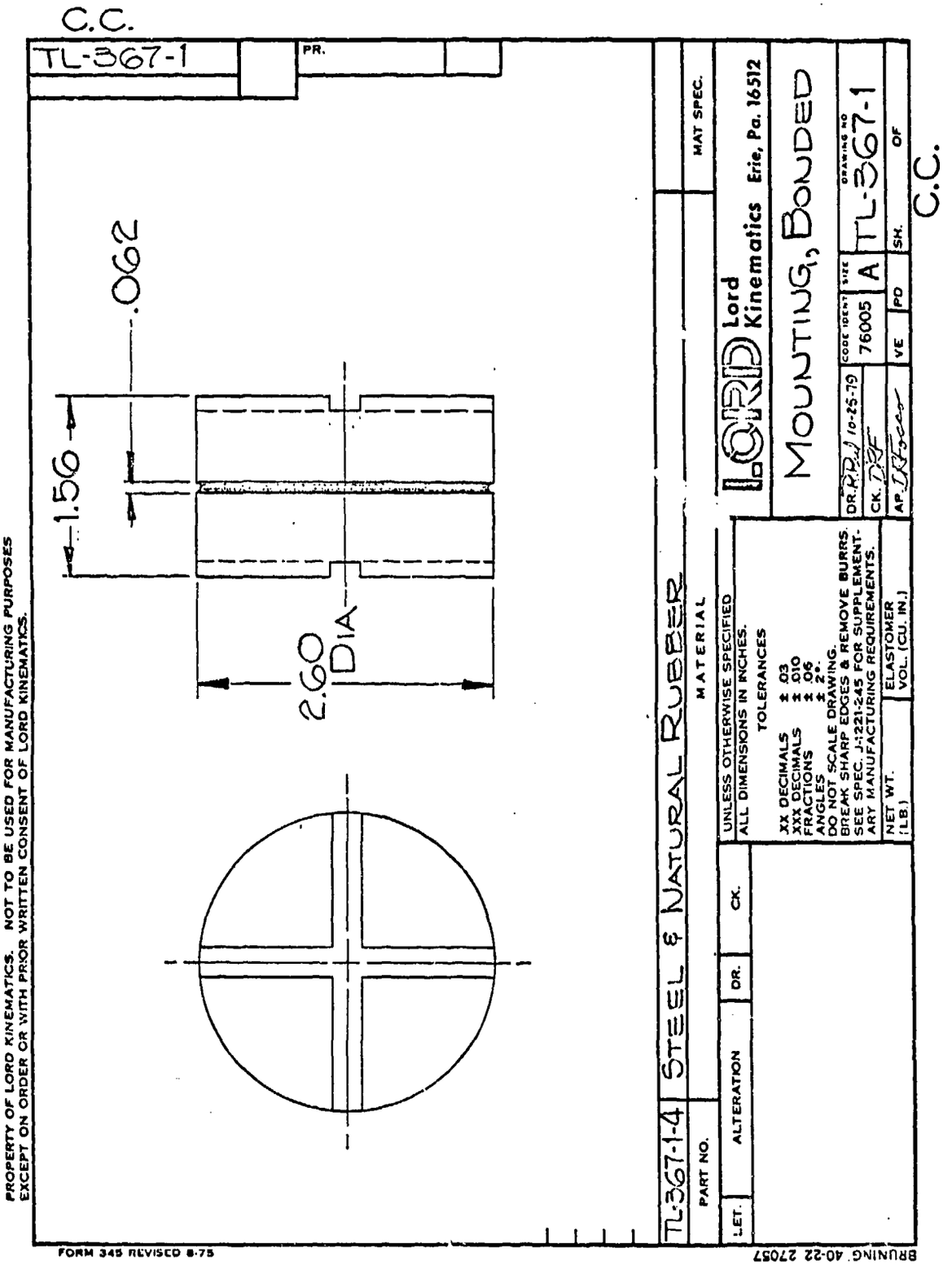



Figure 6 LB5-1035-1-1 Metal Shim Fatigue Life Diagram

Figure 7 TL-367, Elastomeric Laboratory Test Specimen



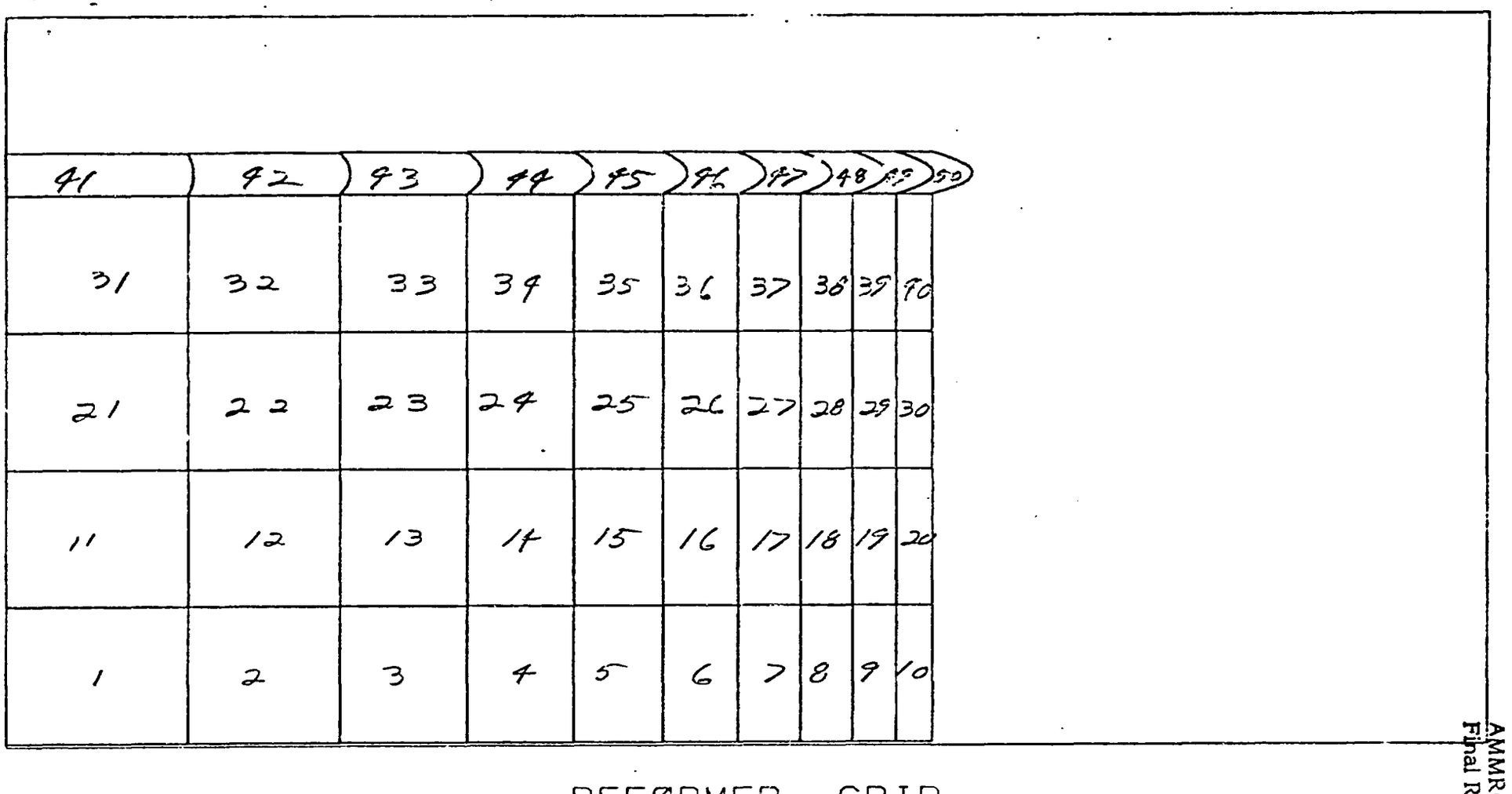
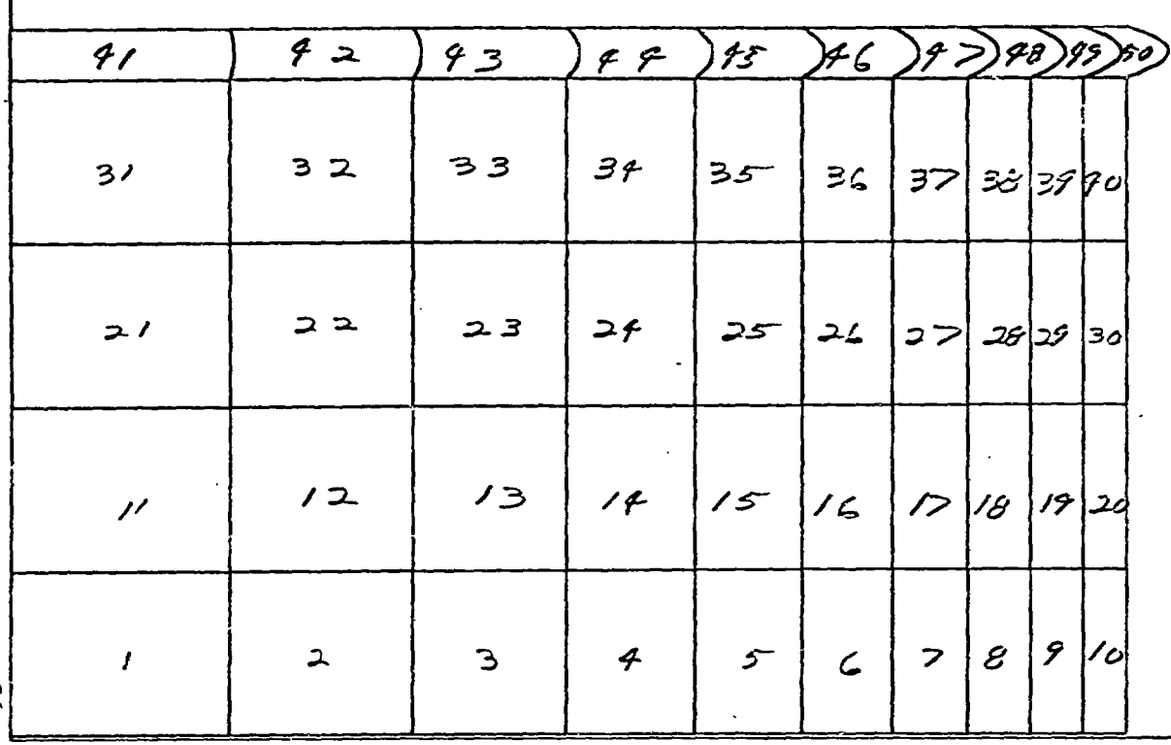



Figure 8 LB4-1034-2-1, Test Specimen Finite Element Model




DEFORMED GRID



1MRC SERVICE LIFE DET CRI LAY MODEL EPG 9/05/78 X833-G AXIAL=.005 TORS.=1 DEG

RLAS

TE 09/05/78

Figure 9 LB5-1034-1-1, Test Specimen Finite Element Model

TABLE 1

Common Physical Parameters Between the Actual Bearings and Test Specimens

| Item | LB4-1034-2-1 | LB5-1034-1-1 |
|---|---|---|
| Critical Layer | 17[a] | 1[b] |
| Elastomer | MAD008 | MAD013 |
| Modulus | 125 psi | 215 psi |
| Test Specimen Compressive Load | 18345 lbs. | 23535 lbs. |

[a] Layers numbered from spherical focal point
[b] Layers numbered from small end plate

Test Procedure and Spectrum

The laboratory specimens were tested in pairs for each point on the S-N curve. The test was conducted under an applied static axial load which produced the same edge shear strain as in the bearing when operated as specified in SES701059. The actual compression load used with each bearing test was presented in Table 1 above. An oscillating torsional input (direct shear strain) was imposed on each pair of test specimens with a total of three pairs of specimens and three different oscillating torsional inputs used to generate the S-N curve. After every 10,000 cycles of input, the static torsional stiffness of each specimen was measured under zero (nominal) applied static axial load. The initial measurement, taken at 1000 cycles, was used as a reference. A data point was permanently recorded when the torsional stiffness changed by 5% or the cycles had doubled since the last recorded data point. When the measured stiffness changed by more than 20% of the reference value, the sample was considered failed, and the number of cycles to reach this point was

taken as the fatigue life of the specimen. The average of the two specimen values at each input condition was taken as the fatigue life to be used in constructing the S-N curve. The above test sequence was conducted two times--once for each of the two Sikorsky UTTAS bearings. It should be noted that during the long term testing three test specimens did not reach the failure criterion of a loss of 20% shear stiffness. The reasons for removal are discussed later in the Test Results section of this report.

The oscillating torsional inputs were selected to give a range broad enough to encompass the shear strains encountered by the bearing, yet provide for a reasonable test time. The actual oscillating torsional angle for each specimen was calculated using Equation 1 below:

$$\theta = \frac{t\ E_S\ (57.296)}{r\ (100)} \qquad (1)$$

where:

$\theta$ = Torsional angle in degrees
$t$ = Specimen elastomer thickness
$r$ = Specimen elastomer radius
$E_S$ = Required direct shear strain in %

The test spectrum is presented in Table 2.

TABLE 2

Test Spectrum

| Bearing P/N | Elastomer | Direct Shear Strain | Test Specimen Torsional Angle |
|---|---|---|---|
| LB4-1034-2-1 | MAD008 | ± 100% | 2.84° |
| | | ± 60% | 1.71° |
| | | ± 27% | 0.77° |
| LB5-1034-1-1 | MAD013 | ± 110% | 3.13° |
| | | ± 70% | 2.00° |
| | | ± 36% | 1.02° |

Test Machines and Data Recording

Lord Kinematics believes that commercially available test machines could have been utilized to perform the testing. However, an existing Lord designed machine was selected to minimize cost. The Lord designation for the test machine is E-297.

The E-297 test machine subjects a thin layer of elastomer to a combination of torsional deflection and compressive force about an axis normal to the layer. Test samples consist of elastomer bonded between plane-sided metal discs. Lord P/N TL367, the sample normally employed, has a diameter of 2.5 inches. Existing configurations and tooling were used to fabricate the samples and to model the strain conditions required.

Each of the two machines available has two test stations. Each station consists of a central rotary hydraulic actuator, with a test sample at each end of its shaft, strain gaged transducers sensitive to both torque and axial force, and a linear hydraulic force actuator at each end. Two samples can be accommodated in each test line, four per machine, giving a total of eight. Control is by closed-loop servohydraulics. Three loops are employed, one for torsional motion, and one for each of the two

axial force actuators. Photographs numbers 15028 and 15029 show the test machine as configured for the test. The performance parameters are given in Table 3. The Lebow Model #6468 thrust-torque sensor and the Brush Metrisite #31 38 10 R VDT were both calibrated prior to starting the test to National Bureau of Standards requirements.

Motion data was taken from the Gilmore 1060 signal conditioners used to handle the feedback signals in the servo loops. Force data was sensed by Lebow type 6468 thrust-torque sensors, connected to Gilmore Model 1050 signal conditioners.

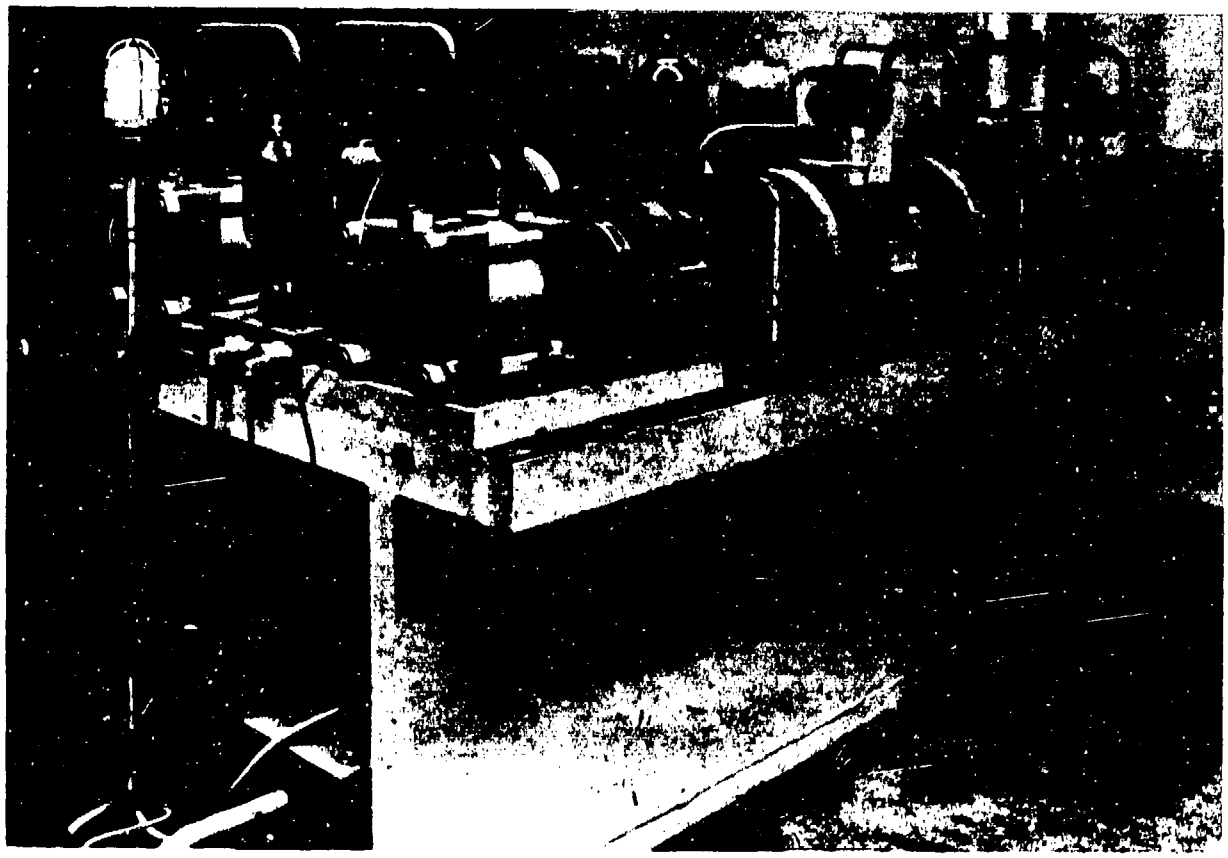
TABLE 3

E-297 Machine Parameters

SUMMARY OF CAPABILITIES:

| | |
|---|---|
| Maximum Compression Load | 80,000 lbs. |
| Compression Cylinder Stroke | ± 1 inch |
| Maximum Torque | 21,700 lb-in |
| Maximum Torsional Angle | 100 ± 5° |
| Opening Size | 2 x 13 x 13 inches |
| Number of Test Stations | 4 (with 2 test samples per station) |
| Instrumentation | Lebow Model #6468 Thrust-Torque Sensor (Fatigue Ratings: 25000 lb-in torque, 75000 lb thrust) |

| | |
|---|---|
| LOCATION | Lord Kinematics High Energy Test Lab |
| FUNCTION | This machine is designed to apply torsion and compression loads to thin rubber discs. It can apply various combinations of static and dynamic torsion or compression. |
| STANDARD TEST SPECIMEN | TL-367-1 |



Photograph 15028
NATURAL RUBBER FATIGUE (E-297) TEST MACHINE

Photograph 15029
NATURAL RUBBER FATIGUE (E-297) TEST MACHINE

Data from the signal conditioners is acquired by multiplexing into a Hewlett-Packard Model 9600E digital computer system. Both force and motion signals are subjected to Fourier analysis and the fundamental components of their waveforms are used to determine the torsional spring rate.

## Results of Test

A frequency verification test was performed to determine the highest of three selected frequencies which did not produce results which differed significantly from the 4.3 Hz results. The 4.3 Hz frequency is equivalent to the operating frequency of the Sikorsky UTTAS main rotor. The test frequencies selected were 10 Hz, 7 Hz and 4.3 Hz. A total of six specimens were tested in three pairs at the most severe input condition and stiffest elastomer stock. The initial test was conducted at 10 Hz with the specimens failing at an average of 975,000 cycles. The control test was run at 4.3 Hz with these specimens failing at an average of 1,270,000 cycles. The indicated spring rate data for the 10 Hz test was erratic when compared to the 4.3 Hz test data. The test machine at 10 Hz required frequent adjusting and tuning, which occasionally required the machine to be shut down, thus indicating that the test machine was strained beyond its capability. These two reasons prompted a third test at 7 Hz.

The two specimens tested at 7 Hz failed at an average of 1,389,000 cycles. This is within 9.3% of the cycles to failure at 4.3 Hz, as compared to 30.3% for the 10 Hz test. There was also no unscheduled stoppage of the test machine. Based on this test a determination was made to conduct the remainder of the test at 7 Hz.

The specimen fatigue test was conducted as described in the Test Procedure section of this report. A total of six test specimens, two at each of three conditions, were tested to develop the S-N curve for the critical layer of each bearing. The data was tabulated in terms of torsional shear spring rate and the number of fatigue cycles

which transpired to effect that spring rate. This tabulated data was then plotted for each specimen as torsional shear spring rate versus cycles to failure. As mentioned earlier, the assumed failure criterion is a 20% loss of shear spring rate when compared to a reference spring rate taken at 1000 cycles. The final method of data presentation is the construction of the actual S-N curve developed from the direct shear strain in percent at which the specimen was tested versus the average cycles to failure between the two specimens tested at that condition. Table 4 is a comprehensive summary of the test results, listing for each bearing the direct shear strain in percent, the cycles to failure of each test specimen, the average cycles to failure and the figure number where the tabulated and plotted data can be found.

It should be noted once again that three of the four test specimens in the least severe test (27% and 36% direct shear strain) did not fail at the assumed failure criteria. The test was terminated because of severe elastomer abrasion and reversion. Photographs numbers 26082, 26083, and 26084 show the individual test specimen condition at the time of termination.

## TABLE 4

### Fatigue Test Result Summary

A. Bearing P/N LB4-1034-2-1

| Location of Test Specimen on Machine | Test Specimen S/N | Elastomer | Direct Shear Strain | Cycles to Failure | Average Cycles for S-N Curve | Figure Numbers Tabulated Data | Figure Numbers Plotted Data |
|---|---|---|---|---|---|---|---|
| West | G-7 | MAD008 | ± 100% | 1749700 | 1765250 | 10 | 11 |
| East | G-8 | MAD008 | ± 100% | 1780800 | | 10 | 12 |
| West | G-9 | MAD008 | ± 60% | 16744900 | 14303000 | 13 | 14 |
| East | G-10 | MAD008 | ± 60% | 11861100 | | 13 | 15 |
| West | G-11 | MAD008 | ± 27% | 42760161 | 42760161 | 16 (3 shts) | 17 |
| East | G-12 | MAD008 | ± 27% | 42760161 | | 16 (3 shts) | 18 |

B. Bearing P/N LB5-1034-1-1

| Location of Test Specimen on Machine | Test Specimen S/N | Elastomer | Direct Shear Strain | Cycles to Failure | Average Cycles for S-N Curve | Figure Numbers Tabulated Data | Figure Numbers Plotted Data |
|---|---|---|---|---|---|---|---|
| West | G-7 | MAD013 | ± 110% | 700306 | 817100 | 21 | 22 |
| East | G-8 | MAD013 | ± 110% | 933900 | | 19 | 21 |
| West | G-15 | MAD013 | ± 70% | 3527600 | 4490400 | 22 | 23 |
| East | G-16 | MAD013 | ± 70% | 5453200 | | 22 | 24 |
| West | G-17 | MAD013 | ± 36% | 42863045 | 38330027 | 25 (3 shts) | 26 |
| East | G-18 | MAD013 | ± 36% | 33797000 | | 25 (3 shts) | 27 |

STATION # 2
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- 2.84
COMPRESSION: 18340. +-

| | WEST | | EAST | |
|---|---|---|---|---|
| SAMPLE #: | G- 7 | | G- 8 | |
| STATUS: | OFF | | OFF | |
| TEST STARTED: | 9:20 | 1 NOV 78 | 9:20 | 1 NOV 78 |
| LAST READING: | 9:48 | 4 NOV 78 | 11:08 | 4 NOV 78 |
| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
| | 139.0 | 0 | 142.0 | 0 |
| REFERENCE: | 131.8 | 1 000 | 132.0 | 1 000 |
| | 131.5 | 2 000 | 131.9 | 2 000 |
| | 130.5 | 4 000 | 131.5 | 4 000 |
| | 129.8 | 8 000 | 130.4 | 8 000 |
| | 130.0 | 25 300 | 130.8 | 25 300 |
| | 129.0 | 55 300 | 130.8 | 55 300 |
| | 127.7 | 115 300 | 129.4 | 115 300 |
| | 129.4 | 237 500 | 130.8 | 237 500 |
| | 129.6 | 477 500 | 131.7 | 477 500 |
| | 122.2 | 598 300 | 119.5 | 588 300 |
| | 135.9 | 599 200 | 126.2 | 599 200 |
| | 128.2 | 609 200 | 134.7 | 659 500 |
| | 120.3 | 1 189 500 | 127.5 | 709 500 |
| | 113.7 | 1 539 700 | 120.5 | 1 399 700 |
| | 106.8 | 1 709 700 | 113.6 | 1 609 700 |
| | | | 106.9 | 1 749 700 |
| | 105.2 | 1 749 700 | | |
| | | | 104.8 | 1 780 800 |

Figure 10, LB4-1034-2-1
Fatigue Test Result
±100% Shear Strain

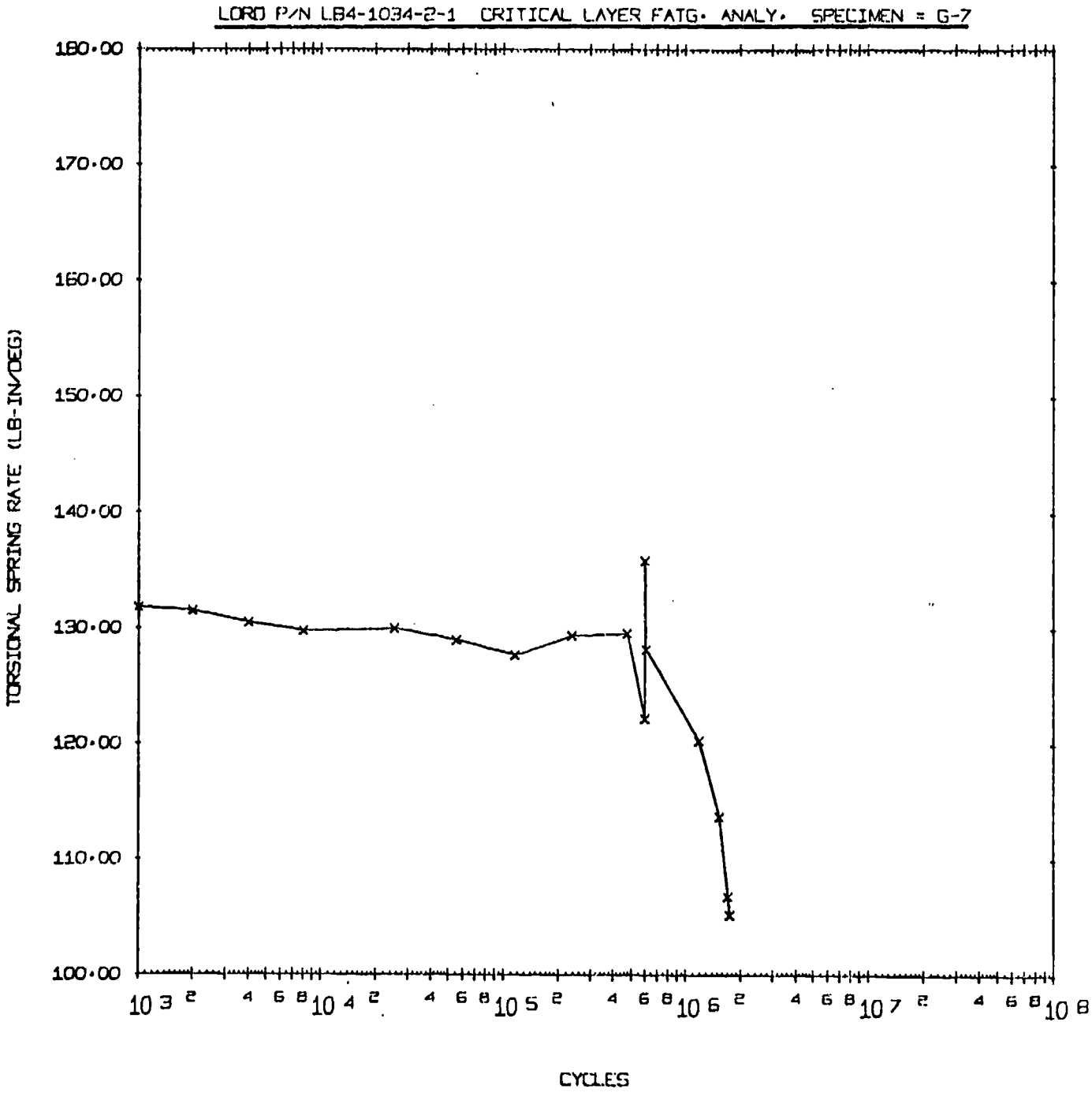

LORD P/N LB4-1034-2-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-7
TORSIONAL SPRING RATE (LB-IN/DEG)
180.00
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 11

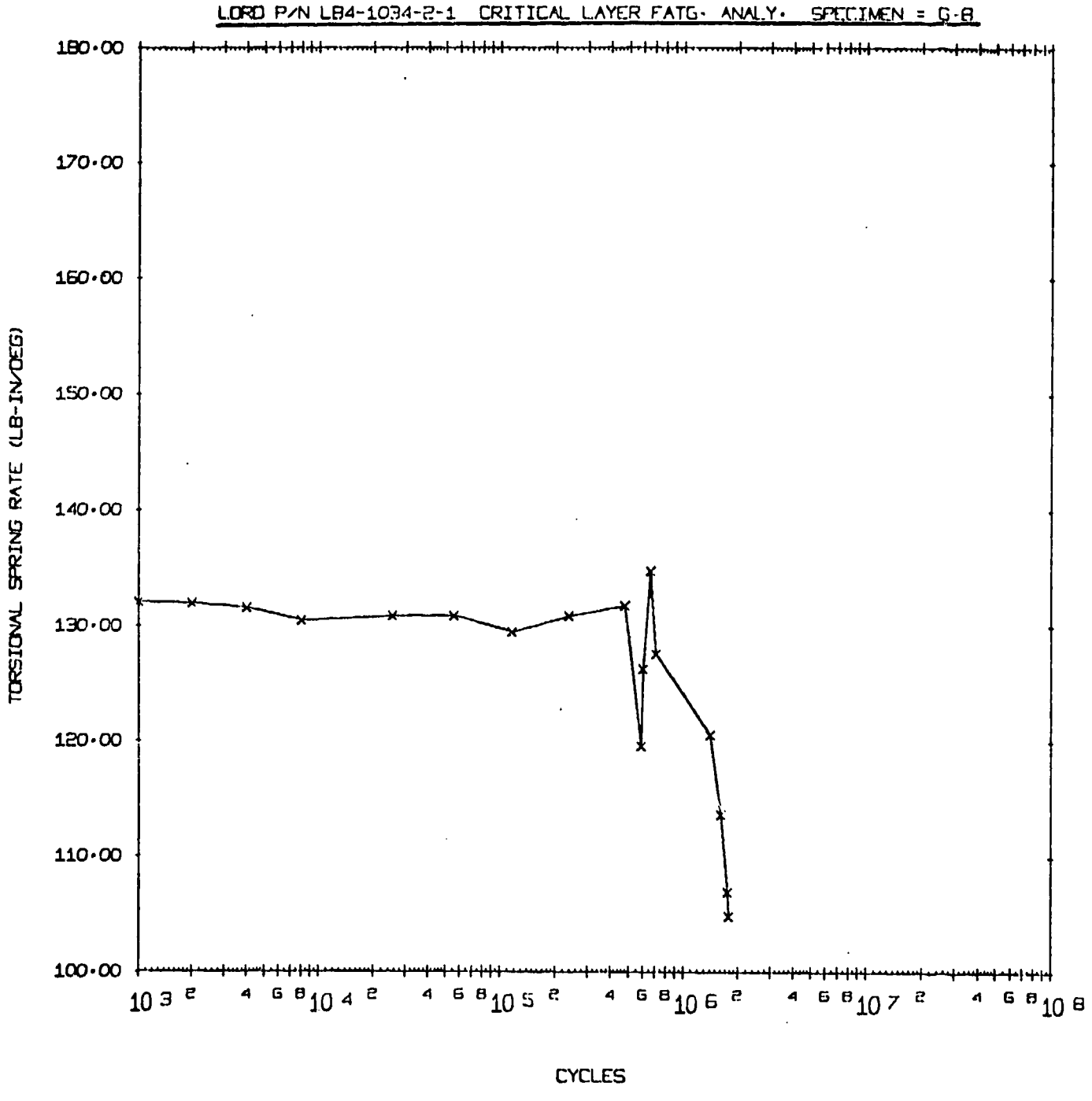

LORD P/N LB4-1034-2-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-B
180.00
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 12

STATION # 2
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- 1.71
COMPRESSION: 18340. +-

| | WEST | | EAST | |
|---|---|---|---|---|
| SAMPLE #: | G- 9 | | G- 10 | |
| STATUS: | OFF | | OFF | |
| TEST STARTED: | 11:01 22 FEB 79 | | 11:01 22 FEB 79 | |
| LAST READING: | 13:11 25 MAR 79 | | 16:13 18 MAR 79 | |
| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
| | 148.6 | 500 | 138.0 | 500 |
| REFERENCE: | 140.5 | 1 500 | 134.8 | 1 500 |
| | 139.6 | 3 500 | 134.2 | 3 500 |
| | 138.4 | 7 500 | 133.6 | 7 500 |
| | 137.3 | 15 600 | 133.0 | 15 600 |
| | 137.1 | 37 900 | 133.5 | 37 900 |
| | 137.2 | 77 900 | 134.1 | 77 900 |
| | 135.9 | 188 400 | 133.1 | 188 400 |
| | 135.5 | 377 300 | 133.9 | 377 300 |
| | 148.0 | 750 600 | 141.3 | 750 600 |
| | 137.4 | 760 600 | 134.4 | 780 600 |
| | 135.5 | 1 530 700 | 136.4 | 1 570 700 |
| | 134.3 | 3 067 300 | 119.1 | 3 138 900 |
| | 141.7 | 4 549 300 | 134.3 | 3 218 700 |
| | 133.6 | 4 649 400 | 127.0 | 3 889 200 |
| | 141.0 | 5 407 100 | 134.1 | 3 919 300 |
| | 133.2 | 5 457 100 | 126.5 | 5 407 100 |
| | 140.6 | 5 707 600 | 141.8 | 5 427 100 |
| | 132.8 | 5 827 600 | 131.9 | 5 437 100 |
| | 140.5 | 8 292 000 | 141.8 | 5 497 100 |
| | 133.3 | 8 552 000 | 132.7 | 5 507 100 |
| | 142.3 | 11 861 100 | 125.8 | 7 527 600 |
| | 132.1 | 11 871 100 | 118.7 | 9 752 000 |
| | 124.9 | 13 009 700 | 111.9 | 11 001 100 |
| | 110.5 | 13 147 500 | | |
| | 132.0 | 13 147 500 | 107.8 | 11 861 100 |
| | 111.9 | 16 744 900 | | |

Figure 13 LB4-1034-2-1
Fatigue Test Result
± 60% Shear Strain

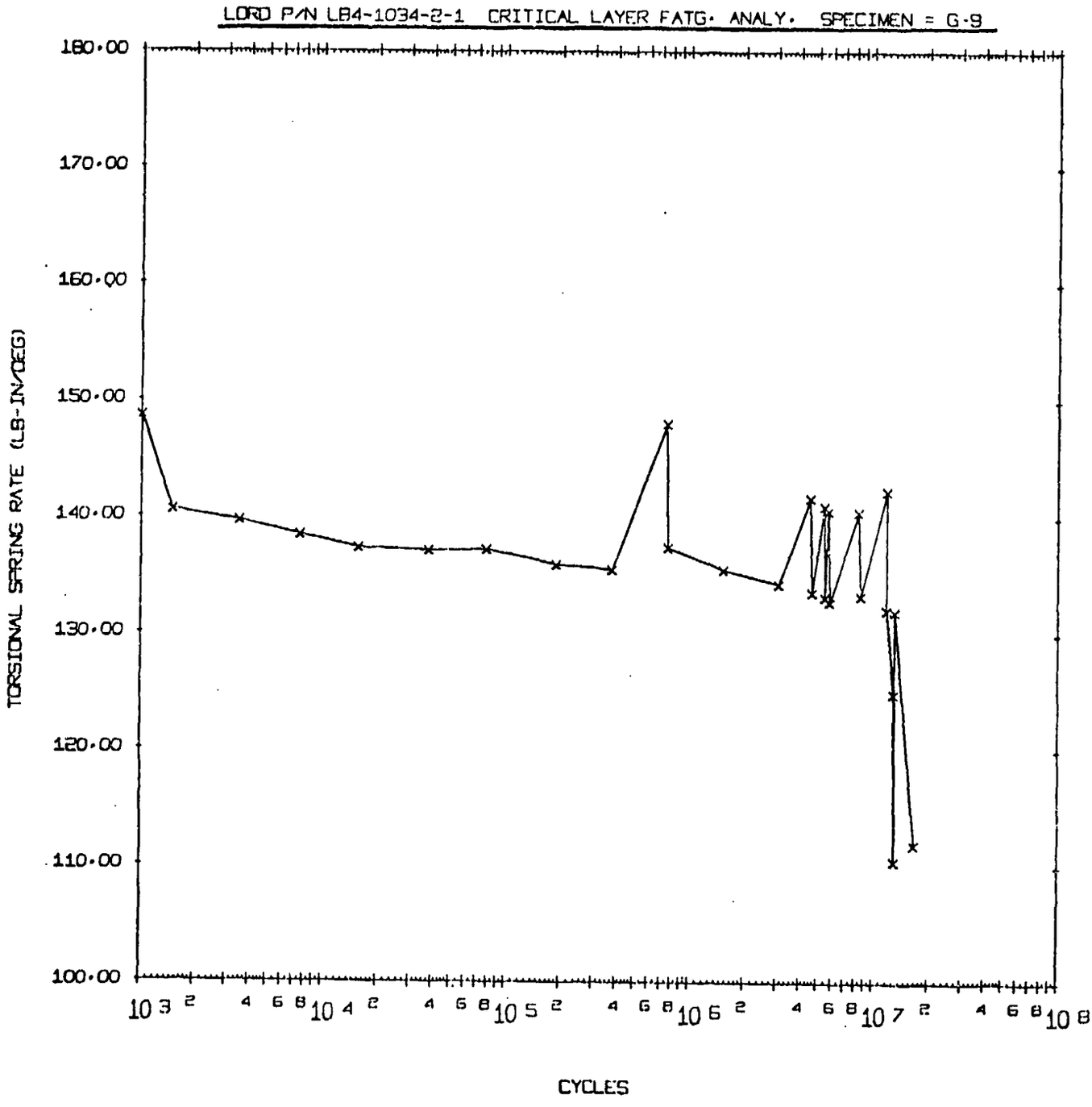

LORD P/N LB4-1034-2-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-9
180.00
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 14

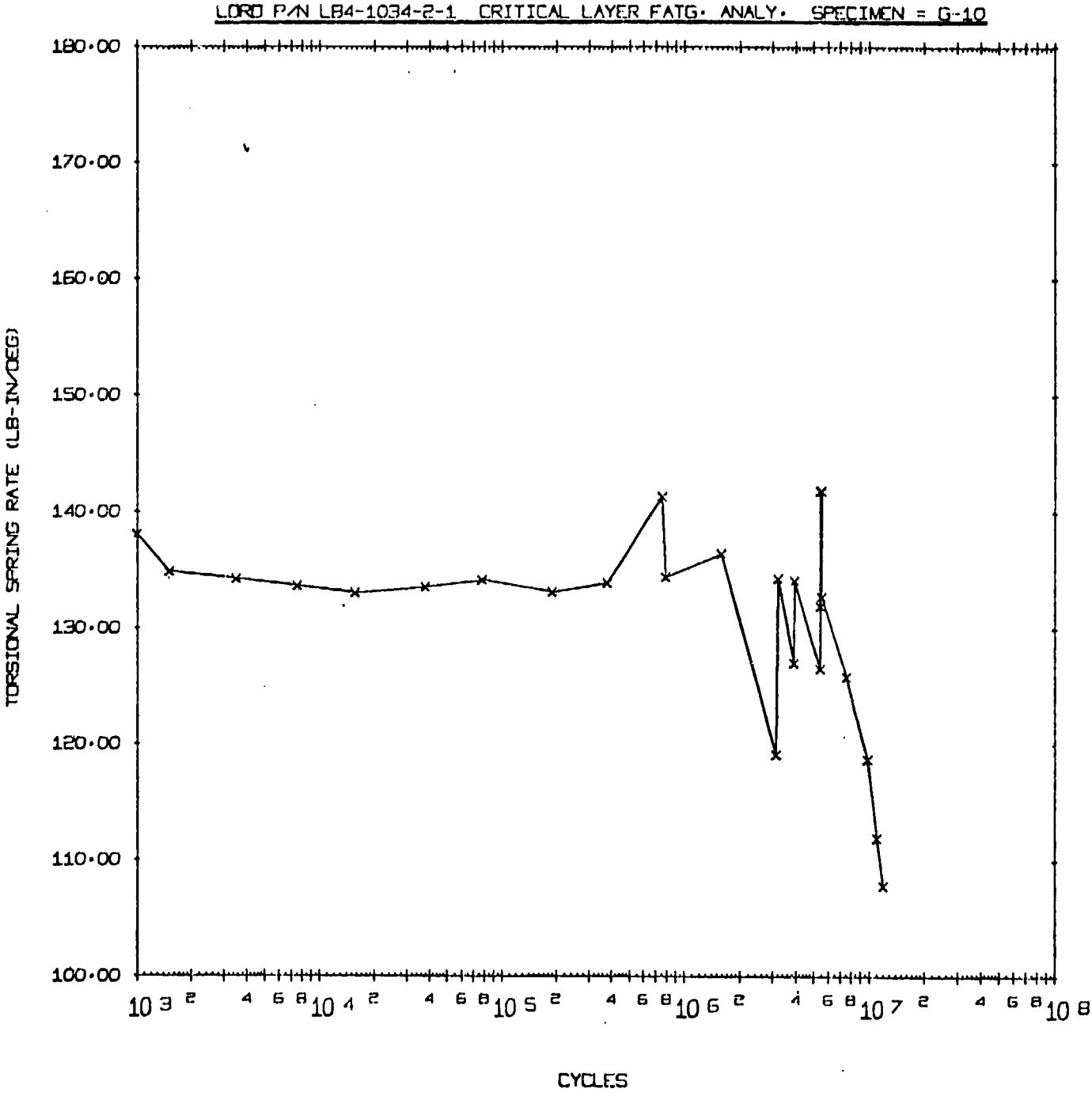

LORD P/N LB4-1034-2-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-10
180.00
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 15

STATION # 1
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- 77
COMPRESSION: 18340. +-

| | WEST | EAST |
|---|---|---|
| SAMPLE #: | G- 11 | G- 12 |
| STATUS: | HOLD | HOLD |
| TEST STARTED: | 10:57 16 JUN 79 | 10:57 16 JUN 79 |
| LAST READING: | 16:15 27 JUL 79 | 16:15 27 JUL 79 |

1st FILE

| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
|---|---|---|---|---|
| | 145.9 | 0 | 130.4 | 0 |
| REFERENCE: | 138.0 | 1 000 | 126.1 | 1 000 |
| | 136.6 | 2 000 | 125.0 | 2 000 |
| | 136.9 | 4 000 | 124.3 | 4 000 |
| | 135.8 | 8 000 | 124.4 | 8 000 |
| | 135.4 | 20 000 | 124.3 | 20 000 |
| | 134.9 | 40 000 | 123.7 | 40 000 |
| | 134.7 | 82 400 | 125.7 | 82 400 |
| | 134.9 | 172 400 | 128.0 | 172 400 |
| | 135.0 | 352 400 | 127.6 | 352 400 |
| | 137.2 | 720 897 | 120.1 | 720 897 |
| | 135.8 | 1 450 997 | 121.6 | 1 450 997 |
| | 137.1 | 2 910 197 | 132.8 | 1 816 497 |
| | 138.3 | 5 824 297 | 121.9 | 2 420 197 |
| | 147.7 | 11 853 609 | 128.8 | 2 460 197 |
| | 140.4 | 11 894 609 | 121.8 | 3 270 497 |
| | | | 128.4 | 3 780 497 |
| | 140.8 | 15 085 309 | 131.8 | 7 564 597 |
| | | | 121.0 | 8 134 797 |
| | | | 130.7 | 8 164 897 |
| | | | 122.4 | 10 697 497 |
| | | | 133.8 | 11 853 609 |
| | | | 124.3 | 11 854 609 |
| | | | 131.6 | 11 874 609 |
| | | | 117.9 | 14 619 709 |
| | | | 124.8 | 14 639 709 |
| | | | 123.0 | 15 085 309 |

Figure 16 LB4-1034-2-1
Fatigue Test Result - ±27% Shear Strain

Sheet 1 Of 3)

** BOOT-UP ****** SET TIME!!!

STATION # 1
PART# TL367-1-5

INPUT CONDITIONS-- TORSION: .00+-- .77
COMPRESSION: 18340.+-

2ND File

| | WEST | EAST |
|---|---|---|
| SAMPLE #: | G- 11 | G- 12 |
| STATUS. | HOLD | HOLD |
| TEST STARTED: | 10:14 30 JUL 79 | 10:14 30 JUL 79 |
| LAST READING: | 10:21 4 SEP 79 | 10:21 4 SEP 79 |

| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
|---|---|---|---|---|
| | 144.2 | 0 | 136.0 | 0 |
| REFERENCE: | 142.1 | 10 000 | 136.5 | 10 000 |
| | 141.6 | 30 100 | 136.6 | 30 100 |
| | 140.5 | 70 100 | 134.9 | 70 100 |
| | 140.1 | 144 000 | 130.2 | 144 000 |
| | 139.2 | 294 000 | 134.2 | 294 000 |
| | 139.1 | 594 000 | 135.4 | 594 000 |
| | 141.8 | 1 194 000 | 137.3 | 1 194 000 |
| | 139.0 | 2 388 100 | 128.2 | 2 148 100 |
| | 139.7 | 4 780 000 | 135.3 | 2 808 100 |
| | 138.6 | 9 568 600 | 127.3 | 3 458 100 |
| | 129.2 | 16 612 000 | 120.3 | 4 500 000 |
| | 138.6 | 18 711 700 | 131.4 | 4 510 000 |
| | | | 118.2 | 8 022 800 |
| | 138.6 | 18 712 100 | 130.3 | 8 322 800 |
| | | | 114.6 | 8 918 600 |
| | | | 124.1 | 8 928 600 |
| | | | 116.6 | 10 748 700 |
| | | | 127.8 | 10 858 700 |
| | | | 119.4 | 12 338 700 |
| | | | 112.2 | 12 498 700 |
| | | | 127.4 | 12 518 700 |
| | | | 118.6 | 13 968 700 |
| | | | 125.5 | 14 148 700 |
| | | | 117.6 | 15 008 700 |
| | | | 125.6 | 15 058 700 |
| | | | 129.6 | 18 712 100 |

Figure 16. LB4-1034-2-1
Fatigue Test REsult-±27% Shear Strain

(Sheet 2 Of 3)

STATION # 1
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- .77
COMPRESSION: 18340. +-

3RD File

| | WEST | | EAST | |
|---|---|---|---|---|
| SAMPLE #: | Q- 11 | | Q- 12 | |
| STATUS: | HOLD | | HOLD | |
| TEST STARTED: | 10:25 4 SEP 79 | | 10:25 4 SEP 79 | |
| LAST READING: | 11:22 24 SEP 79 | | 11:22 24 SEP 79 | |
| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
| | 131.8 | 0 | 124.2 | 0 |
| REFERENCE: | 131.2 | 10 000 | 123.9 | 10 000 |
| | 131.4 | 20 000 | 123.5 | 20 000 |
| | 130.7 | 40 000 | 123.2 | 40 000 |
| | 130.8 | 80 000 | 123.0 | 80 000 |
| | 130.5 | 160 000 | 122.3 | 160 000 |
| | 131.2 | 320 000 | 122.1 | 320 000 |
| | 139.7 | 536 900 | 121.5 | 646 900 |
| | 132.8 | 716 900 | 121.3 | 1 295 000 |
| | 135.1 | 1 440 100 | 121.2 | 2 590 900 |
| | 134.0 | 2 880 900 | 130.1 | 3 203 500 |
| | 142.9 | 5 885 100 | 123.3 | 3 203 500 |
| | 123.3 | 5 894 800 | 116.8 | 6 050 500 |
| | 134.4 | 7 360 852 | 123.1 | 7 360 852 |
| | 142.6 | 7 360 852 | 116.7 | 7 680 852 |
| | 133.0 | 7 370 852 | | |
| | | | 117.0 | 8 962 752 |
| | 132.8 | 8 962 752 | | |

Figure 16 LB4-1034-2-1
Fatigue Test Result-±27% Shear Strain

(Sheet 3 Of 3)

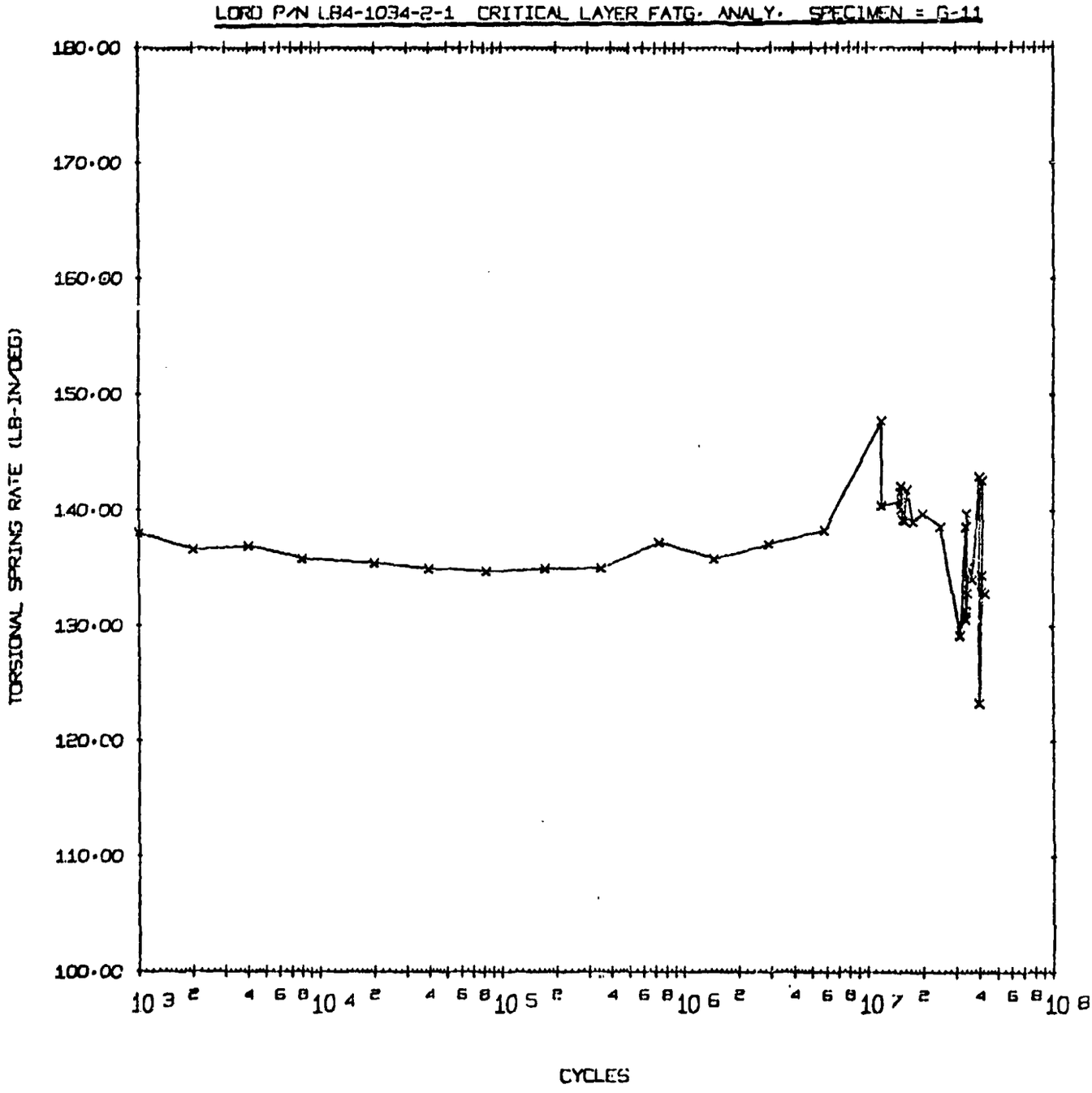

LORD P/N LB4-1034-2-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-11
180.00
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 17

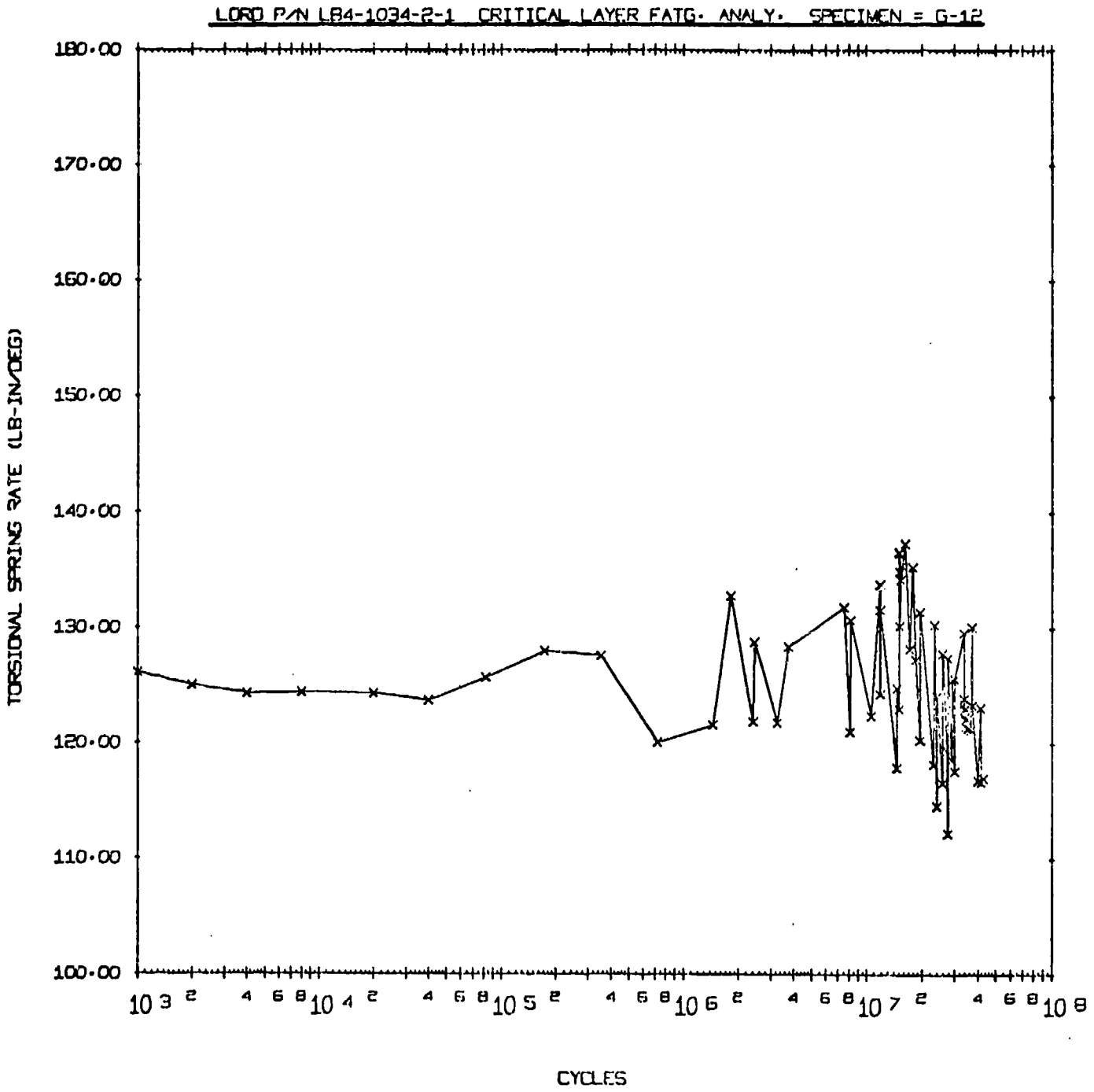

LORD P/N LB4-1034-2-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-12
180.00
170.00
160.00
150.00
140.00
130.00
120.00
110.00
100.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 18

STATION # 2
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- 3.13
COMPRESSION: 23520. +-

| | WEST | | EAST | |
|---|---|---|---|---|
| SAMPLE #: | 0- 7 | | 0- 8 | |
| STATUS: | OFF | | OFF | |
| TEST STARTED: | 14:59 | 6 NOV 78 | 14:59 | 6 NOV 78 |
| LAST READING: | 19:13 | 7 NOV 78 | 18:30 | 8 NOV 78 |
| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
| | 199.3 | 0 | 196.2 | 0 |
| REFERENCE: | 195.8 | 1 000 | 189.3 | 1 000 |
| | 197.6 | 2 000 | 190.8 | 2 000 |
| | 198.3 | 4 000 | 190.8 | 4 000 |
| | 197.9 | 8 000 | 190.8 | 8 000 |
| | 199.5 | 20 300 | 192.4 | 20 300 |
| | 198.8 | 50 300 | 193.1 | 50 300 |
| | 199.0 | 110 300 | 192.2 | 110 300 |
| | 199.5 | 230 300 | 193.9 | 230 300 |
| | 195.5 | 470 300 | 193.8 | 470 300 |
| | 184.9 | 550 300 | 183.6 | 660 300 |
| | 174.4 | 620 300 | 211.1 | 700 300 |
| | 161.8 | 670 300 | 183.4 | 710 300 |
| | | | 173.4 | 773 800 |
| | 155.8 | 700 300 | 163.2 | 863 900 |
| | | | 152.9 | 923 900 |
| | | | 150.1 | 933 900 |

Figure 19 LB5-1034-1-1
Fatigue Test Result-±110% Shear Strain

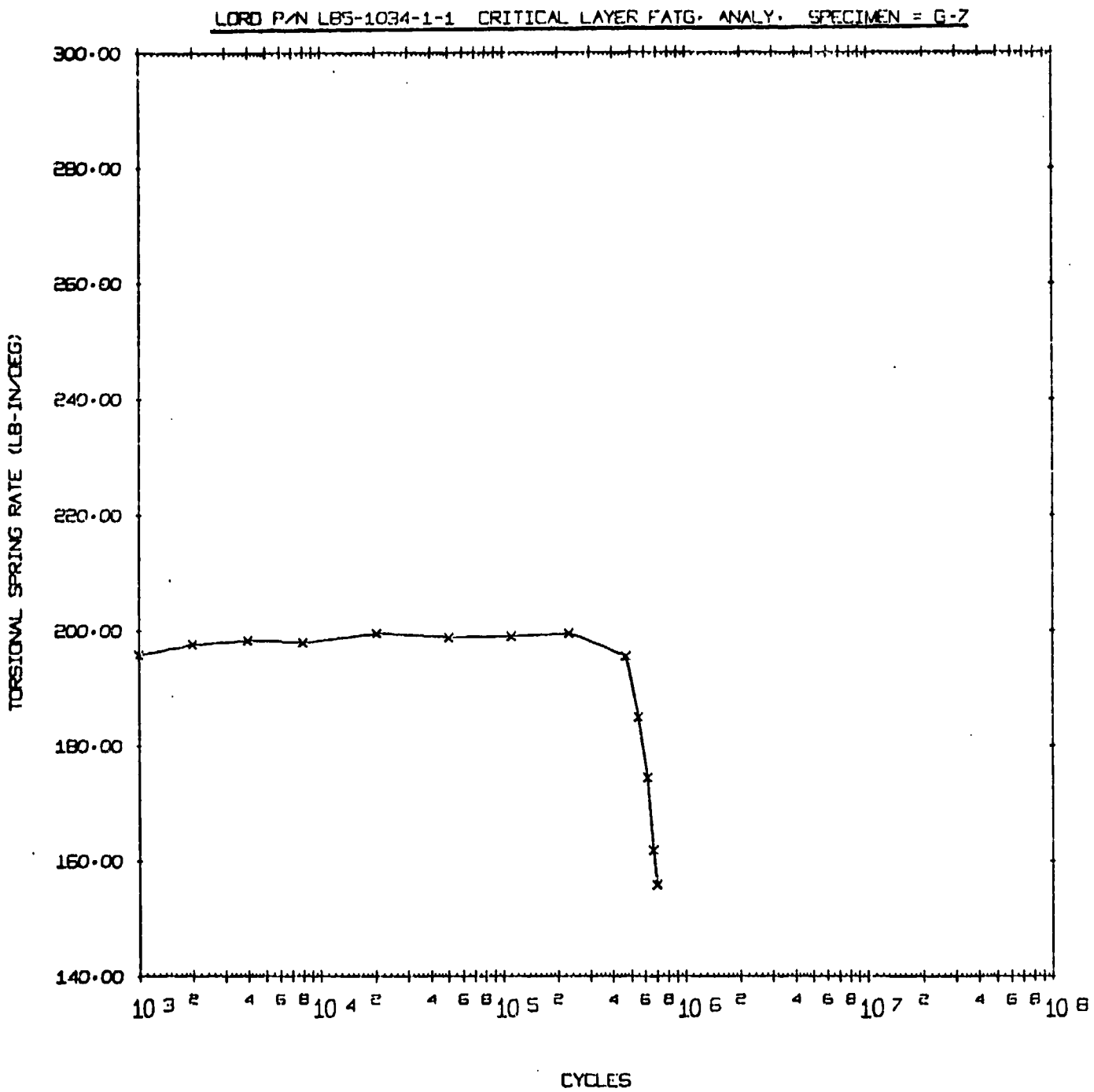

LORD P/N LBS-1034-1-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-Z
300.00
280.00
260.00
240.00
220.00
200.00
180.00
160.00
140.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 20

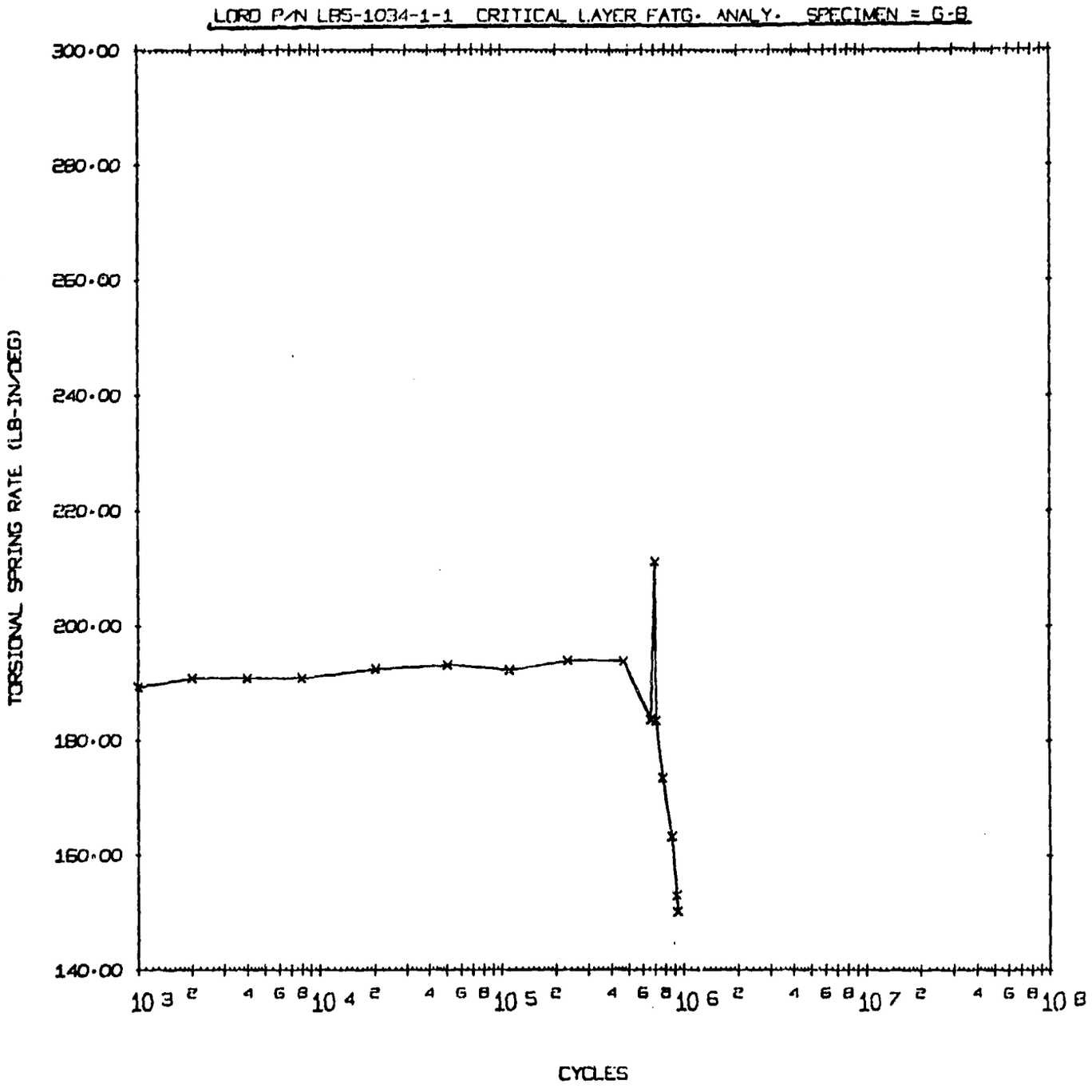

LORD P/N LB5-1034-1-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-B
300.00
280.00
260.00
240.00
220.00
200.00
180.00
160.00
140.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 21

STATION # 2
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- 2.00
COMPRESSION: 23520. +-

| | WEST | | EAST | |
|---|---|---|---|---|
| SAMPLE #: | G- 15 | | G- 16 | |
| STATUS: | OFF | | OFF | |
| TEST STARTED: | 13:46 10 NOV 78 | | 13:46 10 NOV 78 | |
| LAST READING: | 11:53 17 NOV 78 | | 18:50 20 NOV 78 | |
| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
| | 228.2 | 0 | 225.4 | 0 |
| REFERENCE: | 211.4 | 1 000 | 205.1 | 1 000 |
| | 211.2 | 2 000 | 205.8 | 2 000 |
| | 210.8 | 4 000 | 205.2 | 4 000 |
| | 210.9 | 8 000 | 204.5 | 8 000 |
| | 210.3 | 16 000 | 203.7 | 16 000 |
| | 213.0 | 39 000 | 205.7 | 39 000 |
| | 212.6 | 79 000 | 204.4 | 79 000 |
| | 214.0 | 159 000 | 206.8 | 159 000 |
| | 214.0 | 319 000 | 206.9 | 319 000 |
| | 215.2 | 639 000 | 208.5 | 639 000 |
| | 211.9 | 1 279 000 | 213.0 | 1 279 000 |
| | 228.8 | 1 387 800 | 228.2 | 1 387 800 |
| | 214.1 | 1 397 800 | 214.8 | 1 397 800 |
| | 200.7 | 1 777 800 | 227.7 | 2 464 200 |
| | 214.1 | 2 464 200 | 211.4 | 2 474 200 |
| | 199.2 | 2 474 200 | 194.9 | 2 987 600 |
| | 188.2 | 2 774 200 | 206.5 | 2 997 600 |
| | 177.6 | 2 957 600 | 196.0 | 4 147 600 |
| | | | 184.9 | 4 617 600 |
| | 168.5 | 3 527 600 | 174.4 | 5 107 600 |
| | | | 162.7 | 5 453 200 |
| | | | 162.7 | 5 453 200 |

Figure 22 LB5-1034-1-1
Fatigue Test Result-±70% Shear Strain

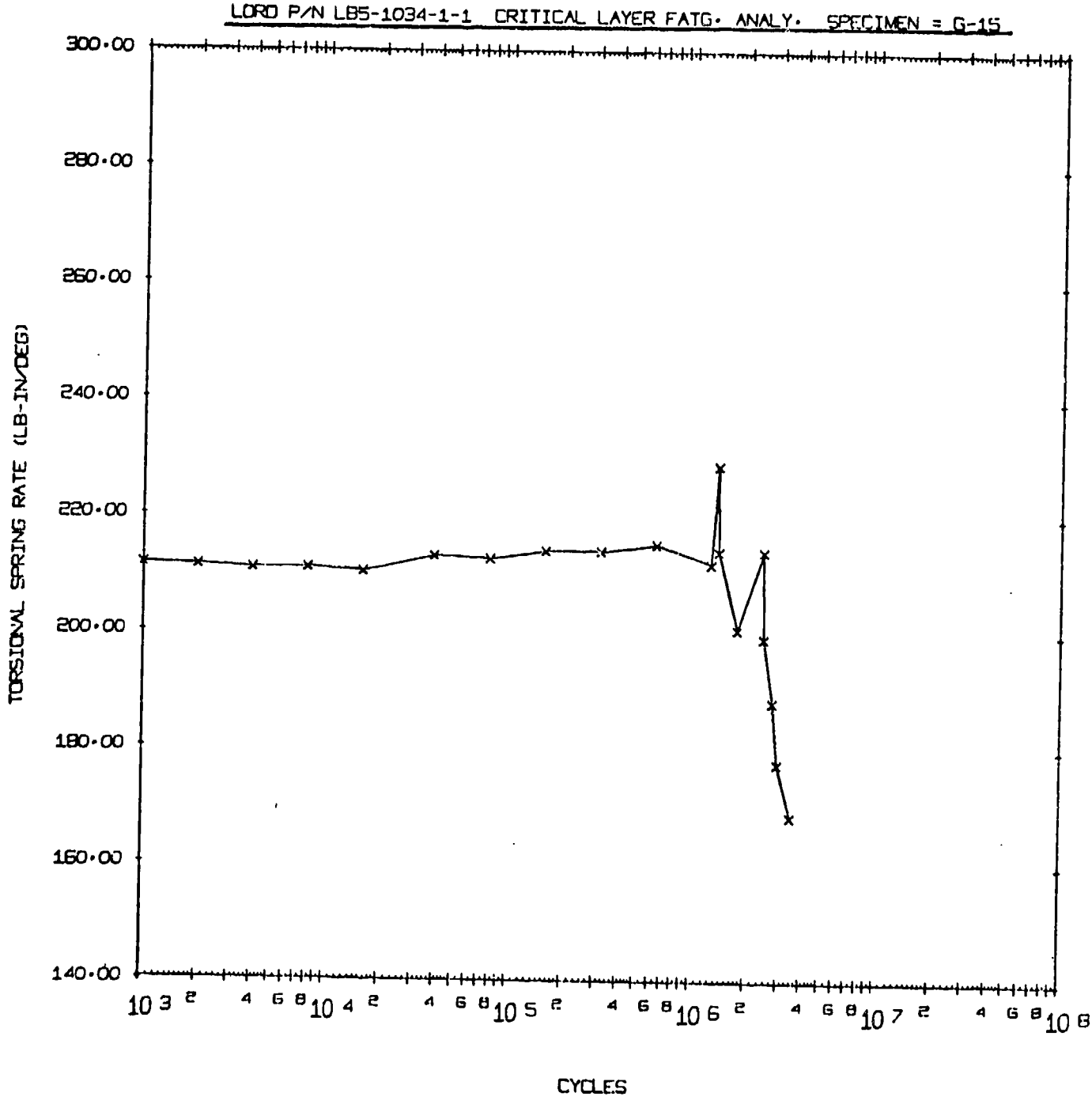

LORD P/N LB5-1034-1-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-15
300.00
280.00
260.00
240.00
220.00
200.00
180.00
160.00
140.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 23

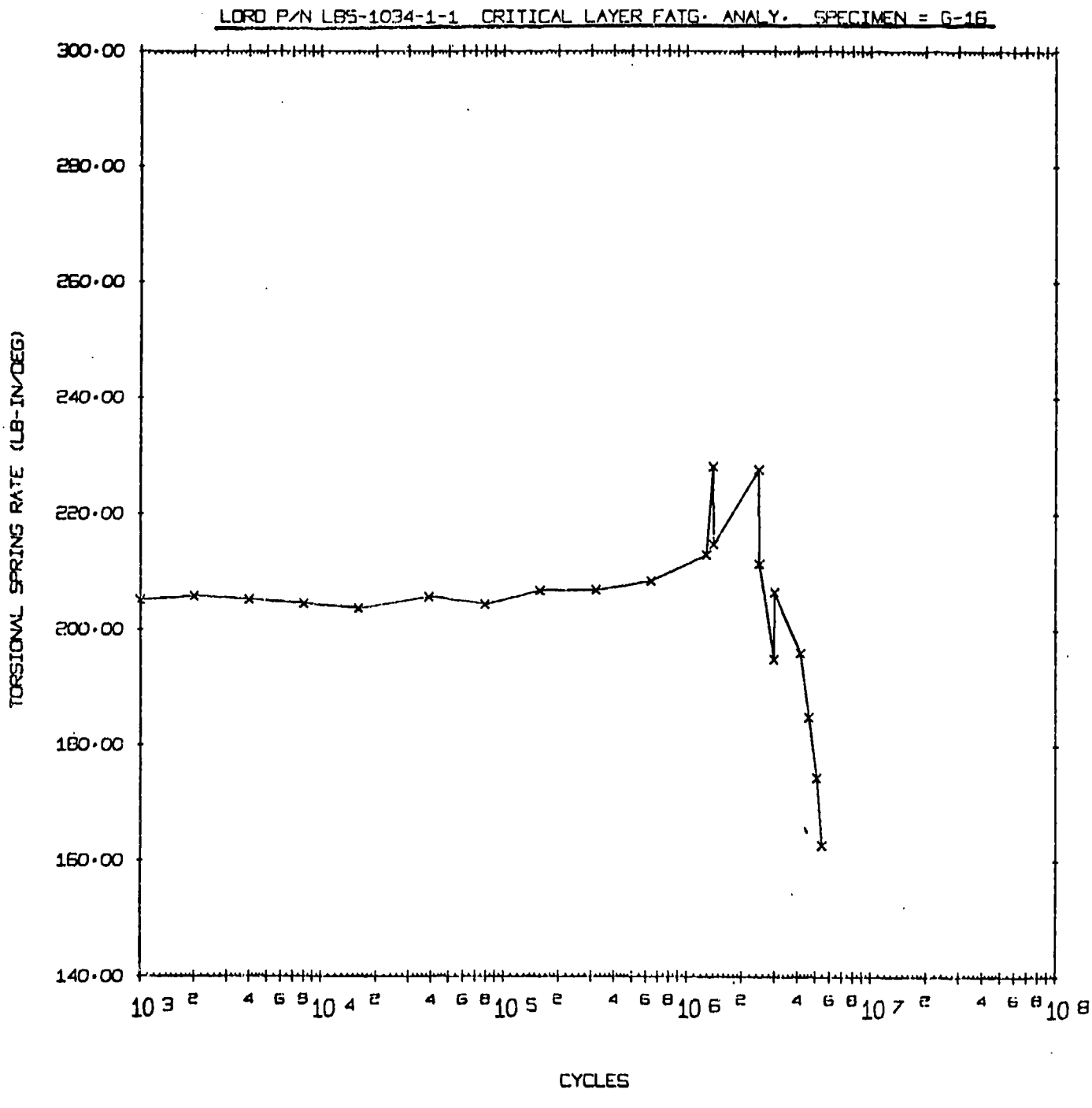

LORD P/N LB5-1034-1-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-16
300.00
280.00
260.00
240.00
220.00
200.00
180.00
160.00
140.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 24.

STATION # 2
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- 1.00
COMPRESSION: 23520. +-

| | WEST | | EAST | |
|---|---|---|---|---|
| SAMPLE #: | G- 17 | 1ST | G- 18 | |
| STATUS: | HOLD | | HOLD | |
| TEST STARTED: | 10:57 16 JUN 79 | | 10:57 16 JUN 79 | |
| LAST READING: | 16:15 27 JUL 79 | | 16:15 27 JUL 79 | |
| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
| | 237.8 | 0 | 233.8 | 0 |
| REFERENCE: | 222.2 | 1 000 | 217.5 | 1 000 |
| | 220.4 | 2 000 | 215.7 | 2 000 |
| | 221.5 | 4 000 | 216.3 | 4 000 |
| | 221.6 | 8 000 | 216.0 | 8 000 |
| | 224.2 | 20 000 | 218.6 | 20 000 |
| | 226.3 | 40 000 | 220.4 | 40 000 |
| | 223.8 | 82 400 | 218.9 | 82 400 |
| | 223.3 | 172 400 | 217.8 | 172 400 |
| | 227.1 | 352 400 | 221.9 | 352 400 |
| | 223.6 | 720 897 | 222.4 | 720 897 |
| | 235.6 | 1 390 997 | 226.2 | 1 450 997 |
| | 222.2 | 1 826 497 | 228.8 | 2 910 197 |
| | 233.7 | 1 876 497 | 246.2 | 2 950 197 |
| | 238.9 | 3 760 497 | 234.9 | 3 070 197 |
| | 240.6 | 7 524 597 | 249.3 | 4 700 497 |
| | 227.0 | 10 697 497 | 234.3 | 4 830 497 |
| | 245.7 | 10 700 297 | 230.0 | 9 666 197 |
| | 264.9 | 11 853 609 | 217.1 | 10 697 497 |
| | 253.0 | 11 853 609 | 235.3 | 11 853 609 |
| | 235.2 | 11 854 609 | 224.3 | 11 853 609 |
| | 254.0 | 12 250 209 | 213.0 | 13 810 009 |
| | 242.8 | 13 225 109 | | |
| | 260.7 | 13 480 009 | 214.5 | 15 085 309 |
| | 249.0 | 13 570 009 | | |
| | 248.4 | 15 085 309 | | |

Figure 25. LB5-1034-1-1
Fatigue Test Results - ±36% Shear Strain

(Sheet 1 Of 3)

STATION # 2
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- 1.00
COMPRESSION: 23520. +-

| | WEST | EAST |
|---|---|---|
| SAMPLE #: | C- 17 | G- 18 |
| STATUS: | OFF | OFF |

2nd File

| | | |
|---|---|---|
| TEST STARTED: | 10:14 30 JUL 79 | 10:14 30 JUL 79 |
| LAST READING: | 0 38 20 SEP 79 | 21:35 3 SEP 79 |

| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
|---|---|---|---|---|
| | 259.3 | 0 | 217.3 | 0 |
| REFERENCE. | 254.5 | 10 000 | 214.4 | 10 000 |
| | 255.3 | 30 100 | 217.3 | 30 100 |
| | 248.4 | 70 100 | 215.6 | 70 100 |
| | 247.5 | 144 000 | 217.1 | 144 000 |
| | 243.7 | 294 000 | 215.0 | 294 000 |
| | 243.6 | 594 000 | 213.6 | 594 000 |
| | 248.6 | 1 194 000 | 214.8 | 1 194 000 |
| | 246.2 | 2 388 100 | 209.6 | 2 388 100 |
| | 248.2 | 4 780 000 | 204.1 | 4 780 000 |
| | 242.5 | 9 568 600 | 193.2 | 8 292 800 |
| | 236.1 | 16 602 000 | 182.2 | 12 338 700 |
| | 239.3 | 16 612 000 | 197.9 | 16 602 000 |
| | 226.5 | 19 429 000 | 182.8 | 16 612 000 |
| | 244.2 | 21 915 600 | 172.0 | 18 061 700 |
| | 226.9 | 21 925 600 | | |
| | 275.1 | 21 971 300 | 171.4 | 18 711 700 |
| | 236.5 | 21 971 300 | | |
| | 223.2 | 22 072 100 | | |
| | 210.3 | 24 763 400 | | |
| | 203.4 | 25 573 400 | | |

Figure 25 - LB5-1034-1-1

Fatigue Test Results - ±36% Shear Strain

(Sheet 2 Of 3)

STATION # 2
PART# TL367-1-5

INPUT CONDITIONS- TORSION: .00+- 1.00
COMPRESSION: 23520. +-

| | WEST | | EAST |
|---|---|---|---|
| SAMPLE #: | G- 17 | 3RD File | G- 18 |
| STATUS: | HOLD | | OFF |

TEST STARTED: 11:40 20 SEP 79
LAST READING: 11:22 24 SEP 79

| | (LB-IN/DEG) | (#CYCLES) | (LB-IN/DEG) | (#CYCLES) |
|---|---|---|---|---|
| | 224.0 | 0 | | |
| REFERENCE: | 226.5 | 10 000 | | |
| | 213.1 | 20 000 | | |
| | 212.6 | 40 000 | | |
| | 207.3 | 602 436 | | |
| | 233.3 | 602 436 | | |
| | 214.0 | 612 436 | | |
| | 206.9 | 1 234 536 | | |
| | 204.7 | 2 204 336 | | |

Figure 25 - LB5-1034-1-1
Fatigue Test Results - ±36% Shear Strain

Sheet 3 Of 3

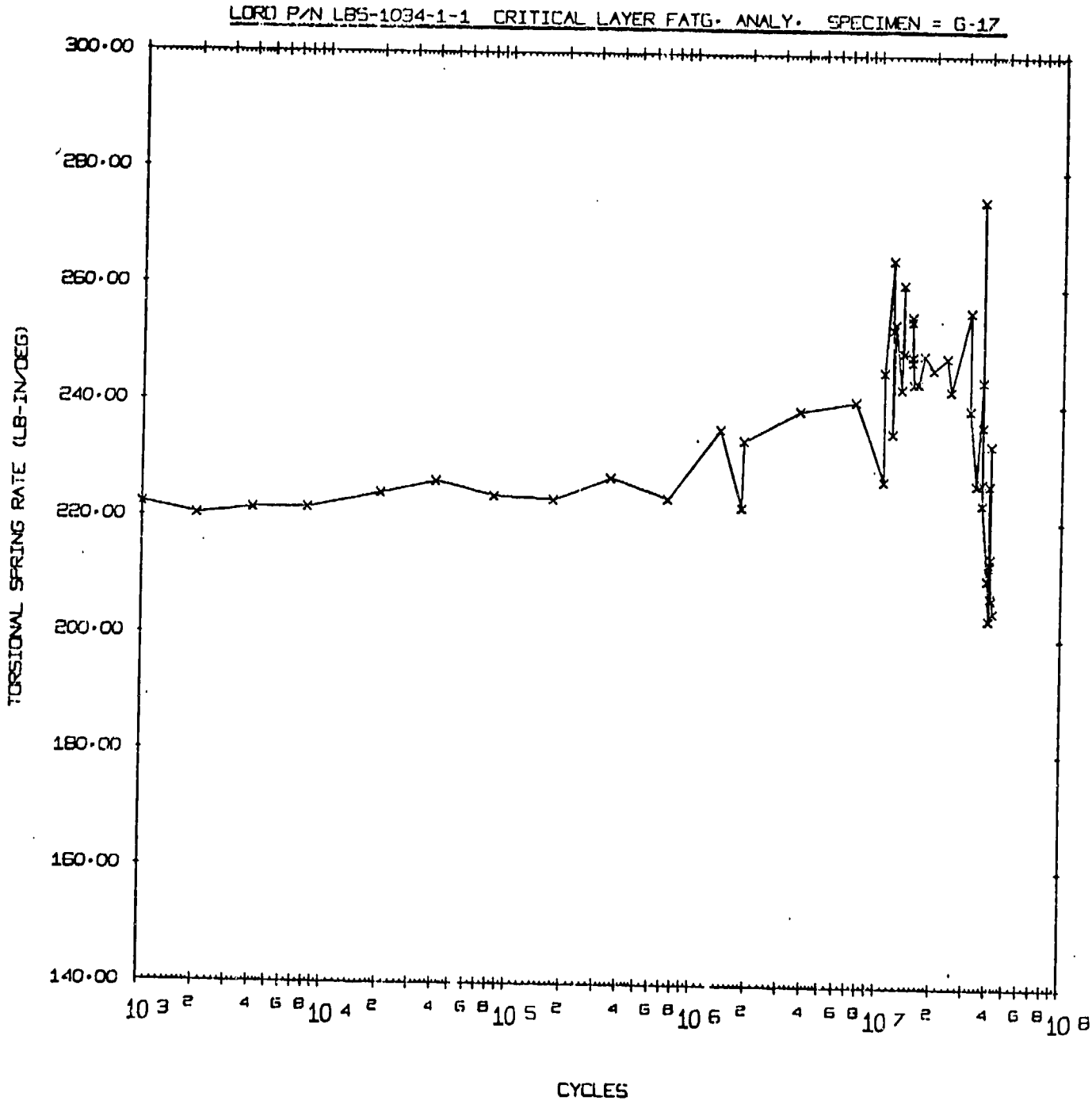

LORD P/N LBS-1034-1-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-17
300.00
280.00
260.00
240.00
220.00
200.00
180.00
160.00
140.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

Figure 26

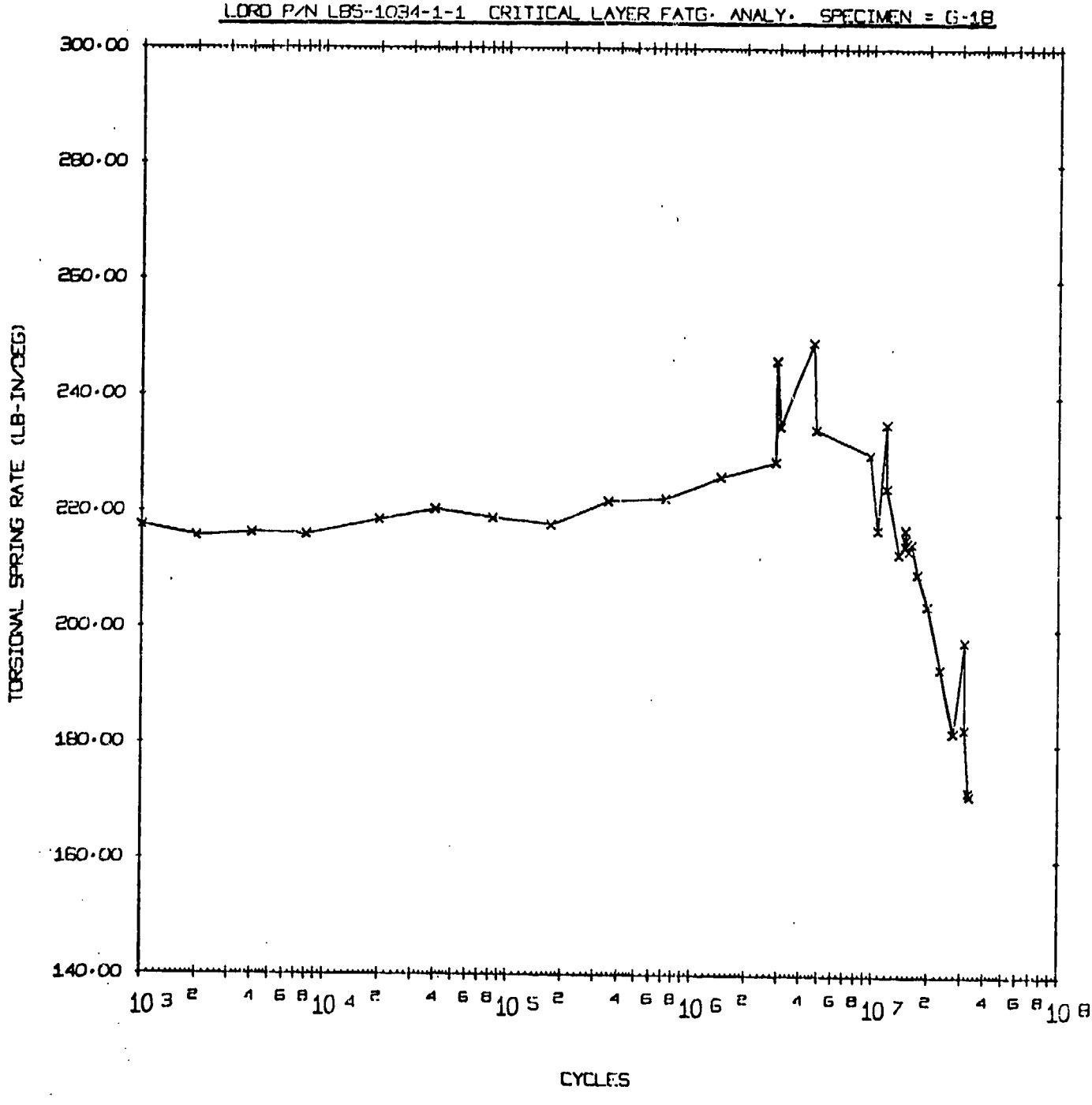

LORD P/N LBS-1034-1-1 CRITICAL LAYER FATG. ANALY. SPECIMEN = G-18
300.00
280.00
260.00
240.00
220.00
200.00
180.00
160.00
140.00
TORSIONAL SPRING RATE (LB-IN/DEG)
10 3 2 4 6 8 10 4 2 4 6 8 10 5 2 4 6 8 10 6 2 4 6 8 10 7 2 4 6 8 10 8
CYCLES

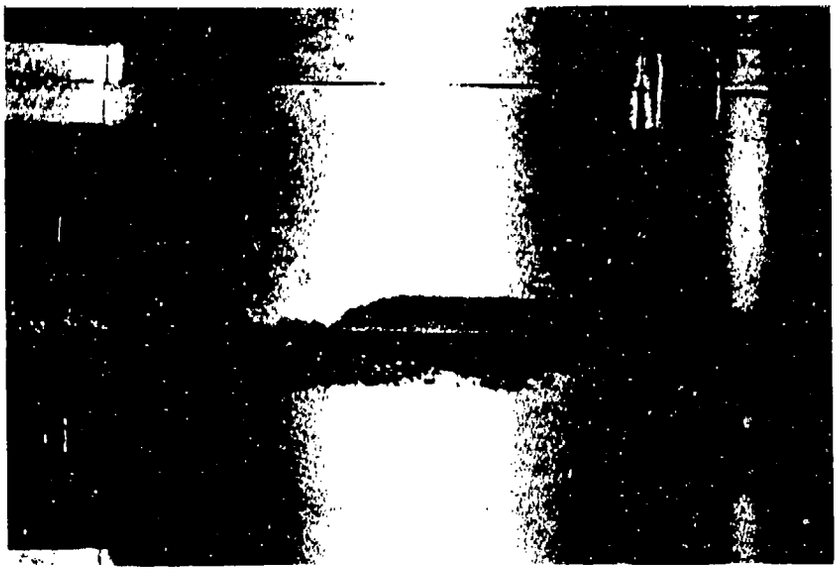
Figure 27

Photograph #25976

TYPICAL FAILURE APPEARANCE OF TEST SPECIMENS
DURING S-N CURVE TESTING

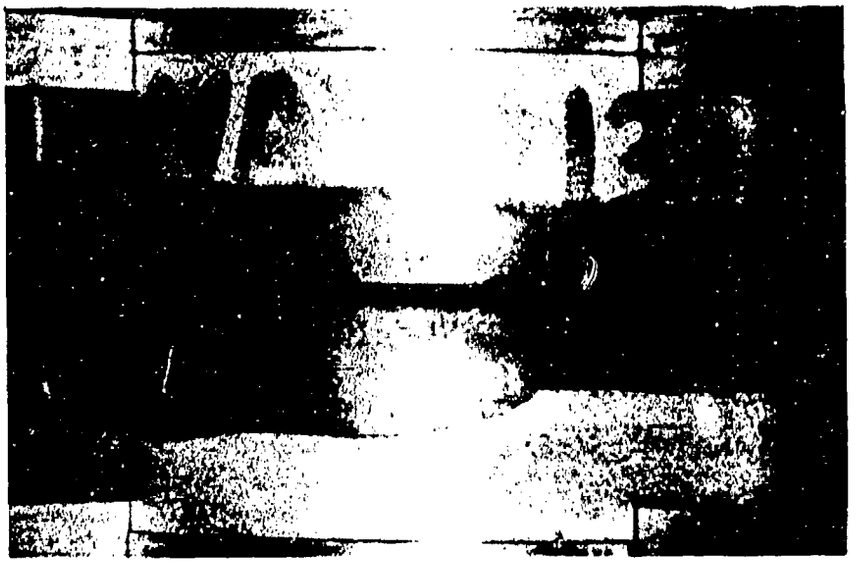
Photograph #26082

TEST SPECIMEN G-11 (Part not failed)



Photograph #26083

TEST SPECIMEN G-12 (Part not failed)



Photograph #26084

TEST SPECIMEN G-17 (Part not failed)

## Test Results Comments

The peaks and valleys visible on the plotted data are results of temporary test machine stoppage in which the elastomeric specimen "recovered" some of its stiffness, but quickly returned to its original stiffness after the test was restarted. This behavior is typical of elastomers, and results primarily from hysteresis heating of a few degrees in the elastomer which tends to decrease the stiffness. When the strain is removed the elastomer returns to room temperature and becomes slightly stiffer.

## Fatigue Curve Presentation

The individual bearing S-N curves are presented in Figures 28 and 29. The curves are constructed on log-log graph paper with alternating direct shear strain as the ordinate, and cycles to failure as the abscissa. The curves can also be approximated by the equation:

$$N = \left[\frac{C}{E_S}\right]^x \qquad (2)$$

where

- $N$ = Cycles to failure
- $E_S$ = Alternating direct shear strain, %
- C&x = Constants particular to the given curve, and determined by curve fit methods

The Least Squares curve fit method was used to determine the constants, which resulted in an approximate fit for the LB4-1034-2-1 curve and a very good fit for the LB5-1034-1-1 curve. The equations and their accuracy at the three test points are presented in Table 5. The Least Squares curve for each bearing is included in the S-N curves, Figures 28 and 29.

## TABLE 5

## S-N Curve Equations

### LB4-1034-2-1

Least Squares Curve Fit Constants

$N$ = Predicted cycles to failure
$s$ = Shear strain in per cent
$C$ = 53900
$x$ = 2.341

Equation:

$$N = \left(\frac{53900}{s}\right)^{2.341}$$

| s | Test Cycles to Failure | N @ s | Variance - % |
|---|---|---|---|
| ± 100% | 1765250 | 2481290 | + 40.6 |
| ± 60% | 14303000 | 8203463 | - 42.6 |
| ± 27% | 42760101 | 53189600 | + 24.4 |

### LB5-1034-1-1

Least Squares Curve Fit Constants

$N$ = Predicted Cycles to Failure
$s$ = Shear strain in per cent
$C$ = 5929
$x$ = 3.429

Equation:

$$N = \left(\frac{5929}{s}\right)^{3.429}$$

| s | Test Cycles to Failure | N @ s | Variance - % |
|---|---|---|---|
| ± 110% | 817100 | 866199 | + 6.0% |
| ± 70% | 4490400 | 4080480 | - 9.1% |
| ± 36% | 38330027 | 39901766 | + 4.1% |

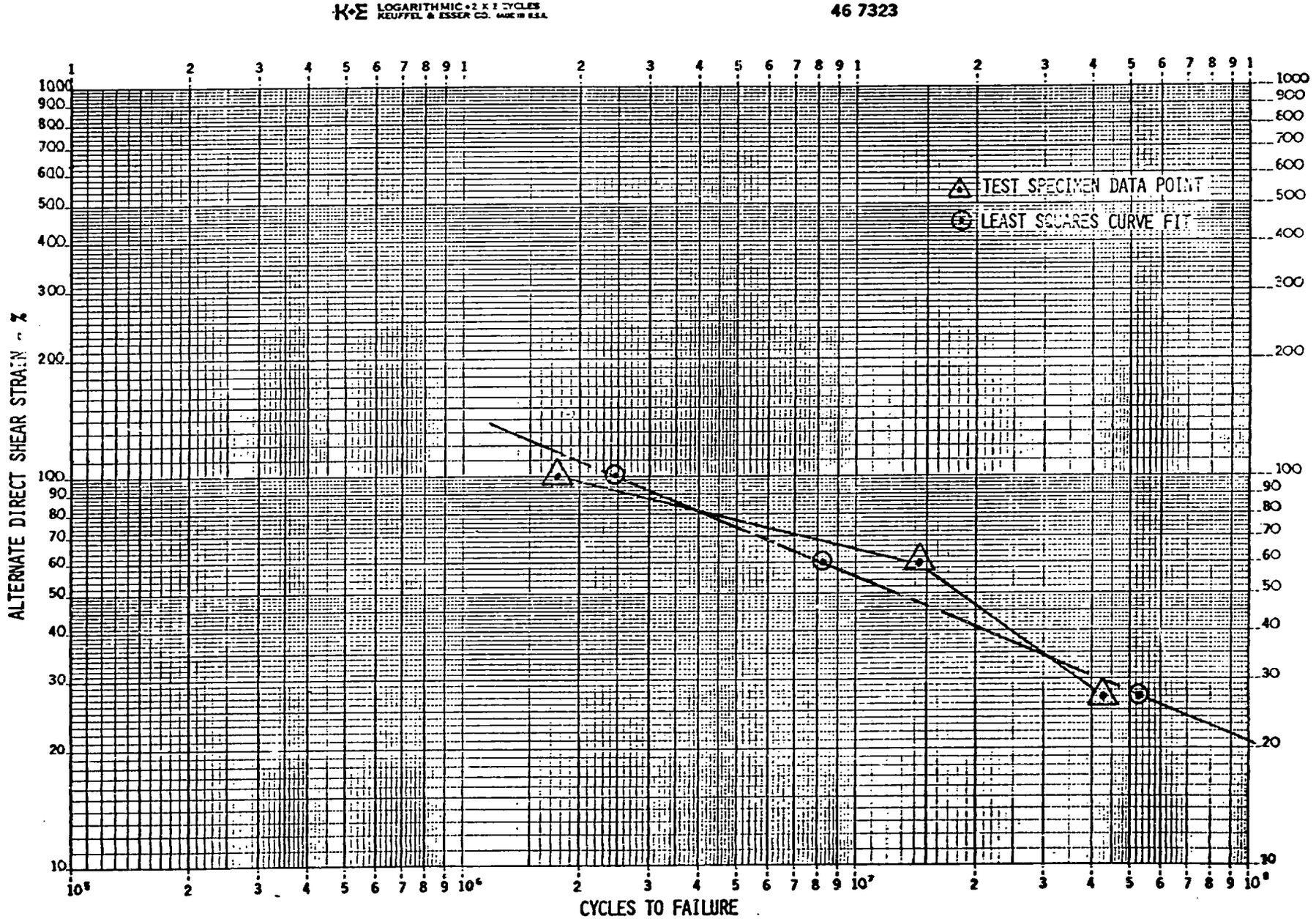



FIGURE 28 LB4-1034-2-1: CRITICAL LAYER S-N CURVE
LAYER NO. - 17TH FROM FOCAL POINT.

ELASTOMER = MAD 008
CURVE NO. = C-4952

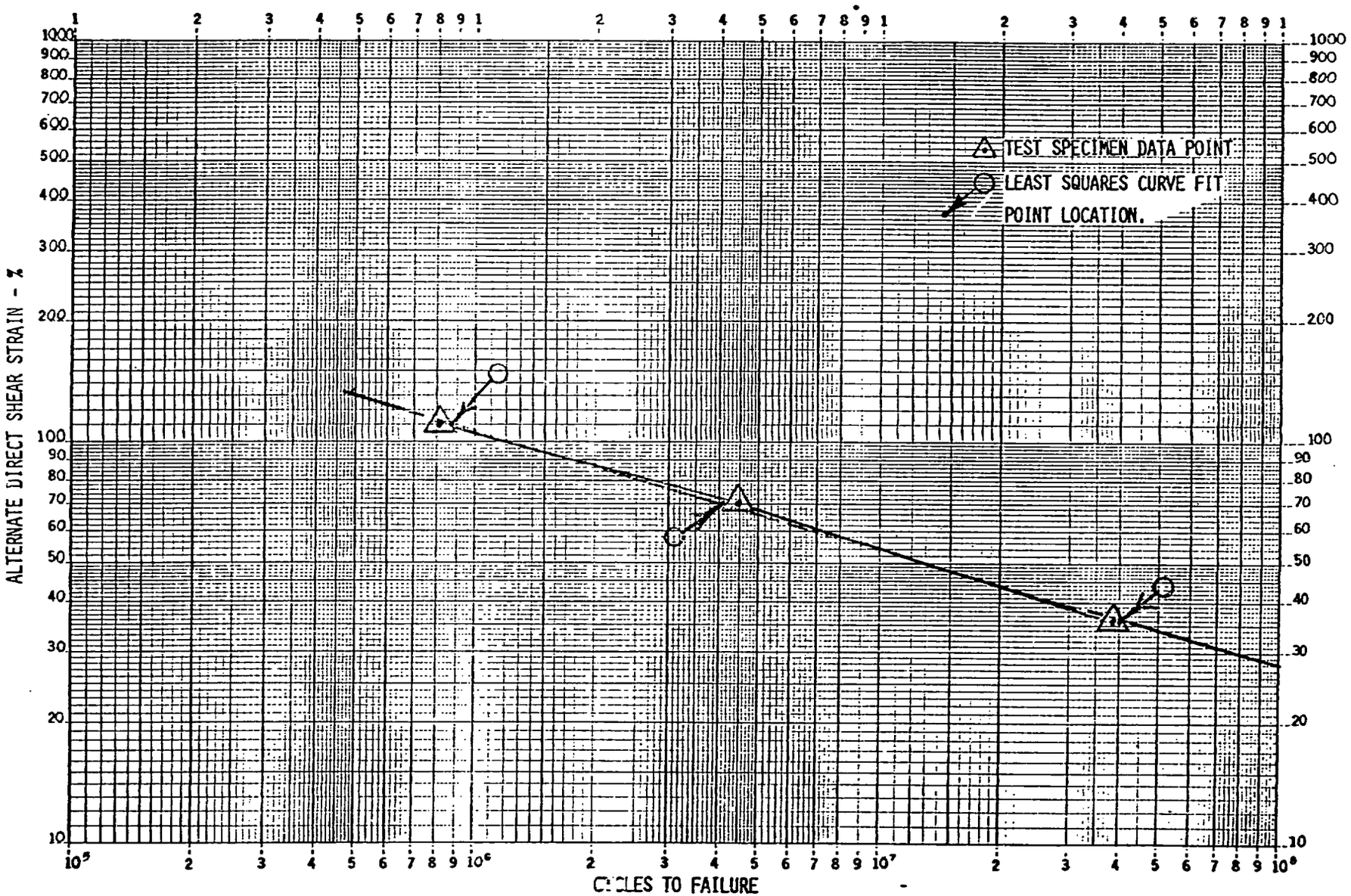



FIGURE 29. LB5-1134-1-1; CRITICAL LAYER S-N CURVE
LAYER NO. - 1ST FROM SMALL END PLATE

ELASTOMER = MAD 013
CURVE NO. = C-4953

## Life Prediction

Service life prediction was based on the Sikorsky Endurance Loads/Motion Spectrum, SES701059 Rev. 4 dated 4/4/77.

Each condition of SES701059 was used to determine a ratio equal to the expected cycles to failure, using the developed fatigue curves, divided by the number of cycles imposed during a specified lifetime. When the summation of these damage ratios is equal to one, the number of cycles will equal the predicted life.

The damage ratios for the LB4-1034-2-1 bearing were computed using the actual S-N curve as shown in Figure 28. The equation was not used due to its high variance from test results. The damage ratios for the LB5-1034-1-1 bearing were all computed from the Least Squares equation. The equation exhibited a close correlation to the test results and provided a means to calculate damage ratios beyond $10^8$ cycles, into which category many of the spectrum conditions fell. Table 6 provides a listing of the damage ratio by spectrum condition for each bearing.

## TABLE 6

### Service Life Prediction

Design Life: 2000 hrs. @ 258 cpm = $3.096 \times 10^7$ cycles

LB4-1034-2-1 Direct shear strain per degree (a)
= 5.68% @ 17th layer from focal point

LB5-1034-1-1 Direct shear strain per degree (a)
= 2.87% @ 1st layer from small end plate

| | | | | LB4-1034-2-1 | | LB5-1034-1-1 | |
|---|---|---|---|---|---|---|---|
| Cond. | % Time | Req'd. No. of Cycles x $10^5$ | Altern. Torsional Angle Degrees | Alterna-ting Direct Shear Strain % | Damage Ratio | Alterna-ting Direct Shear Strain % | Damage Ratio |
| 1 | .9072 | 2.809 | 2.20 | 12.50 | .00312 | 6.31 | .00002 |
| 2 | .6067 | 1.878 | 2.00 | 11.36 | .00190 | 5.74 | .000009 |
| 3 | 1.2135 | 3.757 | 1.20 | 6.82 | (b) | 3.44 | .000003 |
| 4 | 1.2135 | 3.757 | 1.90 | 10.79 | (b) | 5.45 | .000015 |
| 5 | 1.6656 | 5.157 | 2.60 | 14.77 | .00670 | 7.46 | .000059 |
| 6 | 1.8173 | 5.626 | 3.40 | 19.31 | .00938 | 9.76 | .000160 |
| 7 | 6.0673 | 18.784 | 4.30 | 24.42 | .03913 | 12.34 | .001977 |
| 8 | 9.0665 | 28.070 | 5.30 | 30.10 | .07291 | 15.21 | .003666 |
| 9 | 4.5505 | 14.088 | 6.20 | 35.22 | .04335 | 17.79 | .003149 |
| 10 | 1.5111 | 4.678 | 8.30 | 47.14 | .02079 | 23.82 | .002845 |
| 11 | .9072 | 2.809 | 2.20 | 12.50 | .00312 | 6.31 | .000018 |
| 12 | .6067 | 1.878 | 2.00 | 11.36 | .00190 | 5.74 | .000009 |
| 13 | 1.2135 | 3.757 | 1.90 | 10.79 | (b) | 5.45 | .000015 |
| 14 | 1.2135 | 3.757 | 2.60 | 14.77 | .00670 | 7.46 | .000043 |
| 15 | 1.6656 | 5.157 | 3.50 | 19.88 | .00874 | 10.05 | .000163 |
| 16 | 1.8173 | 5.626 | 4.30 | 24.42 | .01172 | 12.34 | .000359 |
| 17 | 6.0673 | 18.784 | 5.20 | 29.54 | .04816 | 14.92 | .002297 |
| 18 | 9.0665 | 28.070 | 6.10 | 34.65 | .08506 | 17.51 | .005942 |
| 19 | 4.5505 | 14.088 | 7.10 | 40.33 | .05031 | 20.38 | .005018 |
| 20 | 1.5111 | 4.678 | 9.10 | 51.688 | .02599 | 26.12 | .003902 |

| Cond. | % Time | Req'd. No. of Cycles x $10^5$ | Altern. Torsional Angle Degrees | LB4-1034-2-1 Alternating Direct Shear Strain % | LB4-1034-2-1 Damage Ratio | LB5-1034-1-1 Alternating Direct Shear Strain % | LB5-1034-1-1 Damage Ratio |
|---|---|---|---|---|---|---|---|
| 21 | .4536 | 1.404 | 3.90 | 22.15 | .00273 | 11.19 | .000064 |
| 22 | .3034 | .939 | 4.30 | 24.42 | .00196 | 12.34 | .000060 |
| 23 | .6067 | 1.878 | 2.90 | 16.47 | .00268 | 8.32 | .000031 |
| 24 | .6067 | 1.878 | 3.00 | 17.04 | .00280 | 8.61 | .000035 |
| 25 | .8328 | 2.578 | 3.80 | 21.58 | .00477 | 10.91 | .000108 |
| 26 | .9087 | 2.813 | 4.90 | 27.83 | .00662 | 14.06 | .000281 |
| 27 | 3.0337 | 9.392 | 5.90 | 33.51 | .02722 | 16.93 | .001771 |
| 28 | 4.5333 | 14.035 | 7.00 | 39.76 | .05013 | 20.09 | .004760 |
| 29 | 2.2752 | 7.044 | 8.00 | 45.44 | .02997 | 22.96 | .003776 |
| 30 | .7555 | 2.339 | 10.10 | 57.37 | .01509 | 28.99 | .002789 |
| 31 | 1.5500 | 4.799 | 5.20 | 29.54 | .01231 | 14.92 | .000587 |
| 32 | 3.0000 | 9.288 | 1.86 | 10.56 | (b) | 5.34 | .000034 |
| 33 | 1.0000 | 3.096 | 4.47 | 25.39 | .00666 | 12.83 | .000226 |
| 34 | .7500 | 2.322 | 7.14 | 40.56 | .00844 | 20.49 | .000843 |
| 35 | .7500 | 2.322 | 3.76 | 21.36 | (b) | 10.79 | .000093 |
| 36 | 1.3350 | 4.133 | 6.49 | 36.86 | .01333 | 18.63 | .001082 |
| 37 | 3.0580 | 9.468 | 7.36 | 41.80 | .03573 | 21.12 | .003811 |
| 38 | 2.3240 | 7.195 | 9.04 | 51.35 | .03787 | 25.94 | .005861 |
| 39 | 4.1980 | 12.997 | 5.05 | 28.68 | .03170 | 14.49 | .001437 |
| 40 | .665 | 2.059 | 2.10 | 11.93 | .00219 | 6.03 | .000011 |
| 41 | .0001 | .0003 | 14.40 | 81.79 | .00001 | 41.33 | .000001 |
| 42 | .0002 | .0006 | 13.50 | 76.68 | .00001 | 38.75 | .000002 |
| 43 | .0004 | .0012 | 12.50 | 71.00 | .00001 | 35.88 | .000003 |
| 44 | .0023 | .0071 | 11.50 | 65.32 | .00006 | 33.01 | .000013 |
| 45 | .0050 | .0155 | 10.50 | 59.64 | .00011 | 30.14 | .000021 |
| 46 | .0220 | .0681 | 9.50 | 53.96 | .00038 | 27.27 | .000066 |
| 47 | .1000 | .310 | 8.50 | 48.28 | .00148 | 24.40 | .000205 |
| 48 | .1100 | .341 | 8.00 | 45.44 | .00145 | 22.96 | .000183 |
| 49 | .3000 | .929 | 7.50 | 42.60 | .00364 | 21.53 | .000399 |
| 50 | .6100 | 1.889 | 7.00 | 39.76 | .00675 | 20.09 | .000641 |
| 51 | 1.308 | 4.050 | 6.50 | 36.92 | .01286 | 18.66 | .001066 |
| 52 | .0001 | .0003 | 14.40 | 81.79 | .00001 | 41.33 | .000001 |
| 53 | .0019 | .00588 | 12.60 | 71.57 | .00007 | 36.16 | .000015 |
| 54 | .0280 | .00867 | 10.90 | 61.91 | .00006 | 31.28 | .000013 |
| 55 | .1200 | .376 | 10.00 | 56.80 | .00243 | 28.70 | .000433 |
| 56 | .3900 | 1.207 | 9.10 | 51.69 | .00635 | 26.12 | .001007 |
| 57 | 1.5600 | 4.830 | 8.20 | 46.58 | .02147 | 23.53 | .002816 |
| 58 | 5.7640 | 17.845 | 7.30 | 41.46 | .06734 | 20.95 | .006987 |
| | | | TOTALS | | .85567 | | .071201 |

(a) - From original bearing analysis

(b) - Indicated results extend beyond $10^8$ cycles.

Predicted life of LB4-1034-2-1 for compression $\pm$ torsional shear

Life = 2000 hrs./.85567 = 2337 hours

Predicted life of LB5-1034-1-1 for compression $\pm$ torsional shear

Life = 2000 hrs./.071201 = 28089 hours*

*The original bearing design was optimized for torsional shear rate.

The comparison between the laboratory test specimen life prediction results and the original design analysis life prediction is given in Table 7.

TABLE 7

Comparison of Life Predictions between the Laboratory Test Specimen and the Original Design Analysis

| Bearing | Damage Ratio Lab. Test Specimen | Damage Ratio Original Analysis |
|---|---|---|
| LB4-1034-2-1 | .85567 | .9062 |
| LB5-1034-1-1 | .071201 | .058189 |

## MINER'S CUMULATIVE DAMAGE THEORY TEST

Miner's Cumulative Damage Theory states that failure will occur when the sum of the damage ratios due to a spectrum of load (or motion) conditions is equal to one. In order to verify the validity of Miner's Law, a spectrum of conditions derived from SES701059 was applied to two laboratory specimens to determine the actual fatigue life for comparison with the predicted life. The number of conditions in the Sikorsky spectrum was reduced by combining all torsional shear motions which had approximately the same magnitude. This method gave a compact spectrum which was representative of the actual spectrum in terms of varying degrees of shear motion occurring for different lengths of time in the bearing's life cycle.

The LB5-1034-1-1 bearing specimen was chosen for the test. To achieve a reasonable test time of approximately 120 hours at 7 Hz or $3.02 \times 10^6$ cycles, the alternating direct shear strain was increased by a factor of six. The change effectively raised the shear strain from approximately 13% to 80%. This modification would not affect the demonstration of the theory, only the point of failure. Table 8 presents the spectrum used with the shear strains and the fatigue life results.

## TABLE 8

### Miner's Cumulative Damage Theory Test Spectrum

| Condition | % Time | Alternating Pitch Motion (Deg.) | Actual Brg. Shear Strains (%) | Test Specimen Shear Strains (%) |
|---|---|---|---|---|
| 1 | 18.07 | 4.96 | 13.0 | 78.0 |
| 2 | 17.84 | 5.25 | 13.7 | 82.2 |
| 3 | 17.75 | 5.52 | 14.3 | 85.8 |
| 4 | 9.03 | 4.38 | 11.3 | 67.8 |
| 5 | 4.54 | 7.41 | 19.3 | 115.8 |
| 6 | 20.54 | 4.05 | 10.6 | 63.8 |
| 7 | 12.23 | 4.51 | 11.8 | 70.8 |

## TABLE 9

### Miner's Cumulative Damage Theory Test Results

Design Test Life = 120 hrs. @ 7 Hz = $3.024 \times 10^6$ Cycles

(a) Life Prediction per Figure 29

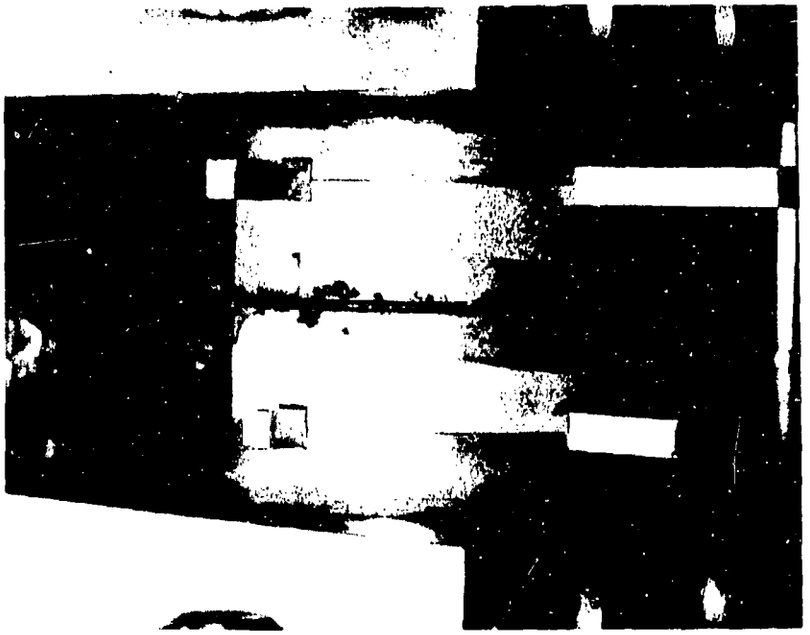
| Condition | % Time | Required No. of Cycles Alternating Direct Shear $\times 10^5$ | Damage Strain % | Ratio |
|---|---|---|---|---|
| 1 | 18.07 | 5.483 | 78.0 | .17687 |
| 2 | 17.84 | 5.413 | 82.2 | .20819 |
| 3 | 17.75 | 5.386 | 85.8 | .25051 |
| 4 | 9.03 | 2.749 | 67.8 | .16232 |
| 5 | 4.54 | 1.228 | 115.8 | .16595 |
| 6 | 20.54 | 6.229 | 63.8 | .08899 |
| 7 | 12.23 | 3.716 | 70.8 | .08445 |
| | | Total | 1.13728 | |

Predicted Failure = $\frac{3.024 \times 10^6 \text{Cyc.}}{1.13728} = 2.659 \times 10^6$ Cyc.

(b) Test Results

| Location of Test Specimen on Machine | Test Spec. S/N | Elastomer | Cycles to Failure | Average Cycles to Failure |
|---|---|---|---|---|
| West | G-2 | MAD013 | 3003200 | 2743300 |
| East | G-4 | MAD013 | 2483400 | |

The predicted failure was within 3.2 per cent of the actual test result when considering the average cycles to failure. The indicated results show that Miner's Cumulative Damage Theory is a reliable method for determining the fatigue damage in the UTTAS elastomeric bearings and similar parts.



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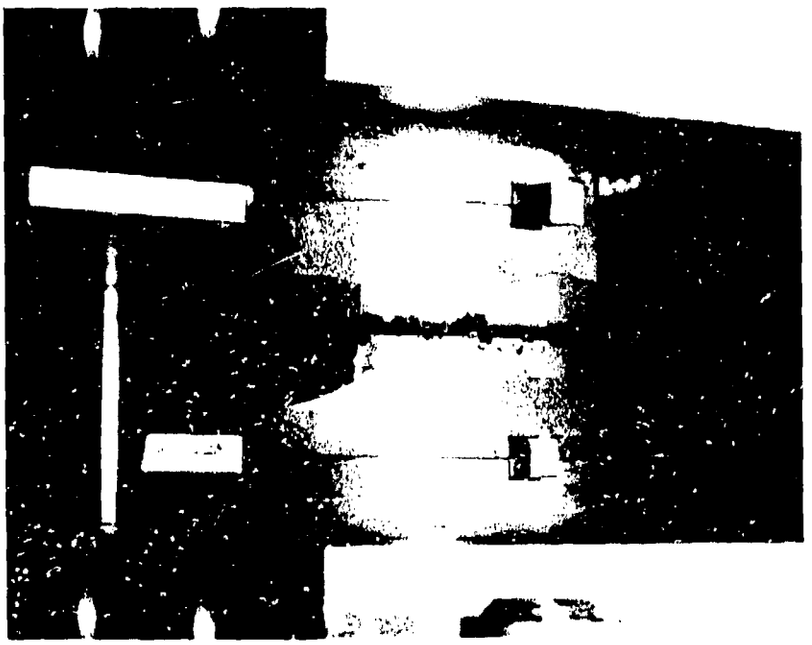
MINER'S THEORY TEST SPECIMEN G-4



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MINER'S THEORY TEST SPECIMEN C-2

## SUMMARY OF CONTRACT REQUIREMENTS AND WORK PERFORMED

The following summary lists each of the contract requirements in the same order as they appear in the "Statement of Work" submitted with the Lord Kinematics proposal.

1. The geometry of both Sikorsky UTTAS elastomeric main rotor bearings were modelled, and the appropriate material properties specified for each bearing component. The individual models for each bearing are shown in Figures 2 and 4.

2. A finite element computer analysis was performed utilizing the models generated in Step 1 above. The Lord Kinematics' computer program "SARLAS" was used to conduct the analysis. The actual analysis was done during the initial bearing design with the results used for this test program.

3. The critical elastomer layers of the Sikorsky bearings were determined in terms of direct and indirect shear strains. The LB4-1034-2-1 spherical bearing's critical layer was the 17th from the spherical focal point. The LB5-1034-1-1 thrust bearing's critical layer was the 1st from the small end plate. The direct shear strains were varied to produce the required S-N curve.

4. The stress level in each metal shim was evaluated for both bearings using a combination of finite element analysis, strain gage data, and parametric analysis. The results of the spherical shim analysis were presented as Figure 5. The results of the thrust shim analysis were presented on a Sikorsky mean $-3\sigma$ S-N curve, shown as Figure 6.

5. The stresses and strains in the critical elastomer layer of each Sikorsky bearing were modelled in a standard Lord Kinematics test specimen (Lord Part Number TL-367), using finite element techniques. The results of the test specimen modelling are shown in Figures 8 and 9 for both Sikorsky bearings.

6. The test specimens were manufactured using the same elastomer, adhesive, and bonding procedures as were used in the respective Sikorsky bearings.

7. The laboratory specimen test conditions were selected to provide the same compression edge shear strain as in the bearing critical layer, while selecting a range of torsional shear inputs to determine the S-N fatigue curve. The test spectrum for each bearing was presented as Table 2. An existing Lord Kinematics test machine (E-297) was used to perform the test. The machine parameters are listed in Table 3.

8. The resulting fatigue data was analyzed and a S-N fatigue curve generated for each of the two Sikorsky bearings. The tabulated data was presented as Table 4 in the text. The spherical bearing (LB4-1034-2-1) S-N curve is given as Figure 28, and the thrust bearing (LB5-1034-1-1) S-N curve is given as Figure 29. The fatigue data is also presented as a Least Squares curve fit approximation to the data. The constants were calculated, with the results and equations presented in Table 5.

9. The predicted service life was calculated for each of the two Sikorsky bearings based on their respective S-N curves, and the Sikorsky spectrum (SES701054). The predicted service life for P/N LB4-1034-2-1 is 2337 hours which compares favorably to a required life of 2000 hours. The predicted life of P/N LB5-1034-1-1 is 28089 hours which has no comparison to the required life of 2000 hours. The latter design had been optimized for shear spring rate to obtain desired bearing performance.

10. A test was conducted to verify that Miner's Cumulative Damage Theory was a valid method in predicting elastomeric life. A spectrum of conditions was derived from the Sikorsky spectrum (SES701059) and applied to two laboratory specimens to determine an actual fatigue life. This life was compared to the predicted life calculated from the approriate elastomeric S-N curve. Tables 8 and 9 presented the test spectrum and test results respectively.

11. A frequency verification test was performed to determine the highest frequency at which the testing could be validly done. The test frequencies selected were 10 Hz. 7 Hz, and 4.3 Hz. The selected test frequency was 7 Hz, with all subsequent testing conducted at this frequency.

12. A monthly report was submitted in accordance with contract line number 0001AA, and DD Form 1423, sequence number A001.

13. This report is the Final Technical Report, submitted in accordance with DI-S-1800 and DD Form 1423.

## CONCLUSIONS

The results of this testing show:

1. There is a correlation indicated between full scale bearing testing and the prediction of an elastomeric bearing fatigue life using finite element analysis with limited laboratory specimen testing. This prediction technique is dependent on accurate modelling of the critical elastomer layer, and reproducing the stresses and strains onto a laboratory test specimen.

2. Miner's Cumulative Damage Theory is a valid premise in predicting elastomeric fatigue life. The average cycles to failure of the laboratory specimens tested was within 3.2 per cent of the predicted failure point.

3. The combination of using laboratory test specimens subjected to the most critical stresses and strains of an elastomeric bearing, along with Miner's Cumulative Damage Theory, provides an effective means to evaluate the service fatigue life of the bearing.

4. This test is only one point and cannot be viewed as universally accurate. It should be recognized that the described method will produce service life predictions for the Lord Kinematics LB4-1034-2-1 (Sikorsky P/N SB-7001-046) and LB5-1034-1-1 (Sikorsky P/N SB-7002-046) only, since the S-N data to be obtained is valid only for Lord Kinematics' materials, adhesive systems, and shims.

5. The test did not consider the effect of low-cycle repeated loading due to Ground-Air-Ground cycling or the effect of maximum load conditions. The bearings must first be designed to withstand G-A-G loading in excess of what is expected so that induced shear does not become a predominant factor in normal flight.

6. Table 20 provides a summary of where the proposed method would be, in terms of accuracy and cost, relative to the more conventional methods.

TABLE 10

Summary of Methods to Predict Service Life

| LEVEL OF COST | TYPE OF TEST | LEVEL OF ACCURACY |
|---|---|---|
| (HIGHEST) | FLIGHT TEST | (HIGHEST) |
| | Real time laboratory tests using actual bearings, load and motion inputs, and environments | |
| | Real time laboratory tests using actual bearings simulated load and motion inputs, without environments | |
| C O S T | PROPOSED METHOD - Analytical plus limited laboratory tests of specimens | A C C U R A C Y |
| | DESIGN GUIDE TECHNIQUES (No specimens, no tests) | |
| (LOWEST) | PARAMETRIC ANALYSIS | (LOWEST) |

## RECOMMENDATIONS

The proposed method has been shown to be valid in one case, which is not directly applicable to any other case without specific modelling and testing of that case. Therefore, additional work and testing is needed on different configurations of bearings to validate in a general sense the proposed method.

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