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APPLICATION OF BORON/EPOXY REINFORCED ALUMINUM STRINGERS AND BORON/EPOXY SKID GEAR FOR THE CH54B HELICOPTER TAIL CONE

PHASE II: FABRICATION, INSPECTION AND FLIGHT TEST

Final Report

by

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Sikorsky Aircraft
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This summary technical report was prepared by Sikorsky Aircraft Division of United Aircraft Corporation under Contract NAS1-10459 and covers the work performed during the period of May 1971 through March 1972. The study was conducted under a NASA contract and was jointly funded by the Army.

This report documents Phase II of a two-phase contract and contains the account and results of the fabrication and flight test program of the boron/epoxy reinforced tail cone. Also documented in this report is the design, fabrication and test of the boron/epoxy skid gear tubes which are installed on this aircraft.

Technical monitor for this program was Richard A. Pride of the Materials Division, NASA Langley Research Center.

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LIST OF SYMBOLS AND ABBREVIATIONS

AFCS F	Automatic Flight Control System - Off
AFCS N	Automatic Flight Control System - On
AOB	Angle of Bank, Degrees
cps	Cycles Per Second
F(s)	Steady Stress, Pounds/Inches^2
F(v)	Vibratory Stress, Pounds/Inches^2
hd	Density Altitude, Feet
IGE	In Ground Effect
KT	Velocity, Knots
Lng.	Longitudinal
N_R	Rotor Speed (%)
OSC	Oscillator
PPD	Partial Power Descent
ROD	Rate of Descent, Feet per minute

APPLICATION OF BORON/EPOXY REINFORCED ALUMINUM STRINGER AND BORON/EPOXY SKID GEAR FOR THE CH54B HELICOPTER TAIL CONE

PHASE II REPORT

FABRICATION, INSPECTION AND FLIGHT TEST

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SUMMARY

CH54B Skycrane® helicopter serial number 70-18490 has been fabricated with boron/epoxy reinforced stringers in the tail cone and boron/epoxy tubes in the tail skid. During the next two years, the aircraft will be periodically inspected to evaluate the performance of composite structures under field service conditions.

Phase I of this contract (NAS1-10459) was a preprototype study for the CH54B tail cone in which component fabrication, testing, and analysis was performed, and the strength adequacy of boron/epoxy reinforced members was verified. Phase II of the program put to practice the techniques and analysis learned in Phase I and culminated in a successful flight test program. The fabrication of the tail cone was made with conventional tooling, production shop people, and with no major problem areas.

The vertical stiffness of the CH54B tail cone was maintained and a 14.1% weight saving was achieved by the application of boron/epoxy reinforced stringers. A 17.1% weight reduction is obtainable with the removal of the conservative criterion of analysing for the assumed condition of no boron/epoxy reinforcement under static loading conditions.

The flight test program included a stress and vibration survey using strain gages and vibration transducers located in critical areas. It was demonstrated that divergent vertical bounce could not be induced in the aircraft. Strain gage readings indicate that the stresses on the individual structural elements of the boron/epoxy reinforced stringer and the stresses on the conventional structure are such that the criteria of a 10,000 hour life with a factor of four was exceeded. Higher ground-air-ground cycle stresses were recorded, however, on the boron/epoxy stringers in the water ballasted aircraft configuration, than were predicted. These conditions result in a 10,000 hour life with a factor of 1.2 on the bond of

the boron/epoxy reinforced stringers. The bond integrity will be monitored in the field. Degradation of the bond is not critical to the structural integrity of the aircraft.

The boron/epoxy skid gear tubes, made interchangeable with the production structure, were fabricated and installed on the aircraft. The criteria of interchangeability with present fittings limited the weight savings, relative to conventional aluminum tubes, to 35%.

1.0 INTRODUCTION

The original CH-54A helicopter airframe structure was designed for the applied static loads due to flight and ground conditions. During the flight development phase of the CH-54A, it became necessary to provide additional structure to increase the vertical bending stiffness of the tail cone and tail cone transition section in order to satisfy a dynamic fuselage requirement. Skin gages 0.040 inches in thickness on the top and the bottom of the tail cone and transition section were replaced with skins 0.080 - 0.140 inches in thickness. The weight increase due to stiffening was approximately 160 pounds.

Preliminary analysis of boron/epoxy reinforced stringers indicated that the required tail cone stiffness of the CH-54B could be achieved by using the original thin skins, and reinforcing the top and bottom stringers with approximately thirty (30) pounds of boron/epoxy.

This study, Phase II of a two phase program, was successfully completed with flight tests, in February 1972. The investigations conducted in Phase I provided the feasibility of fabrication, analysis, structural integrity, and field maintenance procedures for the aircraft and formed the basis for this phase. Phase II extended this program to actually fabricating and flight testing a CH54B reinforced tail cone. Part of this study is to be an in-service evaluation of this new structure until March 1974.

Also incorporated on this aircraft, for environmental evaluation are boron/epoxy tail bumper or skid gear support tubes. This composite skid gear is interchangeable with a normal production gear.

The CH54B with the boron/epoxy reinforced tail cone and boron/epoxy skid gear is shown in flight in Figure 1-1.

FIGURE 1-1. CH-54B SKYCRANE HELICOPTER

2.0 TAIL CONE FABRICATION

Objective

The objective of this phase of the program was to fabricate a boron/epoxy reinforced tail cone for flight test and field evaluation.

Approach

The tail cone was fabricated using the bonding and manufacturing techniques developed in Phase I, reference 7-1. In summary, 0.25 by 0.75 inch boron/epoxy strips were bonded to the vertical legs of the top and bottom conventional aluminum tail cone stringers. This permitted the removal of heavy aluminum skins while maintaining the vertical tail cone stiffness.

Discussion

Twelve boron/epoxy strips were fabricated for installation on the tail cone stringers. Five were for installation on the top skin panels and seven were for installation on the bottom skin panels. The boron/epoxy reinforcements ranged in length from eight (8) to fifteen (15) feet, and were fabricated with a twelve inch taper on each end with a two layer fiberglass insert at the beginning of the tapers. The fiberglass insert reduces the peak adhesive shear stresses. The boron/epoxy strips were inspected by means of a pulse-echo ultrasonic instrument and no defects were found.

Holes were drilled in the boron/epoxy strips for the installation of stringer/frame clips and brackets. The reinforcements were then bonded to the vertical leg of the respective aluminum stringers and the bonded assemblies inspected by means of the ultrasonic Fokker bond tester. No disbonds were found. It should be noted that the frame/stringer holes in the aluminum were not drilled at this time but were to be drilled on installation.

In previous studies the reinforced stringers test specimens were riveted to the skin panels by means of an automatic riveting machine. This method of riveting could not be used in the final assembly as parts had to be riveted together in the holding fixture. A boron/epoxy test panel was therefore fabricated and the stringers hand riveted to assess the effect of the vibration from the riveting gun on the bonds. The panel was inspected by means of the Fokker bond tester and no bond defects were found.

The reinforced tail cone was assembled in a production holding fixture with frames located at the proper stations in the fixture. The side skin/stringer assemblies were then riveted to the frames. Boron/epoxy reinforced stringers were passed through modified cut-outs in the frames as shown in Figure 2-1. A Mylar rivet template was laid on the stringers to locate the skin rivet pattern. All rivet holes were then drilled into the reinforced stringers. The thin gage top and bottoms skins were set in place and rivet holes were drilled into the skins using the drilled reinforced stringers as a locator. The rivet holes were deburred and the top and bottom skins were team riveted to frames and reinforced stringers. A polished bucking bar with a modified head was used to upset the rivets. The polished bucking bar was used to protect the boron/epoxy fibers.

Upon completion of all tail cone riveting, the bonding of the reinforced stringers were again inspected this time by the Fokker bond tester. At this time two bond deviations were found: a nine (9) inch partial debond on stringer -105, B.L.0 at station 618; and a three (3) inch debond in the upper left hand stringer -119 at station 629. These areas are shown in Figure 2-2.

The nine inch partial disbond was found in the vicinity of the compass bracket which is fastened by three (3) Hi-LOK fasteners, see Figure 2-3, while the three (3) inch disbond was found in the area of a stringer/frame clip and fasteners. It is felt that the disbonds were caused by the drilling of holes in the aluminum stringers through the predrilled holes in the boron/epoxy reinforcement strips.

These bond deviations were acceptable as they are in an area of Hi-LOK fasteners which provide a structural load path between the aluminum stringer and the boron/epoxy reinforcement. They are also in an area of negligible load transfer between the aluminum stringer and the boron reinforcement.

The tail cone was painted and the inside was subjected to the normal protective prime coat. The structure was then assembled to the pylon and transition section of the fuselage and the aircraft readied for flight test and delivery to the Army.

Conclusion

The application of boron/epoxy to this tail cone achieved a weight reduction of 67.3 pounds out of a total tail cone weight of 464.4 pounds. The decision to maintain the tail cone strength with no boron reinforcement accounted for 12.5 pounds of skin panel reinforcement. The deletion of this criteria would have permitted a weight reduction of 79.8 pounds in the tail cone.

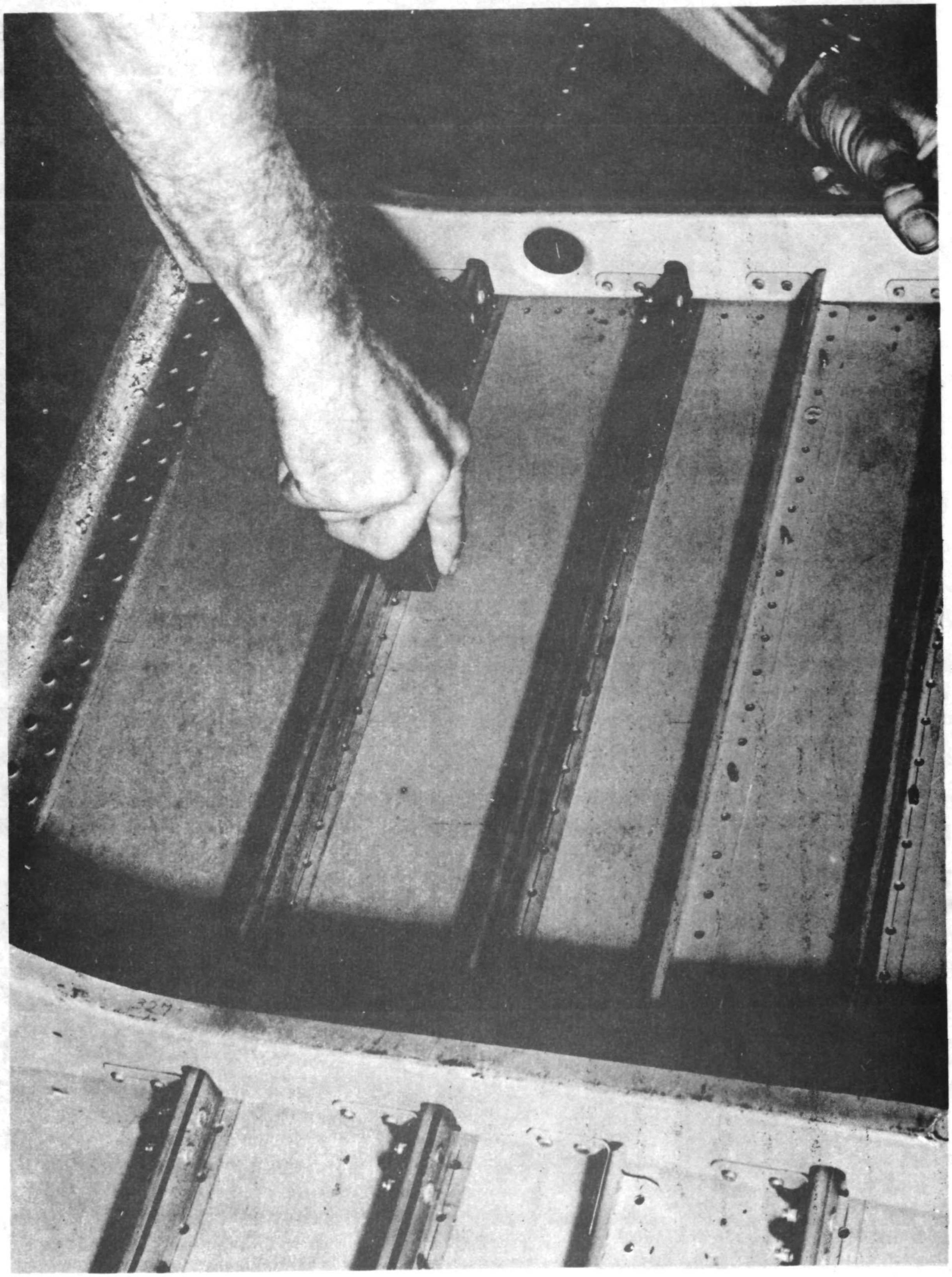


FIGURE 2-1. BORON/EPOXY TAIL CONE FABRICATION

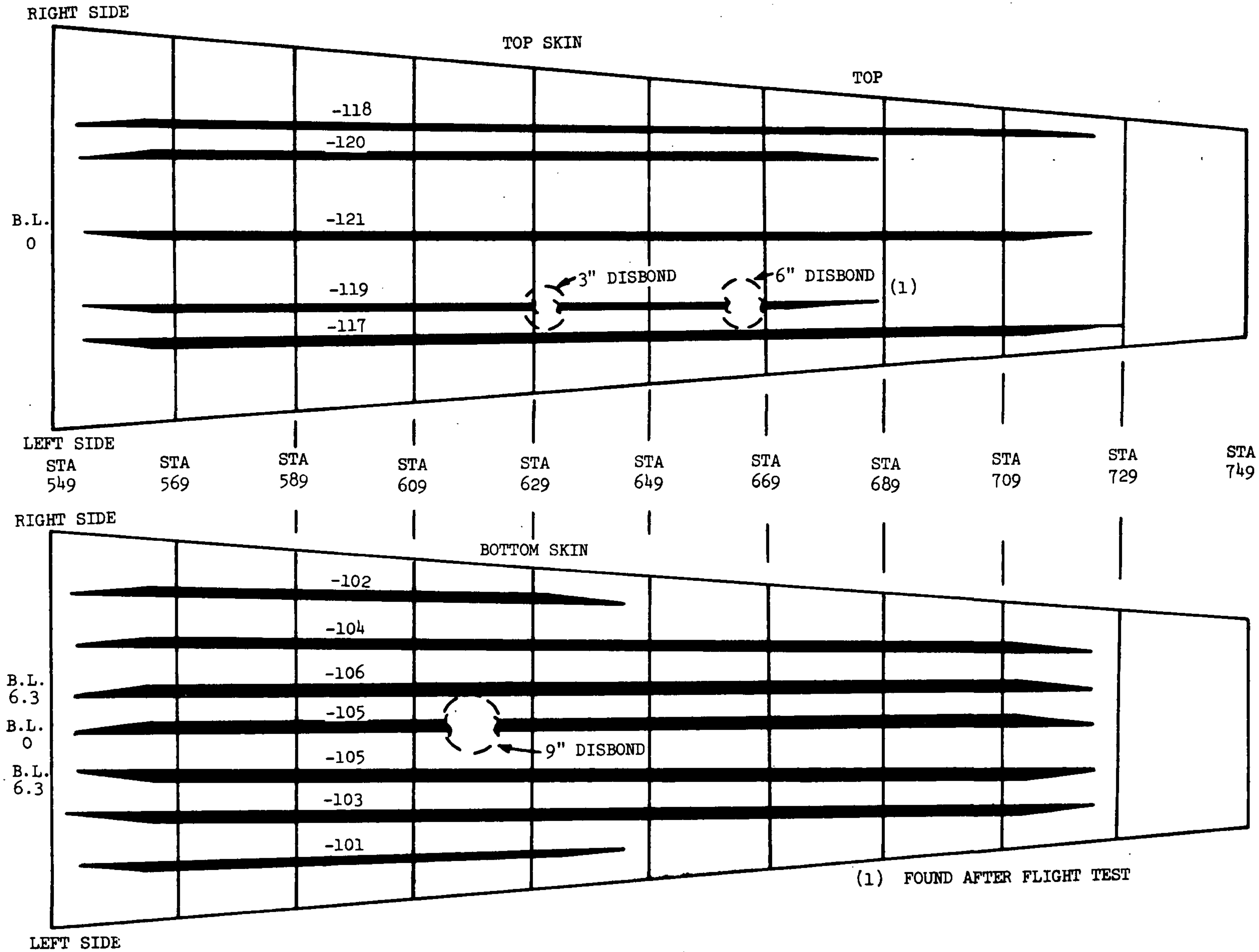


FIGURE 2-2. TAIL CONE BOND DEVIATIONS FOUND IN FABRICATION AND FLIGHT TEST INSPECTION.

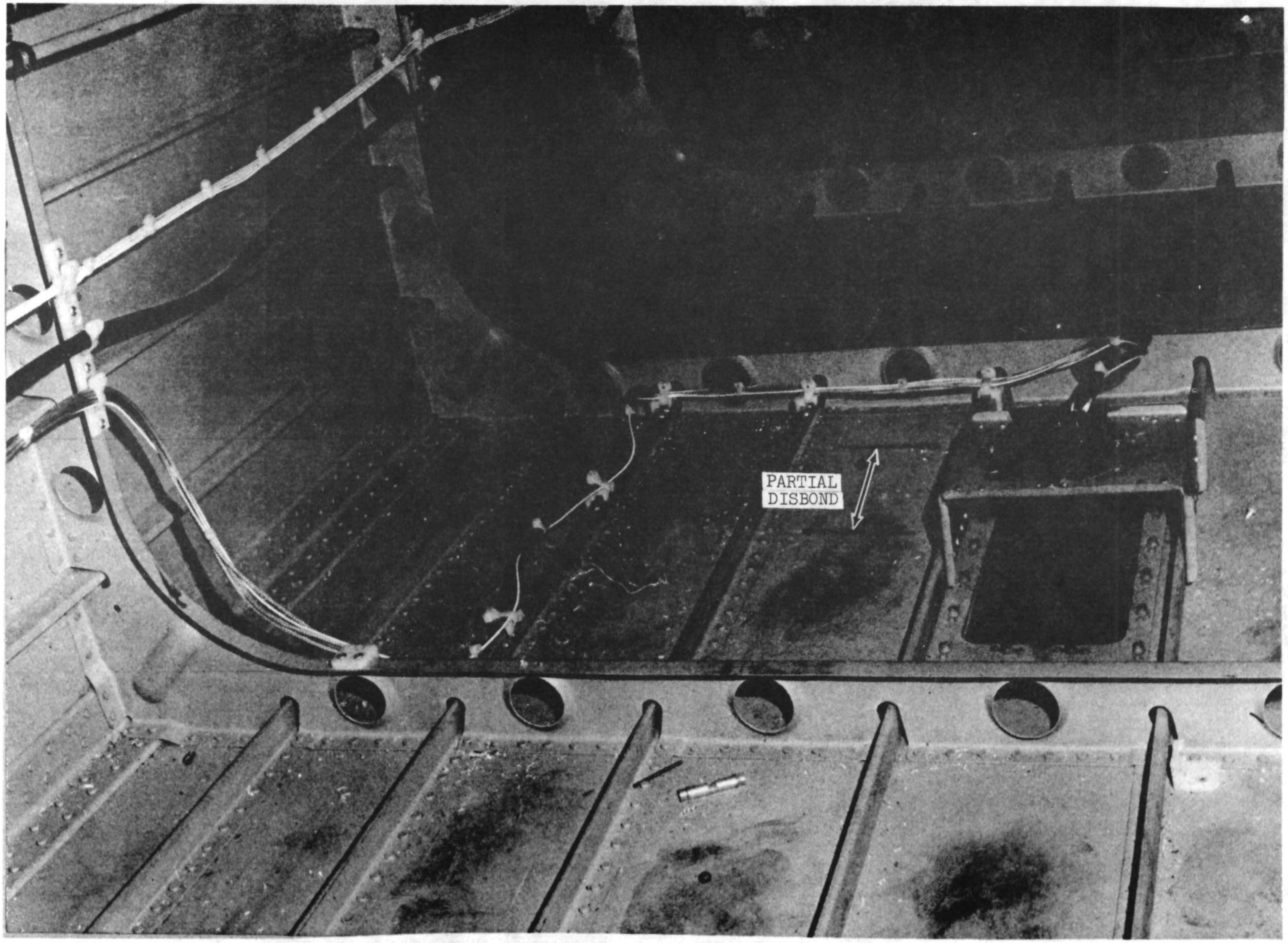


FIGURE 2-3. PARTIAL BOND DEVIATION UNDER COMPASS BRACKET.

3.0 TEST PLAN AND PROCEDURES

Objective

A flight test plan was generated to conduct a stress and vibration survey, which would establish the structural integrity of the boron/epoxy tail cone and identify the airframe dynamic response characteristics.

Approach

The aircraftwas intrumented with strain gages and vibration transducers. The flight test was designed to obtain test data throughout the flight envelope of the aircraft at gross weights of 43,600 and 47,000 pounds and with center of gravity extremes of 328 inches and 346 inches. Single point loads of 15,000 and 20,000 pounds were carried to evaluate the airframe dynamic response in flight. Ground tests were performed to investigate changes in the vertical and lateral response of the tail cone as compared to a production aircraft.

Discussion

Twenty-three strain gages were installed on the boron/epoxy reinforced tail cone to assess the structural integrity of the structure. The type of gages and their locations are shown in Figure 3-1. To measure the aircraft's first mode response four (4) accelerometers were installed on the aircraft: one at the tail rotor gear box, one at the horizontal stabilizer, one at the nominal center of gravity, and one in the pilot's compartment. The aircraft was flown in two basic flight configurations: with the water ballast tank, which facilitated center of gravity changes, and with single point hoist loads as shown in Figures 3-2 and 3-3. The attempts to excite the tail cone were made in the single point hoist conditions.

The test measurements included principal strain gage locations selected from previous test data on a production CH-54B as well as new gage locations for analysis of the boron/epoxy reinforced structure.

The ground evaluation of the natural frequency of the current production aircraft and the boron/epoxy reinforced aircraft was performed by jacking the aircraft off the tires exciting the tail cone and measuring the dynamic response with accelerometers. This test set up is shown in Figure 3-4.

Flight tests were conducted throughout the normal airspeed and rotor speed envelope of the aircraft and included several maneuvers such as autorotations, turns, control reversals and partial power descents. The specified test regimes listed in Table 3-1 of the flight test plan were established by the pilot using standard aircraft flight instruments. The flight test engineer recorded each test with an average data burst of five seconds for each trimmed condition and for the duration of the maneuver during transient conditions.

Additional hovering flights were conducted to determine if the first vertical mode or vertical bounce could be excited. Test configuration for the latter flights included 15,000 and 20,000 pound single point loads at various lengths as well as positioning one blade a nominal two (2) inches out of track to provide a one per rev main rotor exciting force.

A longitudinal stick displacement calibration was performed before and after each flight by physically moving the control stick to its extreme positions and recording the transducer response. The airframe vibration data was recorded using Consolidated Electronic Corporation (CEC) accelerometers, model 4-202 which were laboratory calibrated for an appropriate range of frequencies, 8 to 140 cps, and displacements prior to installation. Each transducer was then resistance calibrated before and after each flight to define galvomometer sensitivity and stability of the bridge voltage.

All data was recorded on a fifty (50) channel CEC oscillograph and was processed using a Telecordex Data Reduction System to generate punched cards output and combined with the Univac 1108 computer program to provide engineering data.

TABLE 3-1

FLIGHT TEST CONDITIONS

No.	
1.	Gross weight 47,000 lb. @ 328 in. center of gravity.
2.	Gross weight 47,000 lb. @ 346 in. center of gravity.
3.	Gross weight 47,000 lb.; 20,000 lb. single point load.
4.	Gross weight 47,000 lb.; 20,000 lb. single point load, one blade two (2) inches out of track.
5.	Gross weight 43,600 lb.; 15,000 lb. single point load.

TABLE 3-2

SEQUENCE OF FLIGHT TEST MANEUVERS

Plan A, Conditions 1 and 2 Sea Level

Sequence	
1.	Rotor engagement.
2.	Ground run from ground idle to maximum rotor speed (10% increments to 96%, 2% increments to maximum N_R)
3.	Left taxi turn 100% N_R
4.	Right taxi turn 100% N_R
5.	Hover @ 96, 100, 104 and maximum % N_R
6.	Left hover turn 100% N_R (15 seconds)
7.	Right hover turn 100% N_R (15 seconds)

Sequence

8. Longitudinal reversal @ 0 KT @ 100% N_R

9. Lateral reversal @ 0 KT @ 100% N_R

10. Rudder reversal @ 0 KT @ 100% N_R

11. Left sideward flight @ 10, 20, 30 kts. @ 100% N_R

12. Right sideward flight @ 10, 20, 30 KT @ 100% N_R

13. Rearward flight @ 20 KT @ 100% N_R

14. Oscillate cyclic control to attempt to product divergent "vertical bounce"

Sequence — Plan B, Condition 1 and 2, 1000' hd

1. Hover IGE @ 100% N_R

2. Take off and climb @ 7900 HP, 100% N_R

3. Climb at 63 KTS utilizing 6600 HP, 100% N_R

4. Hover or Vmin @ 96, 100 and 104% N_R

5. 20 KT @ 100% N_R

6. 40 KT @ 96, 100 and 104%

7. 60 KT @ 100% N_R

8. 80 KT @ 96, 100 and 104% N_R

9. 100 KT @ 100% N_R

10. 105 KT @ 96, 100 and 104% N_R

11. 116 KT @ 96, 100 and 104% N_R

12. Right turn, 70 KT @ 100% N_R (30° AOB)

13. Left turn, 70 KT @ 100% N_R (30° AOB)

14. Left turn, 105 KT @ 100% N_R (30° AOB)

Sequence

15. Right turn, 105 KT @ 100% N_R (30° AOB)

16. Longitudinal reversal, 105 KT @ 100% N_R

17. Lateral reversal, 105 KT @ 100% N_R

18. Rudder reversal, 105 KT @ 100% N_R

19. Symmetrical pullout, 105 KT @ 100% N_R

20. Partial power descent, 70 KT @ 100% N_R @ 500, 1000, 1500 ft/min ROD.

21. Partial power descent, 105 KT @ 100% N_R @ 500, 1000, 1500 ft/min ROD.

22. Enter autorotation @ 70 KT.

23. Autorotation 70 KT @ min. 100 and max % N_R

24. Recovery from autorotation @ 70 KT

25. Enter autorotation @ 105 KT

26. Autorotation 105 KT @ min, 100 and max % N_R

27. Recovery from autorotation @ 105 KT

28. Rough approach to IGE hover

29. Normal approach to 50 ft. hover

30. Vertical landing from 50 ft. hover

Sequence — Plan C, Conditions 3, 4 and 5, Sea Level

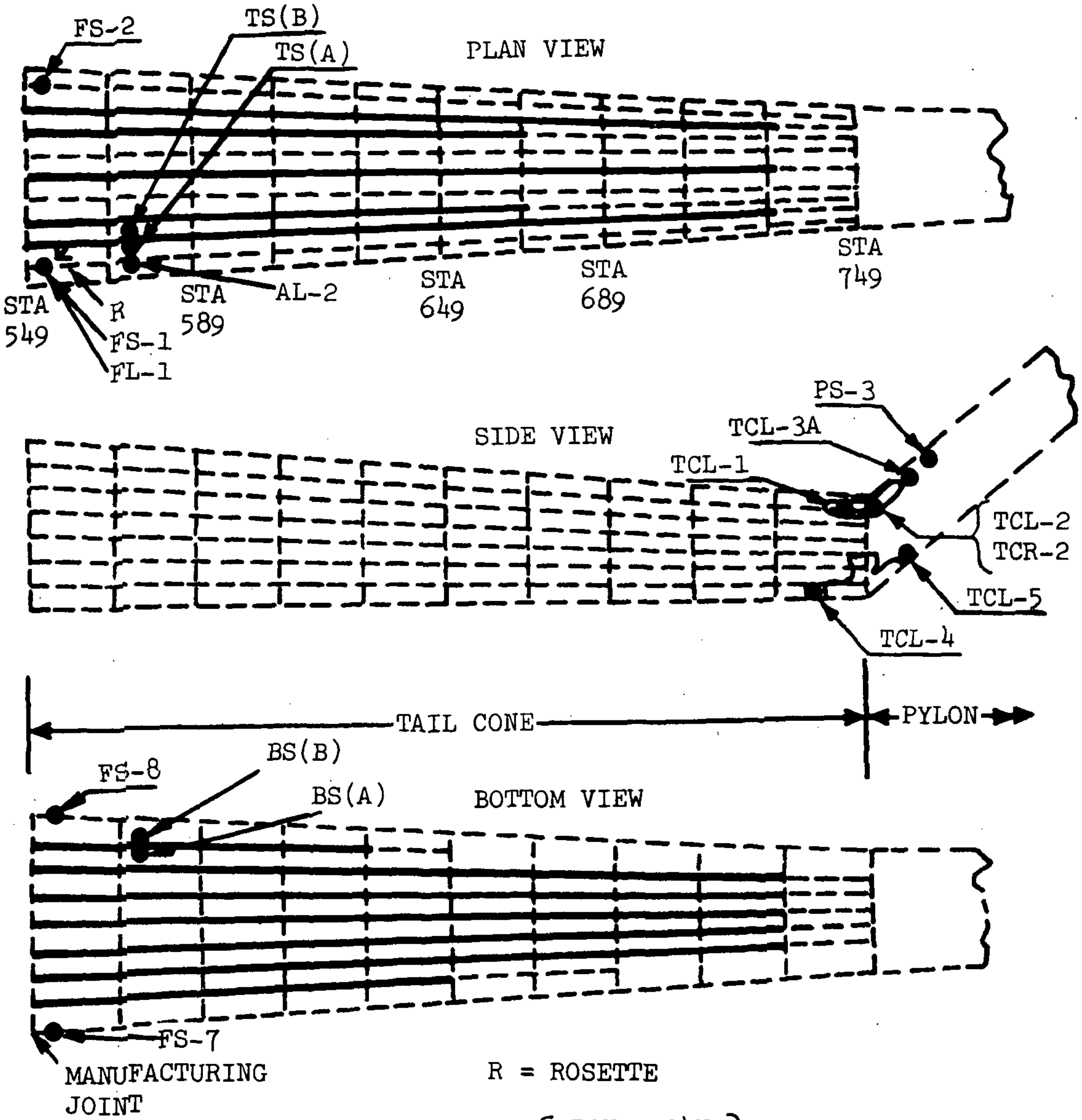
1. Record at hoist cable extensions of 0, 20, 30, 40, 60, 80 and maximum feet during hover at 100% N_R

2. Repeat Item No. 1 at 104% N_R

3. Oscillate cyclic control to attempt to produce "vertical bounce" at cable lengths of 20, 30 and 40 feet during hover at 100 and 104% N_R

Sequence

4. Check aircraft stability in left sideward flight and right hovering turn



R = ROSETTE

INSIDE	R1N	R4N	OUTSIDE
	R2N	R5N	
	R3N	R6N	

FS = Fuselage Stress
FL = Fuselage Left
AL = Aft Longeron
TS = Top Stringer
BS = Bottom Stringer

TCL = Tail Cone Left
TCR = Tail Cone Right
PS = Pylon Stress
(B) = Boron
(A) = Aluminum

FIGURE 3-1. STRAIN GAGE LOCATIONS.

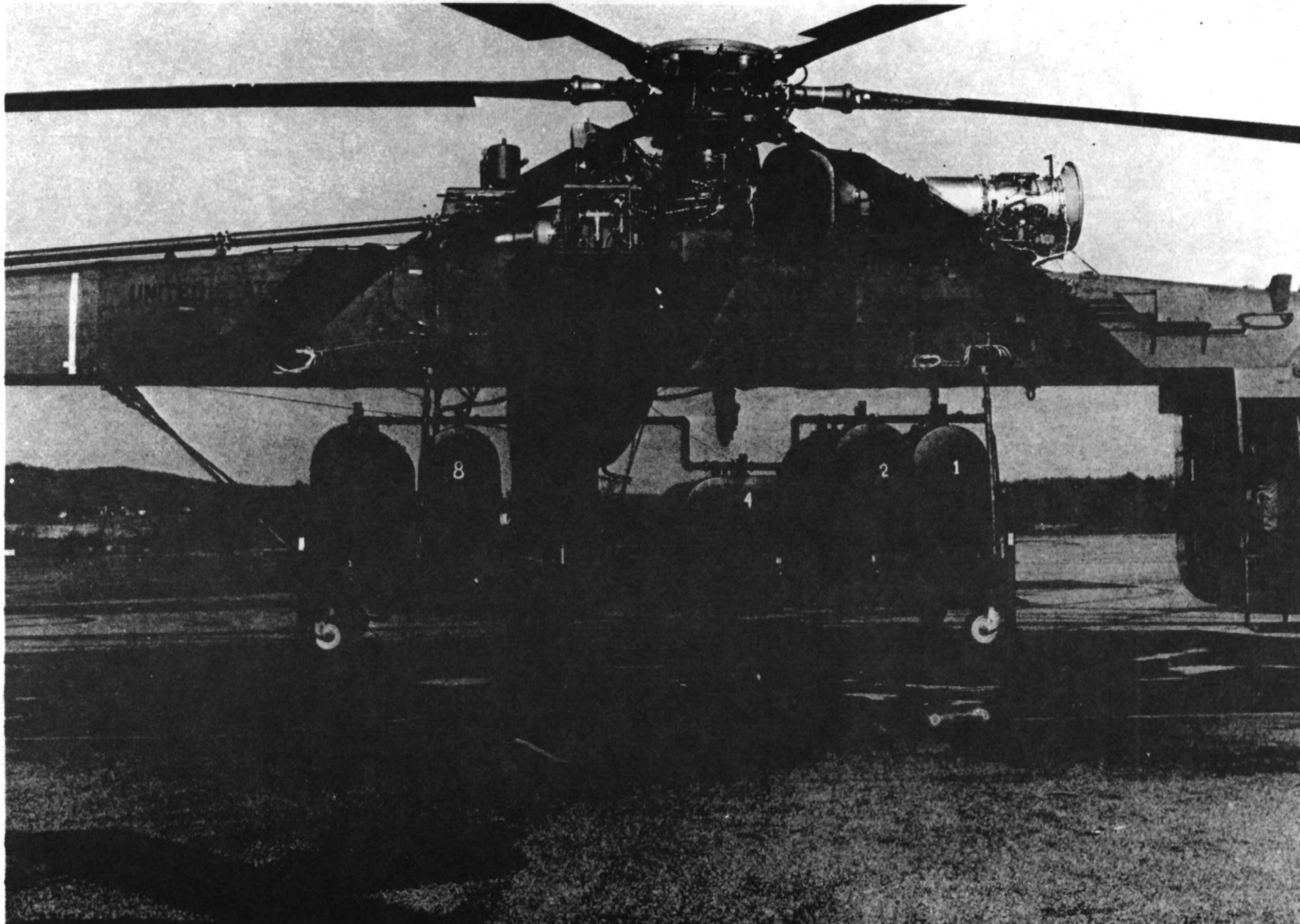


FIGURE 3-2. WATER BALLAST TANK CONFIGURATION FOR CENTER OF GRAVITY EXTREMES

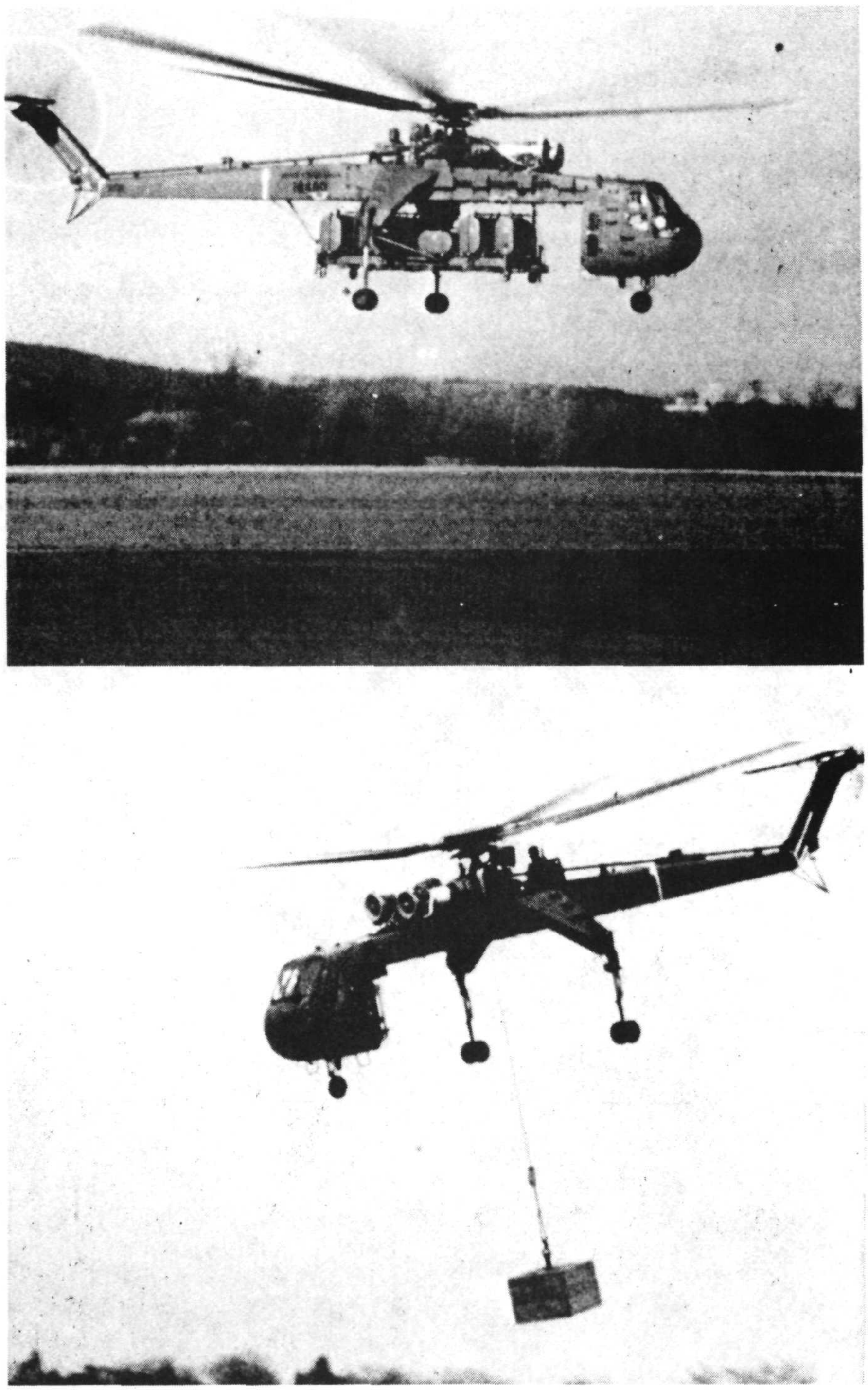


FIGURE 3-3. FLIGHT TESTS OF CH-54B HELICOPTER

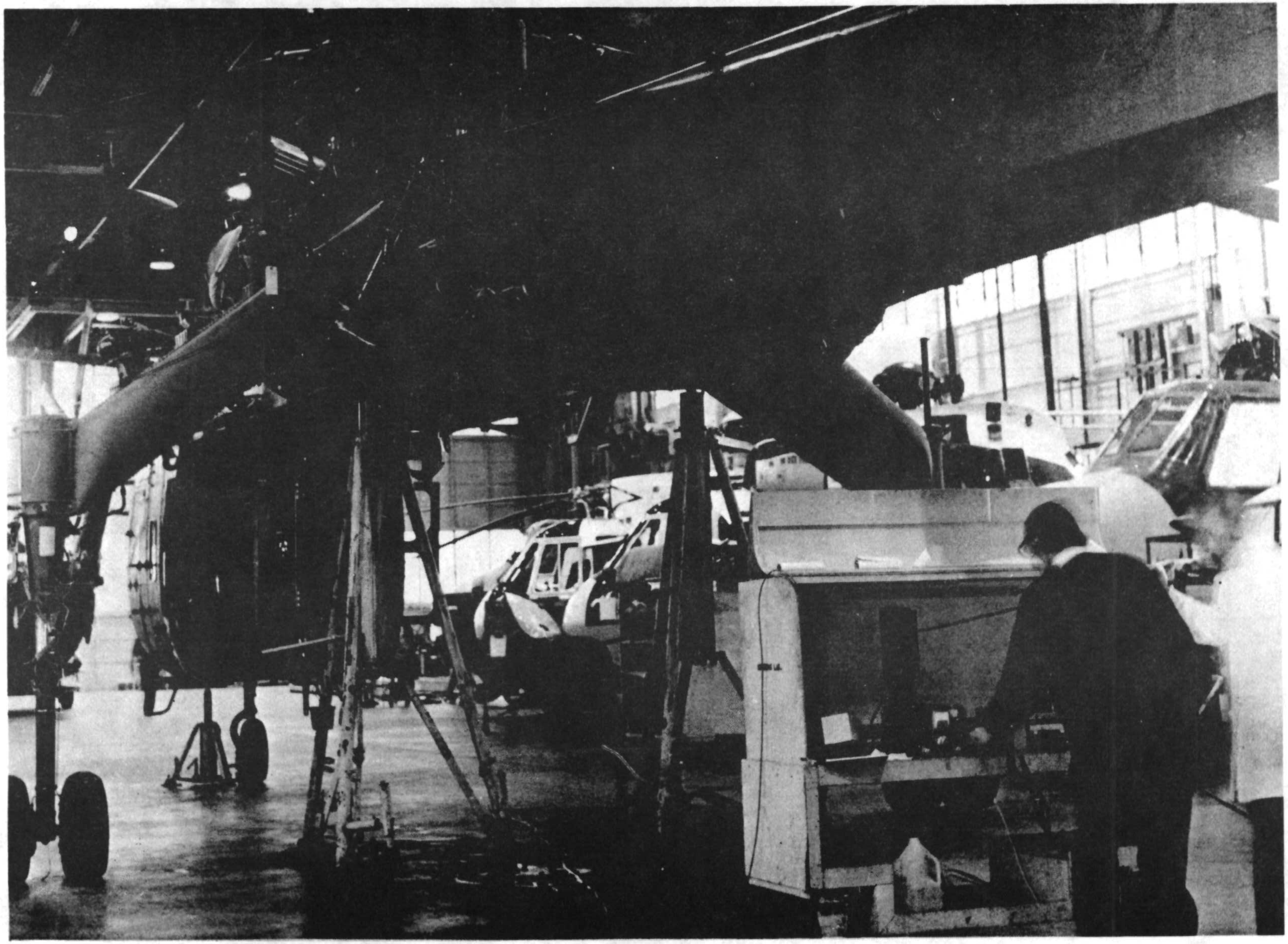


FIGURE 3-4. DETERMINATION OF NATURAL FREQUENCY TEST SET UP

4.0 FLIGHT/GROUND TESTS AND RESULTS

Objective

The objectives of this study were to: determine stress patterns from the full range of flight spectra; to use these values to predict the fatigue life of the tail cone, and to check that divergent "vertical bounce" could not be induced in the aircraft.

Approach

The strain gage data obtained throughout the flight test program was reviewed and the maximum stresses compared against the material fatigue allowables. Stress measurements at principle gage locations on the boron/epoxy tail were compared to previous data obtained from a standard aircraft. Differences in airframe response with the standard aircraft and the boron/epoxy tail cone aircraft were investigated. The tail cone was inspected for bond deviations at the conclusion of the test program.

Discussion

Stress Survey

Flight testing was accomplished in 4.5 hours of flying time and the order in which the tests were conducted and the conditions are shown in Table 4-1.

The effect of in-flight stresses on the boron/epoxy modified tail cone was investigated by flight tests throughout the operating aircraft spectrum. Tests were also conducted to produce airframe excitation to demonstrate the absence of divergent "vertical bounce".

Stress measurements were obtained at representative locations on the tail cone in the area of the boron/epoxy design modification as shown in Figure 3-1. Stress measurements were also obtained at representative tail cone/pylon locations for comparison with the standard tail cone/pylon structure under the same aircraft operating spectrum.

Maximum in-flight stress measurements are included in the tabulation of stresses in Tables 4-2 and 4-3. Table 4-2 contains the maximum transient stresses recorded in the excitation conditions, flights 2 through 5. These transient stresses occurred only during excitation maneuvers which were induced by the pilot through unconventional and rapid control movements. These conditions therefore, are not representative of conditions for fatigue analysis and the stresses are treated as static conditions.

Table 4-3 documents the maximum recorded in-flight stresses during flights 1, 6 and 7. These stresses are considered representative of the low stress/high cycle spectrum for fatigue analysis of the tail cone structure.

The ground-air-ground (GAG) stresses are shown in Table 4-4 and are calculated from the minimum to maximum stress excursions experienced in ground and flight conditions for flights 1, 6 and 7. The minimum stress condition usually occurs during the ground operation while the maximum stress condition occurs during flight. The mean stress was the average of the minimum to maximum, and the vibratory was the difference of the maximum and the mean. Since the GAG stresses were all calculated using the high gross weight of 47,000 pounds, the procedure is conservative. In actual practice, the gross weight will vary from the light gross weight of 28,653 lbs. to 47,000 lbs. and reduced GAG stresses would result if an average were made of the gross weight spectrum.

The vibratory loads for the boron/epoxy reinforced stringer are obtained by multiplying the stresses of Tables 4-2 and 4-3 by the areas of the skin, stringer and boron/epoxy. The following areas were used and were obtained from Reference 7-1.

$$A_{skin} = 0.224 \text{ in}^2$$

$$A_{stringer} = 0.086 \text{ in}^2$$

$$A_{B/E} = 0.188 \text{ in}^2$$

In Figure 4-1, the fatigue loadings for the boron/epoxy stringer are shown in Goodman diagrams developed from laboratory test data of Reference 7-1. The in-flight (low stress/high cycle) stresses are shown to be well within 1.5×10^6 cycle range which represents 10,000 hours of aircraft usage with a life factor of 4.1.

The Goodman (constant life) diagrams shown in Figure 4-1 are based on test data from Reference 7-1. The constant life line of $.175 \times 10^6$ cycles is derived from the fatigue testing of the stringer panel and the test point for static failure. As such, this line represents 10,000 hours or fifteen (15) years of aircraft usage with a factor of 7.3.

However, the GAG stresses observed in the flight and ground survey were above the constant line, and an extrapolation of life was made using the method shown in Figure 4-2. Using the mean stress of 2475 pounds, as shown in the Goodman diagram of Figure 4-1, the fatigue test data (Reference 7-1) was used to construct the S-N diagram of Figure 4-2. Extending the line to the GAG survey data shows the resulting cycles would be approximately 29,000 cycles mean life for the boron/epoxy reinforced stringers. Using the estimate of 2.38 GAG cycles, found from previous stress surveys (Reference 7-1), the projected usage would be limited to 3050 hours with a life factor of 4.0. However, no safety of flight is involved since the failure mode is debonding of the boron reinforcement whereas the aluminum stringer by itself is capable of withstanding many more cycles. The bond integrity will be monitored during the in spection periods. It should also be noted that the 10,000 hours usage could be met with a reduced life factor of 1.2.

It should be noted that the projected life is based on one set of GAG measured stresses and that the maximum gross weight was used to determine the in-flight maximum stress values. The preceding analysis indicates that the boron/epoxy reinforced stringers are structurally adequate. However, the actual acceptability of the installation will be determined from the observation of the structure during its operational usage, in which the aircraft will fly at various gross weights, with various payloads and under various operational conditions. The two-year period of observation will be the deciding factor for the structural adequacy.

The small specimen S-N data, obtained from Reference 7-2, for 2024-T3 aluminum is shown in Figure 4-1 (upper). Full scale airframe and wing data of Reference 7-3 shows that the effect of acrued construction using riveting lowers the S-N relationship. The reduction is due to the effect of stress concentration at the rivets and fretting at the interface of the stringer and skins. From the upper diagram of Figure 4-3 a K_f relationship for cycles can be constructed. The term K_f is the ratio of small specimen (K_t = 1) and full scale fatigue strength at the particular cycle count. As shown in the lower diagram of Figure 4-3, the K_f value would be 4.3 for the high cycle/lower stresses corresponding to the in-flight cycle range, and 3.3 for the lower cycle/higher stresses corresponding to the GAG cycle range.

The maximum in-flight and GAG stresses shown in Figure 4-4 through 4-9 are below the 10,000 hour usage with a life factor of 4.0 (low stress/ high cycle 1.25×10^6 cycles; and high stress/low cycle 1×10^5 cycles).

A steel strap is used at the tail cone-pylon joint for both the production CH54B and the reinforced tail cone model. The steel construction has a geometric stress concentration of 3.0 (K_t). The fretting between the surfaces would increase the effective stress concentration, but since steel exhibits less fretting than aluminum the K_f values, determined for aluminum, were conservatively used.

The strain gage readings on the boron/epoxy reinforcements were taken in a nominal stress area. A stress concentration factor of 2.12 is used in deriving Figure 4-11. This factor is computed by standard stress concentration procedures using the boron/epoxy geometric section characteristics. The boron/epoxy element is 0.75 inches wide, 0.25 inches thick with a .312 inch hole. Therefore:

$$K_t = \frac{3d}{a+d} = \frac{3.00 \times 0.75}{0.312 + 0.75} = 2.12$$

a = hole diameter, inches

d = width of boron/epoxy strip, inches

This stress concentration factor is considered to be conservative since the boron element loads in each fiber in the vicinity of the hole discontinuity is directly proportional to the fiber cross sectional area (or number of boron fiber elements). Fiber element load redistribution is introduced by shear lag in the area surrounding the hole. All the recorded stresses are well within the 10,000 hour life factor of 4.0 curve as shown in Figure 4-11.

Strain gage data existed on the production aircraft in the water ballasted configuration and a comparison of the data on the two aircraft were made. A plot of this data is presented in Figures 4-12 through 4-17. In general it can be noted that there is no substantial difference from stress levels previous experienced on the CH-54B aircraft.

Dynamic Response

An evaluation of the airframe dynamic response was performed using two techniques to excite the basic airframe modes in hover. The first was to introduce a longitudinal control input to excite the aircraft and the second was to excite the aircraft by reeling out the single point load and bringing it to a stop at various cable lengths. Both methods produced no adverse dynamic response characteristics or divergent vertical bounce. Cable length and one blade two (2) inches out of track appeared to have little effect on the airframe response characteristics.

In the attempts to excite the tail cone it was noted by the pilots that the aircraft felt more sensitive than a production model in that the aircraft felt "softer". The induced vibrations damped out in approximately 4.5 cycles versus one to two cycles for a production aircraft. Although the vertical rigidity of the reinforced tail cone has been increased by the application of the boron/epoxy above that of the production tail cone the torsional rigidity has been decreased due to the thinner skin gages and the fact that the unidirectional boron/epoxy does not contribute to the torsional stiffness. The slight difference in response that the pilots noted is felt to be due to the lower torsional stiffness.

A ground check of the airframe natural frequency produced the following results;

	CH-54B (Standard)	CH-54B (Boron/Epoxy)
1st Vert. Bending	2.2 cps	2.4 cps
1st Lat. Bending	5.1 cps	4.9 cps

This test was performed on the boron/epoxy and standard aircraft with the aircraft in a jacked position using two accelerometers and a ground recorder. The excitation force was provided manually in the vertical and lateral direction.

The results obtained above indicated an increase in vertical stiffness and a decrease in lateral stiffness. These data do not reflect the true 1st mode response of the aircraft due to the aircraft being on jacks, however, it is considered a valid test for determining the relative stiffness of the two tail cone structures which appear to be very similar.

Inspection

At the conclusion of the flight test program and before debailment to the Army, the boron/epoxy tail cone was inspected using the coin tap inspection procedure. This inspection was conducted: to determine whether or not it was practical for a man to conduct this type of inspection in the limited confines of the tail cone and to determine if the coin tap inspection procedure was effective in finding bond discrepancies. The answer to both these questions was affirmative.

A bond inspection procedure for possible use in the field was generated using a battery operated pulse-echo ultrasonic instrument. The procedure worked well on unprimed surfaces, but the roughness of the primed surface deteriorated the signal signature to such an extent that it was not useful. The inspection procedure used therefore was that recommended for field inspection, the coin tap method.

No physical problems were encountered in conducting this inspection and a six (6) inch disbond area was found in the upper left hand stringer -119 at station 669. This area is shown in Figure 2-2. The debonded area appears to be similar to those found in the fatigue test specimen, (Reference 7-1) which did not propagate after the initial disbond. It is adjacent to a stringer/frame clip and is not critical.

The coin tap method of inspection was unable to find the disbonded area around Hi-LOK fasteners that were noted in the fabrication phase, reference section 2.0. Apparently the Hi-LOK fasteners pull the boron reinforcement and aluminum stringers together such that when coin tapped, it resonates like a bonded structure. The periodic field inspections will monitor these areas and will be able to detect if the bond deviations propagate beyond the influence of the fasteners.

Conclusions

The measured stresses on the metal and composite structural elements were within the original criteria of a 10,000 hour fatigue life with a life factor of four. The low stress/high cycle loads on the boron/epoxy reinforced stringer also met the original fatigue criteria. The only area of concern is the high stress/low cycle GAG loadings on the bonded reinforced stringer. An estimate indicates that the 10,000 hour life is met on the bonded stringer with a reduced life factor of 1.2 However, since the mode of failure is disbonding of the stiffening reinforcement, no safety of flight is involved.

Divergent vertical bounce could not be induced and the aircraft's handling characteristics, although slightly more sensitive to pilot's control, is acceptable for service and field evaluation.

The coin tap inspection method is acceptable for field inspection.

TABLE 4-1 THE ORDER AND CONDITIONS

IN WHICH THE FLIGHT TESTS WERE MADE

Flight	Take Off Gross Weight (lb.)	C.G. (in.)	Condition (Ref. Table 3-2)	Configuration (1)	Date Conducted
1	47000	328.	A-1	W.B.	1/21/72
2	28653	334.6	C-5	S.P.	1/27/72
3	28653	334.6	C-5	S.P.	2/1/72
4	28653	334.6	C-3	S.P.	2/2/72
5	28653	334.6	C-4	S.P.	2/7/72
6	47000	328	B-1	W.B.	2/9/72
7	47000	346	A-2, B-2	W.B.	2/10/72

(1)

W.B. - Water Ballast

S.P. - Single Point Hoist

TABLE 4-2 MAXIMUM MEASURED STRESSES IN EXCITATION CONDITIONS

Gage No. (Ref. Figure 3-1)	Material	Flight No. (Ref. Table 4-1)	Flight Regime	Stresses (psi) F(s)	F(v)
TS(A)	7075-T6 Al Sheet	2	Lng OSC 20' Cable AFCS F	3080	1930
TS(B)	Boron/Epoxy	2	Lng OSC 20' Cable AFCS F	7430	5870
BS(A)	7075-T6 Al Sheet	2	Lng OSC 20' Cable AFCS F	-2520	1430
BS(B)	Boron/Epoxy	2	Lng OSC 20' Cable AFCS F	-7070	4340
FL-1	2024-T4 Al Extrusion	2	Lng OSC 20' Cable AFCS F	2530	1220
AL-2	2024-T4 Al Extrusion	2	Lng OSC 20' Cable AFCS F	4560	2040
TCL-2	7075-T73 Al Forging	5	Lng OSC 40' Cable Hover/104 N_R	5570	4590
TCR-2	7075-T73 Al Forging	5	Lng OSC 40' Cable Hover/104 N_R	-4890	4510
TCL-3A	4130 Steel HT 125000	5	Lng OSC 40' Cable Hover/104 N_R	10860	7474
FS-1	2024-T3 Alclad	5	Lng OSC 40' Cable Hover/104 N_R	9540	3390

TABLE 4-2 MAXIMUM MEASURED STRESSES IN EXCITATION CONDITIONS (con't.)

Gage No. (Ref. Figure 3-1)	Material	Flight No. (Ref. Table 4-1)	Flight Regime	Stresses (psi) F(s)	F(v)
FS-2	2024-T3 Alclad	5	Lng OSC 40' Cable Hover/104 N_R	-6970	4650
FS-7	2024-T3 Alclad	5	40' Cable AFCS on Hover/104 N_R	4930	3120
FS-8	2024-T3 Alclad	2	Lng OSC 20' Cable AFCS N	-7900	4100
TCL-1	2024-T3 Alclad	5	Lng OSC 40' Cable Hover/104 N_R	4610	3990
TCL-4	2024-T3 Alclad	2	Lng OSC 20' Cable AFCS N	1440	1670
TCL-5	2024-T3 Alclad	5	Lng OSC 40' Cable Hover/104 N_R	3640	3960
PS-3	2024-T3 Alclad	5	Lng OSC 40' Cable Hover/104 N_R	6630	4080

TABLE 4-3 MAXIMUM MEASURED NORMAL OPERATING FLIGHT STRESSES

Gage No. (Ref. Figure 3-1)	Material	Flight No. (Ref. Table 4-1)	Flight Regime	Stresses (psi) F(s)	Stresses (psi) F(v)
TS(A)	7075-T6 AL Sheet	6	Hover to Land	2790	1400
TS(B)	Boron/Epoxy	6	Hover to Land	9710	3840
BS(A)	7075-T6 AL Sheet	7	Hover to Land	-1310	980
BS(B)	Boron/Epoxy	6	Hover to Land	-3690	3030
FL-1	2024-T4 Al Extrusion	6	Hover to Land	2160	970
AL-2	2024-T4 Al Extrusion	6	Hover to Land	3910	1510
TCL-2	7075-T73 Al Forging	6	Hover to Land	2680	3020
TCR-2	7075-T73 Al Forging	6	Hover to Land	-3750	2400
TCL-3A	4130 Steel H.T. 125000	6	Hover to Land	5870	4720
FS-1	2024-T3 Alclad	6	Hover to Land	6640	2580
FS-2	2024-T3 Alclad	6	Hover to Land	-4970	2940
FS-7	2024-T3 Alclad	6	Hover to Land	3360	2310
FS-8	2024-T3 Alclad	6	Hover to Land	-4680	3210
TCL-1	2024-T3 Alclad	6	Hover to Land	2290	2550
TCL-4	2024-T3 Alclad	6	Hover to Land	600	1050
TCL-5	2024-T3 Alclad	6	Hover to Land	2160	2190
PS-3	2024-T3 Alclad	6	Hover to Land	3130	2450
Rosette	2024-T3 Alclad	7	Cyclic Osc	2893	783

TABLE 4-4 GROUND-AIR-GROUND STRESSES

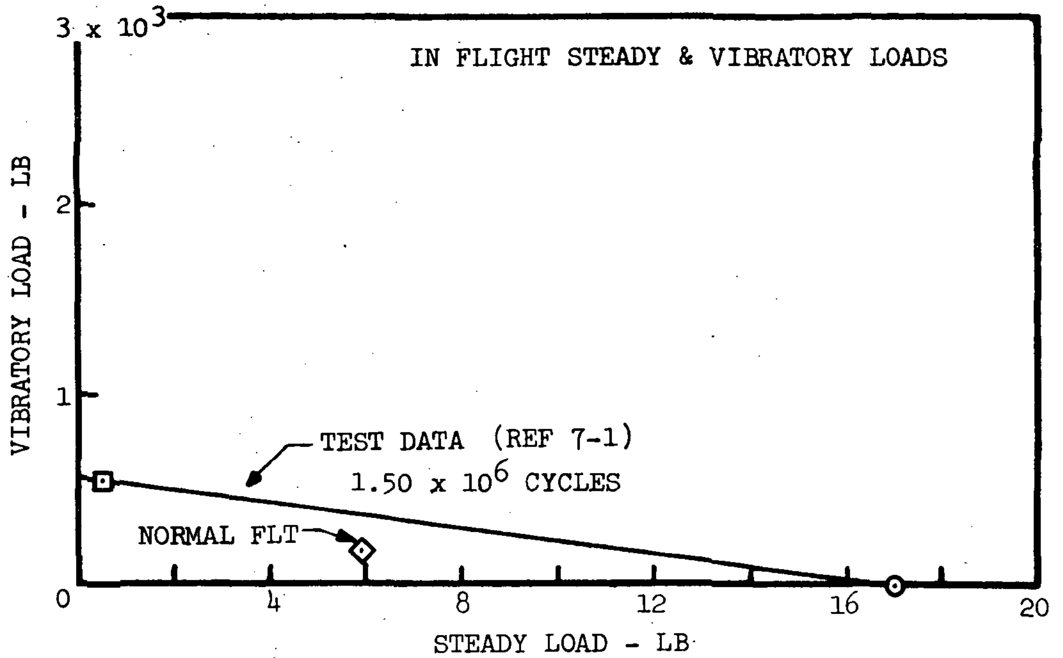
GAGE NO.	MAX STRESS STEADY (1)	MAX STRESS VIB (2)	MIN STRESS STEADY (3)	MIN STRESS VIB (4)	COND. MAX	COND. MIN	$F_{(s+v)}$ MAX (5)	$F_{(s+v)}$ Min (6)	G.A.G. STRESS F_s (7)	G.A.G. STRESS F_v (8)
TS(A)	+6700	±170	-520	±190	6 Climb	7 Gr. Run	+6870	-710	+3080	±3090
TS(B)	+29050	±650	-4270	±450	6 Climb	7 Gr. Run	+19700	-4720	+7440	±12260
BS(A)	-4830	±400	+1460	±180	1 Rev	7 Auto	-5230	+1640	-1795	±3435
BS(B)	-12470	±1060	+3760	±640	1 Rev	7 Auto	-13530	+4400	-4565	±8975
FL-1	+4070	±360	-1120	±100	6 Rt Turn	7 Gr. Run	+4430	-1220	1605	±2825
AL-2	+9120	±330	-990	±90	6 Climb	7 Gr. Run	+9450	-1080	4185	±5265
TCL-2	+10220	±590	-1620	±360	6 Climb	6 Auto	+10810	-1980	4415	±6395
TCR-2	-9790	±300	0	±230	1 Rud. Rev	7 Gr. Run	-10090	+230	-4930	±5160
TCL-3A	+19940	±840	-1110	±610	6 Climb	6 Auto	+20780	-1720	+9530	±11250
FS-1	+12880	±280	-1350	±360	6 Recov.	7 Rot. Eng	+13160	-1710	+5725	±7435
FS-2	-10330	±760	+510	±530	7 Hov. Rud Rev	6 Recov	-11090	+1040	-5025	±6065
FS-7	+7270	±610	-1100	±570	7 Hov. Rud Rev	7 Auto Rec	+7880	-1670	+2605	±5275
FS-8	-11670	±1220	+3310	±620	1 Rud Rev	7 Auto	-12890	+3930	-4480	±8410
TCL-1	+6590	±730	-1170	±270	6 Rt Turn	6 Auto	+7320	-1440	+2940	±4380

TABLE 4-4 GROUND-AIR-GROUND STRESSES (CON'T)

GAGE NO.	STEADY (1)	VIB (2)	STEADY (3)	VIB (4)	COND. MAX	COND. MIN	$F_{(s+v)}$ MAX (5)	$F_{(s+v)}$ MIN (6)	G.A.G. STRESS F_s (7)	F_v (8)
TCL-4	+2710	±130	-720	±180	1 Rud. Rev	6 Rud. Rev	+2840	-900	+970	±1870
TCL-5	+7720	±390	-1430	±350	1 Rud. Rev	7 Auto Ent	+8110	-1780	+3165	±4945
PS-3	+12790	±670	-2170	±480	6 Climb	6 Auto	+13460	-2650	+5405	±8055
Rosette	+5836	±67			6 Climb		+5836		+2951	±2885

NOTE:

COL. (5) = (1)+(2)
COL. (6) = (3)+(4)
COL. (7) = $\frac{(5)+(6)}{2}$
COL. (8) = (5)-(7)



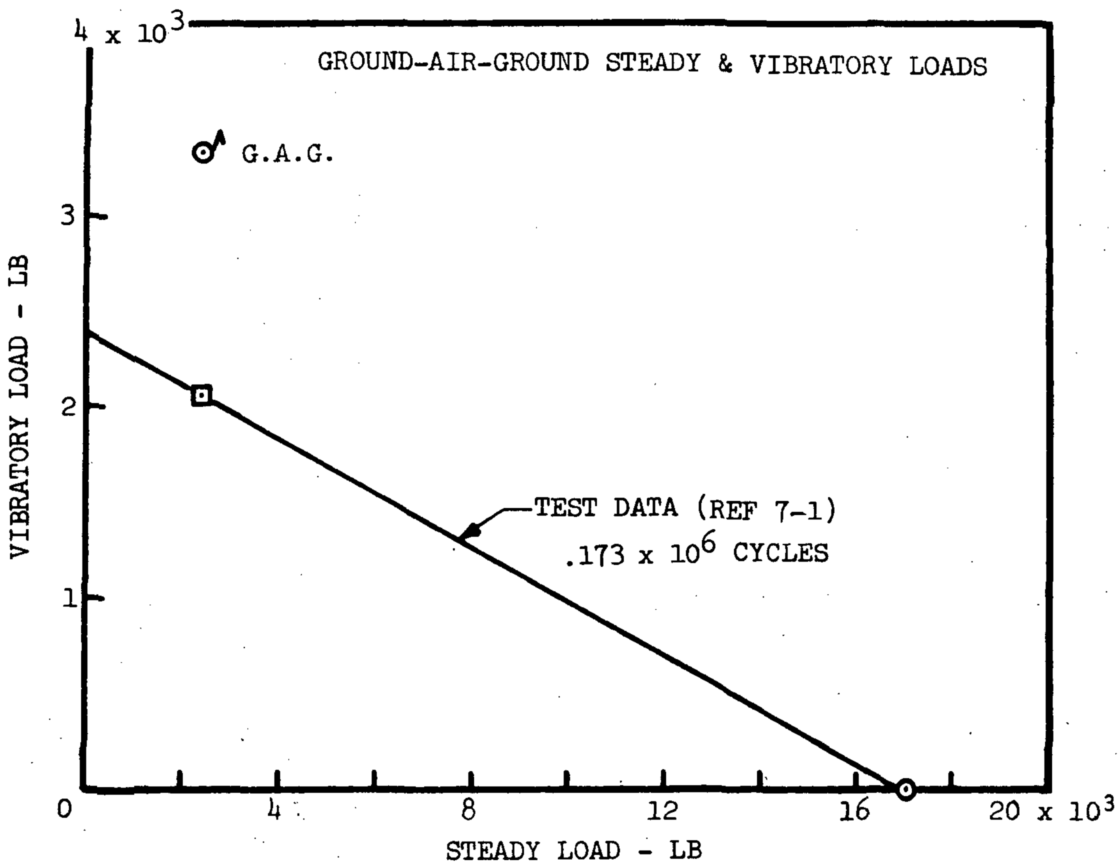


FIGURE 4- 1. FATIGUE LOADINGS FOR BORON EPOXY REINFORCED STRINGER.

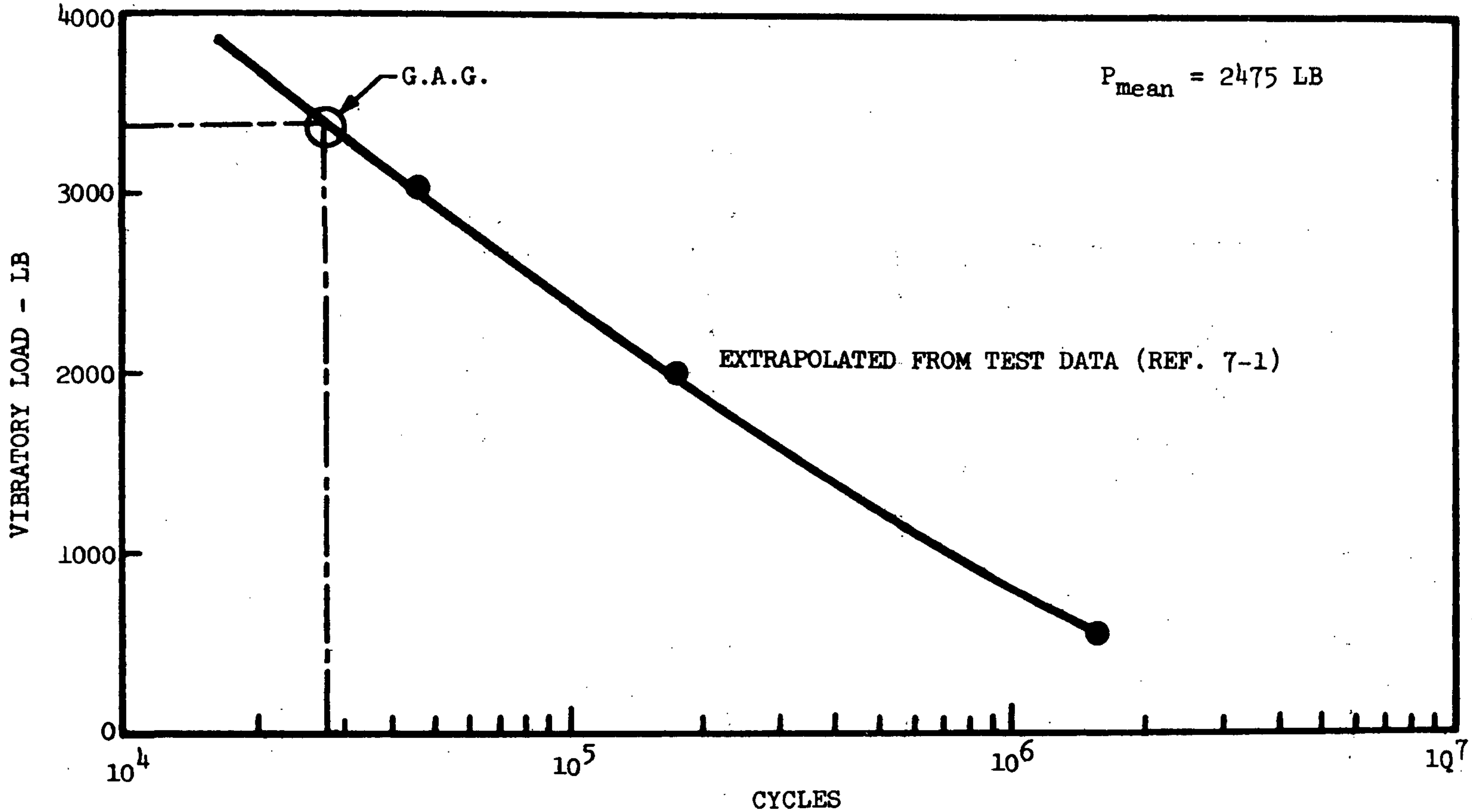


FIGURE 4-2. LOAD-CYCLE DATA FOR BORON/EPOXY REINFORCED STRINGER.

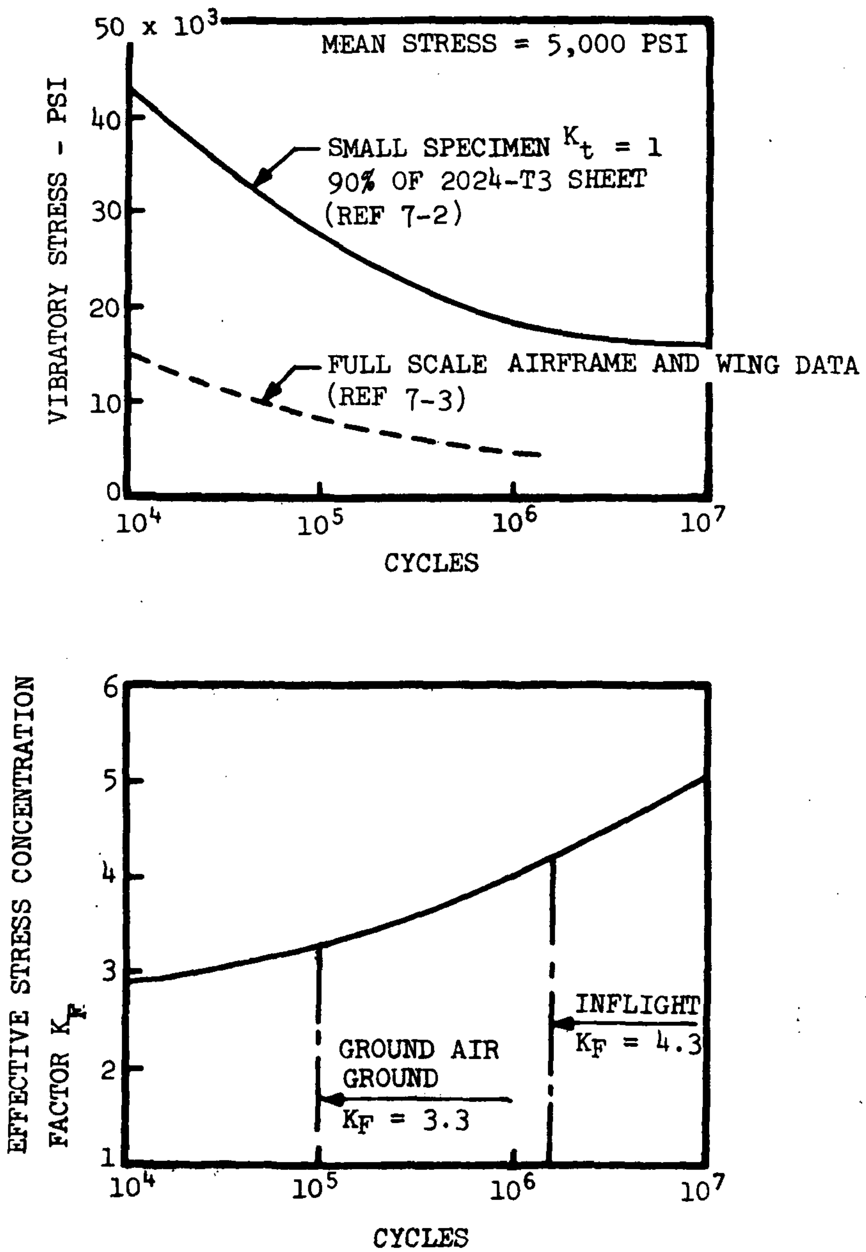


FIGURE 4-3. EFFECTIVE FATIGUE STRESS CONCENTRATION FOR AIRFRAME CONSTRUCTION.

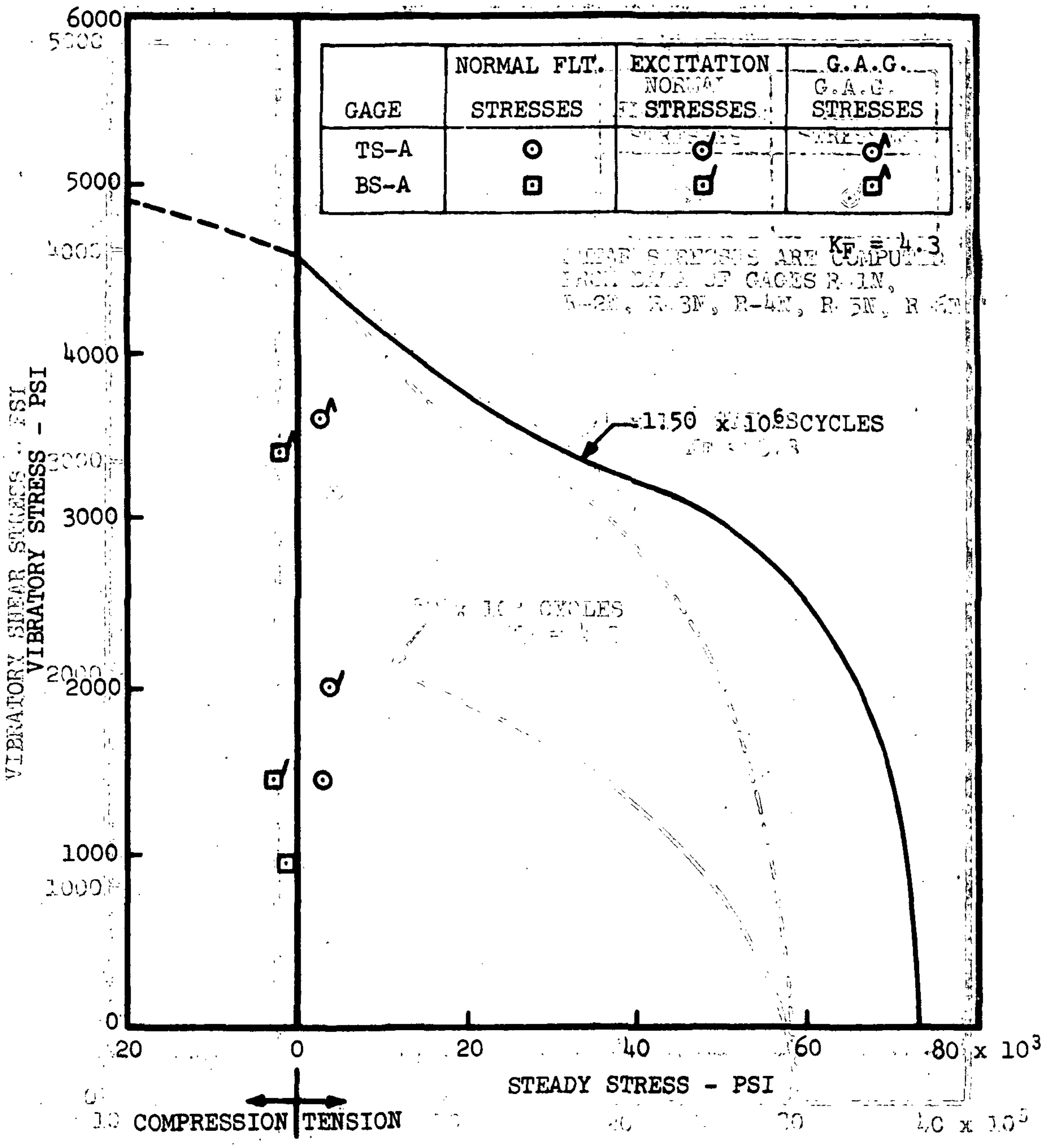


FIGURE 4-4. CONSTANT LIFE FATIGUE DIAGRAM AND MEASURED STRESSES - 7075-T6 ALUMINUM SHEET.

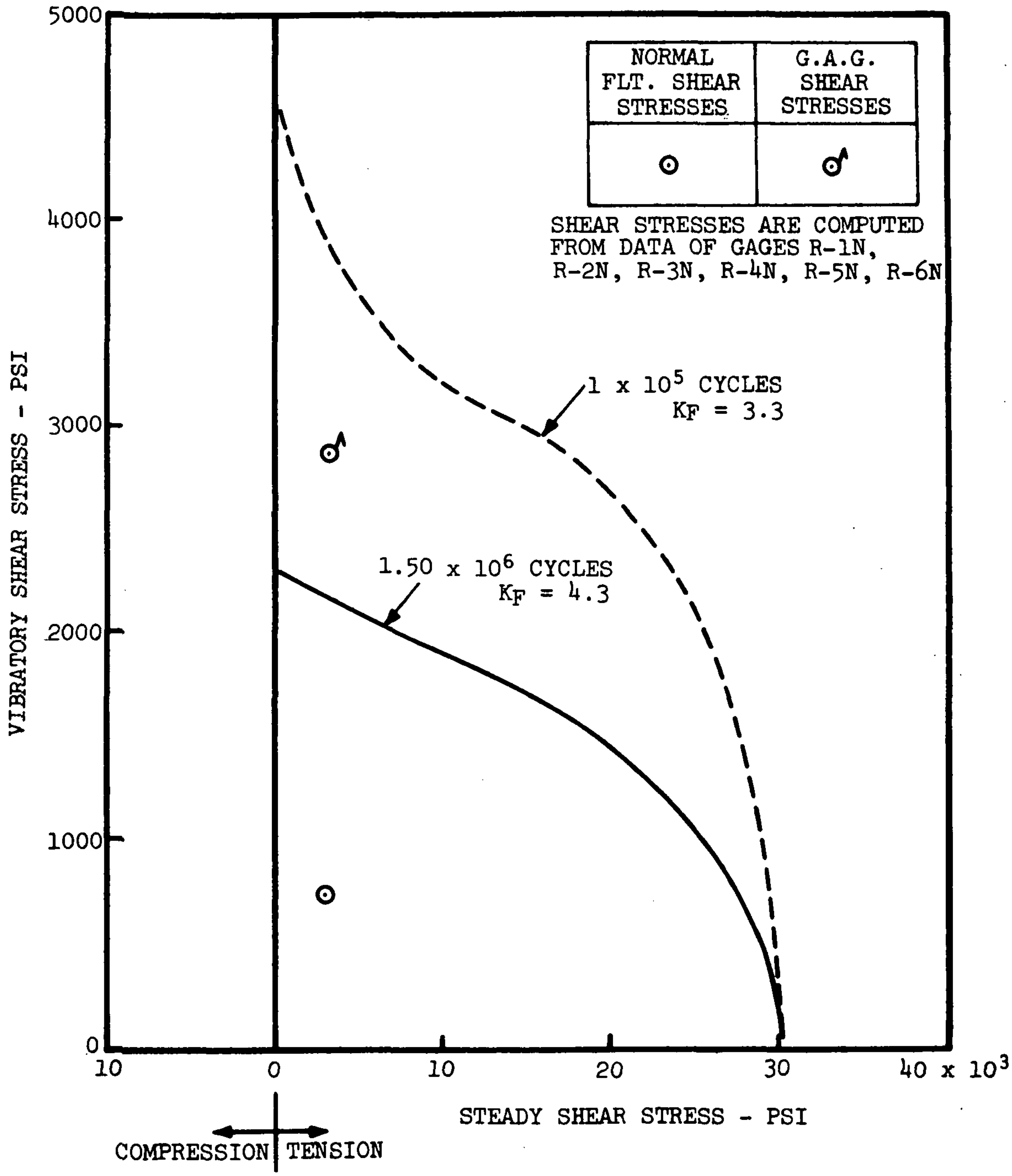


FIGURE 4-5. CONSTANT LIFE FATIGUE DIAGRAM AND MEASURED STRESSES - 2024-T3 ALCLAD SHEET.

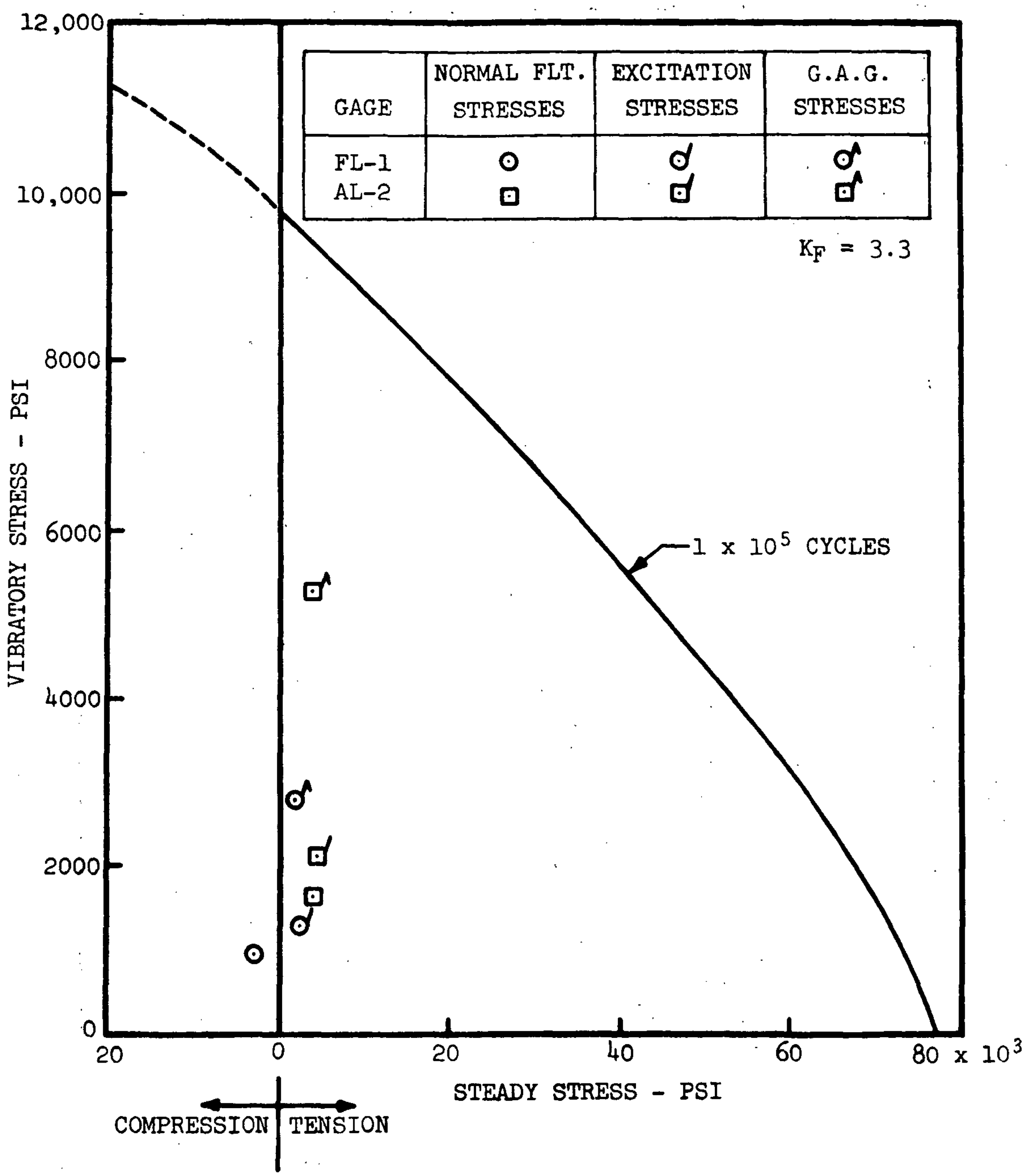


FIGURE 4-6. CONSTANT LIFE FATIGUE DIAGRAM AND MEASURED STRESSES - 2024-T4 ALUMINUM EXTRUSION.

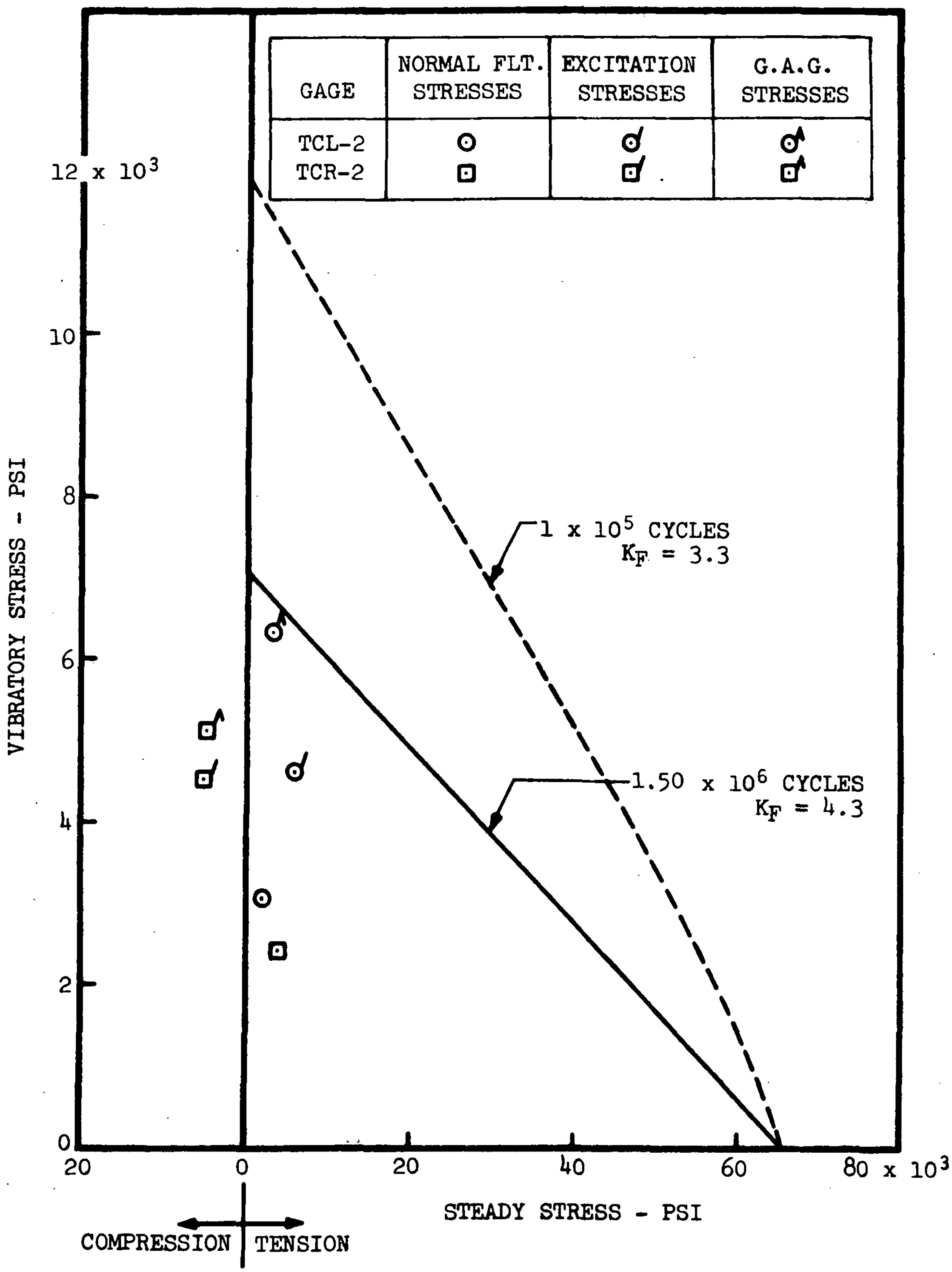


FIGURE 4-7. CONSTANT LIFE FATIGUE DIAGRAM AND MEASURED STRESSES - 7075-T73 ALUMIMUM ALLOY.

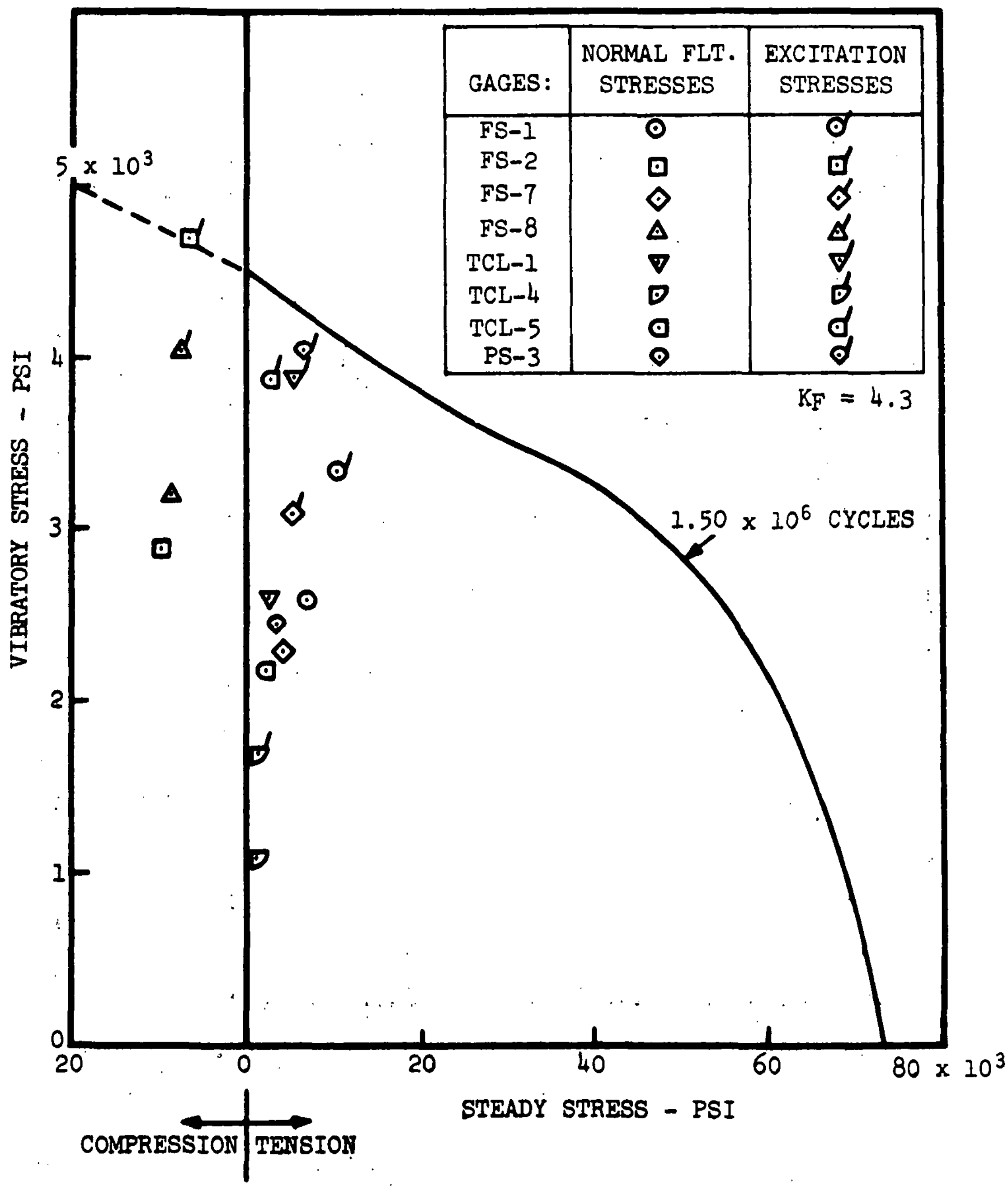


FIGURE 4-8. CONSTANT LIFE FATIGUE DIAGRAM AND MEASURED STRESSES - 2024-T3 ALCLAD SHEET.

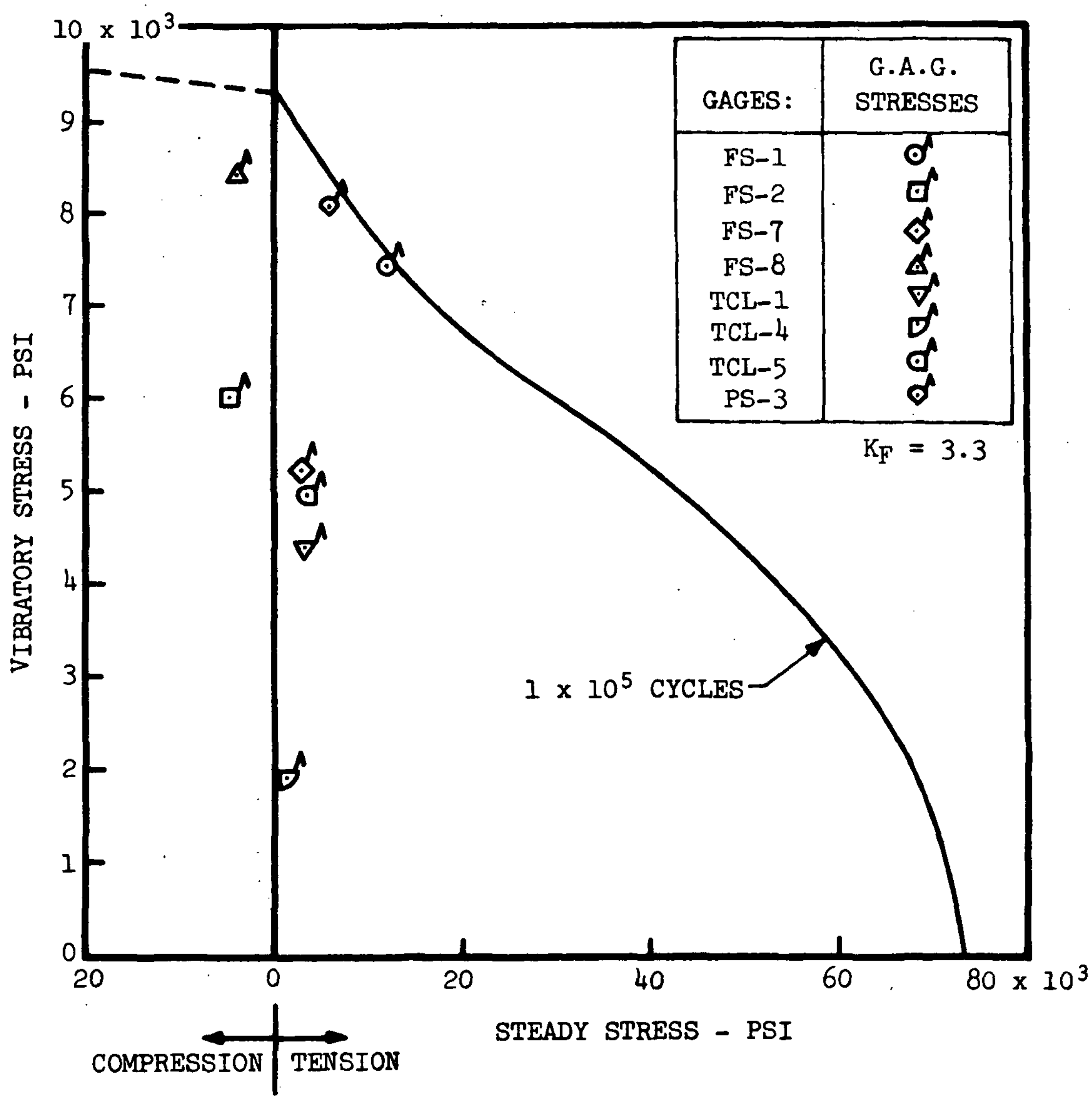


FIGURE 4-9. CONSTANT LIFE FATIGUE DIAGRAM AND G.A.G. STRESSES - 2024-T3 ALCLAD SHEET.

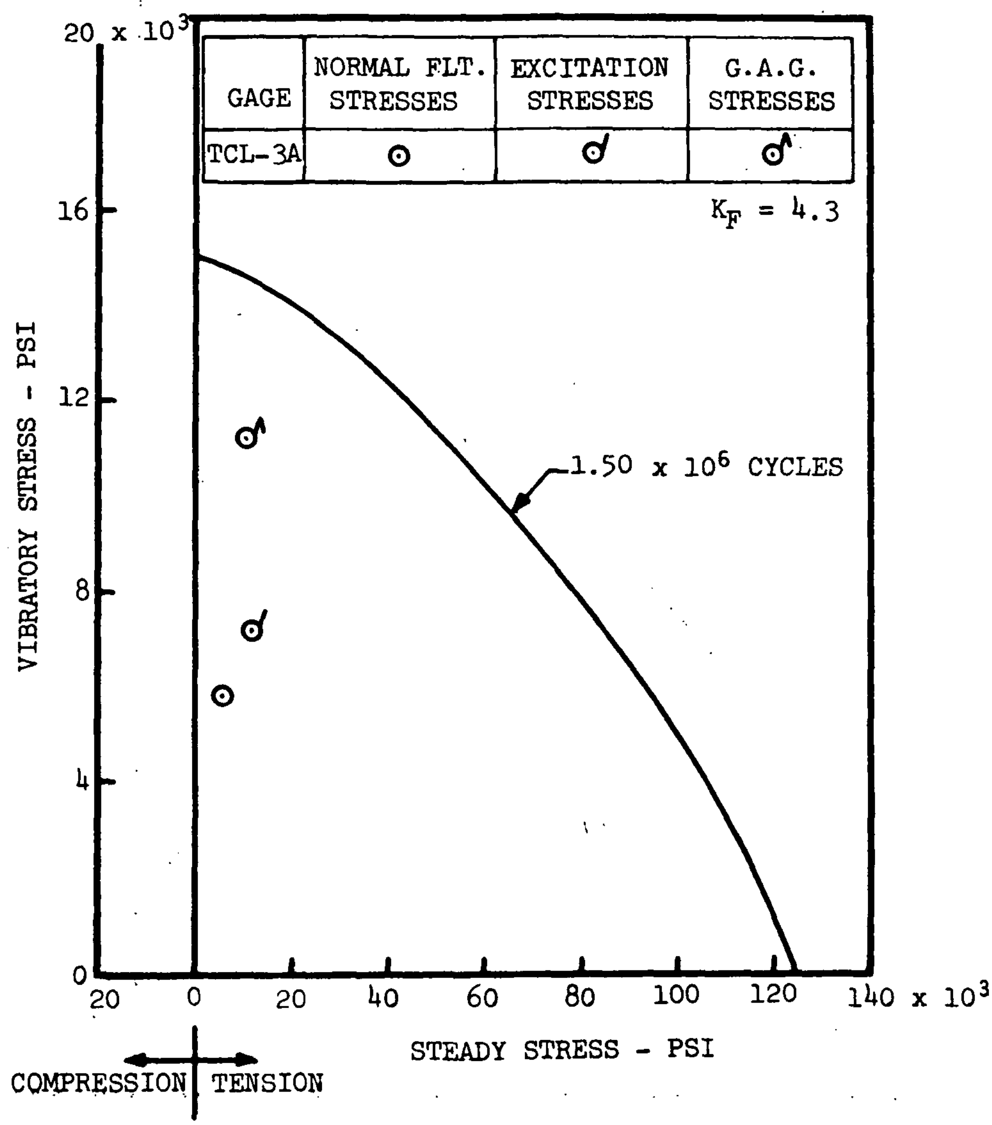


FIGURE 4-10. CONSTANT LIFE FATIGUE DIAGRAM AND MEASURED STRESSES - 4130 STEEL F_{tu} = 125000.

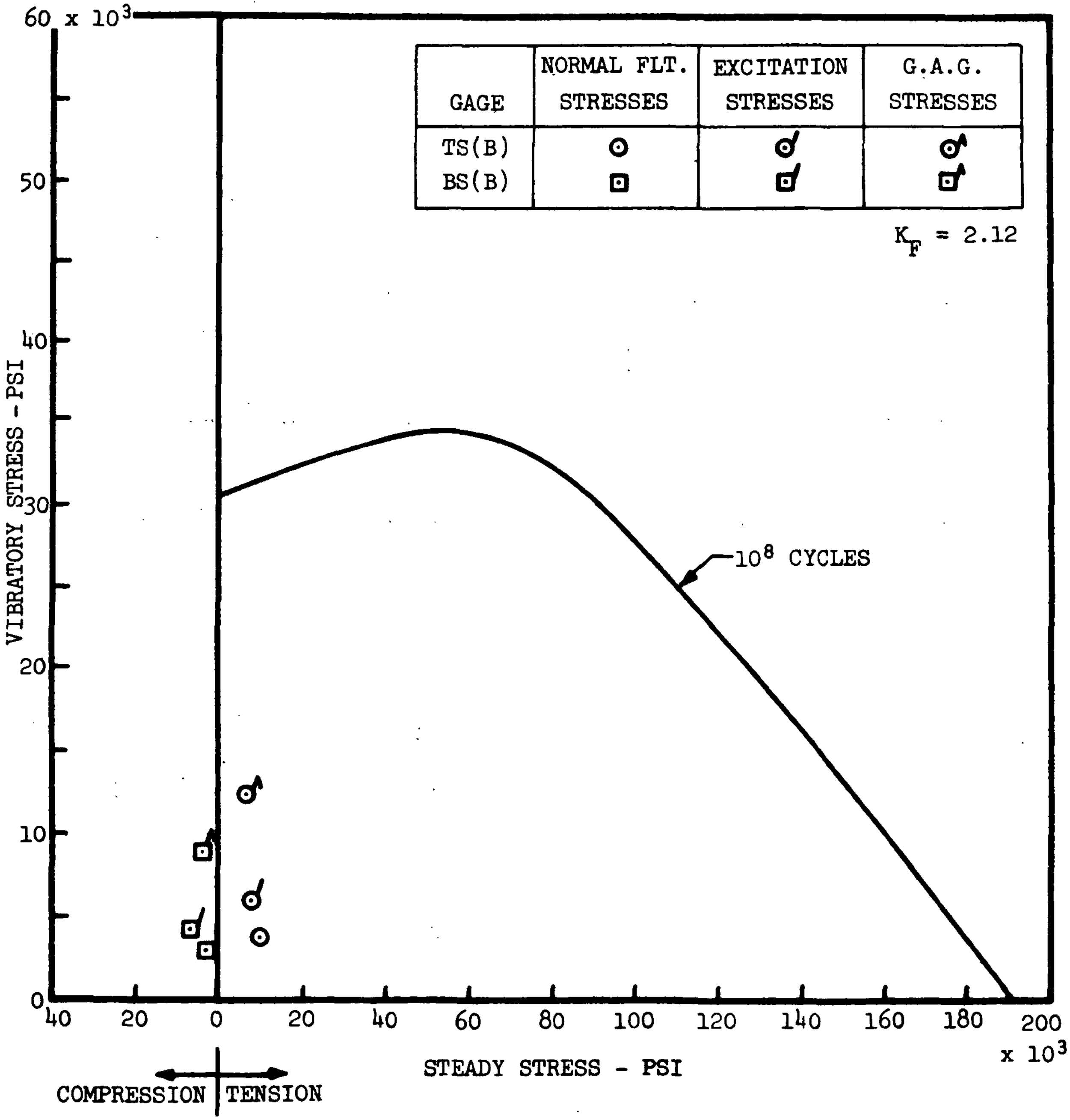


FIGURE 4-11. CONSTANT LIFE FATIGUE DIAGRAM AND MEASURED STRESSES - BORON/EPOXY.

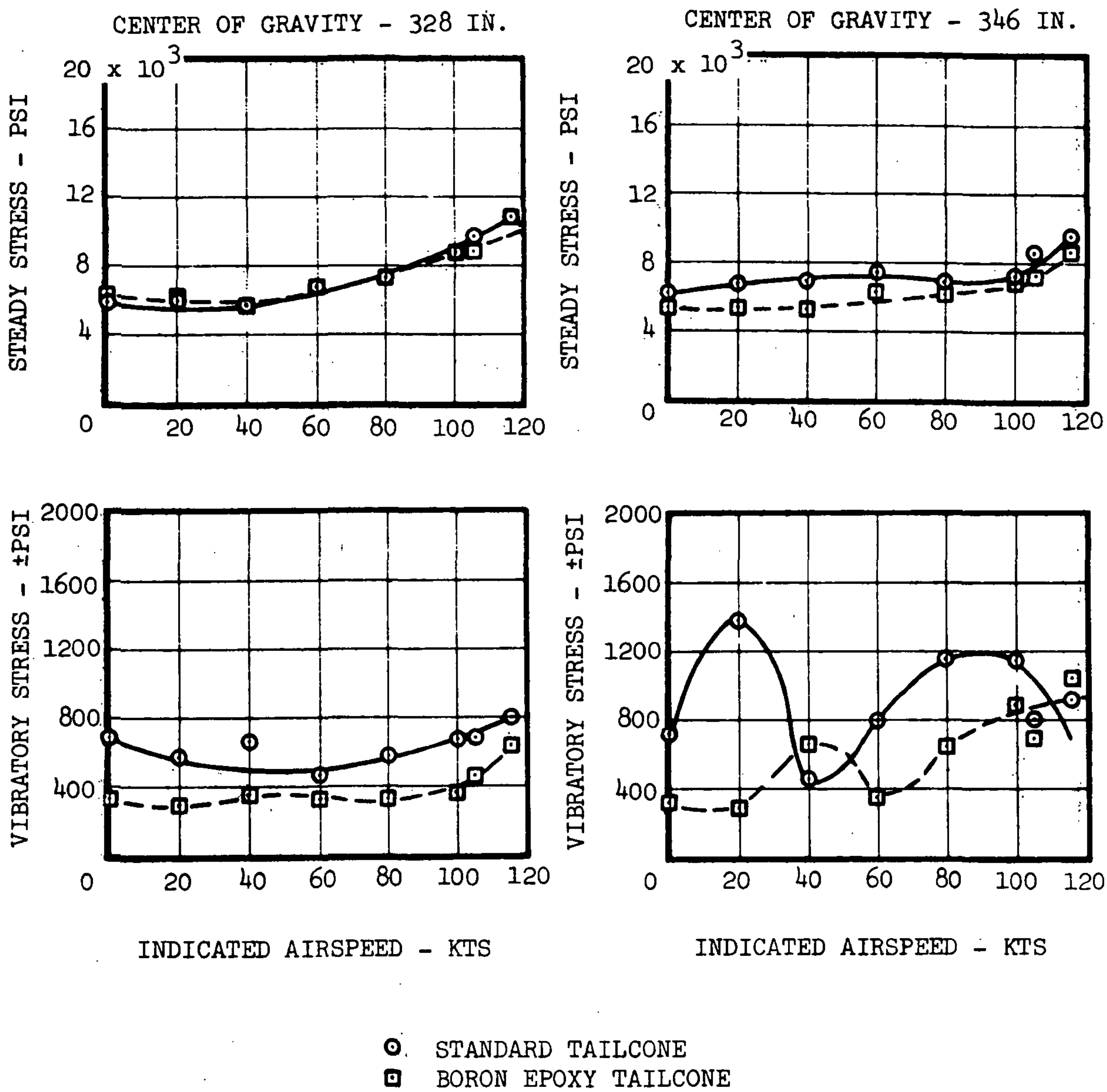


FIGURE 4-12. STRESS COMPARISONS FOR BORON/EPOXY AND PRODUCTION AIRCRAFT - STRAIN GAGE PS-3.

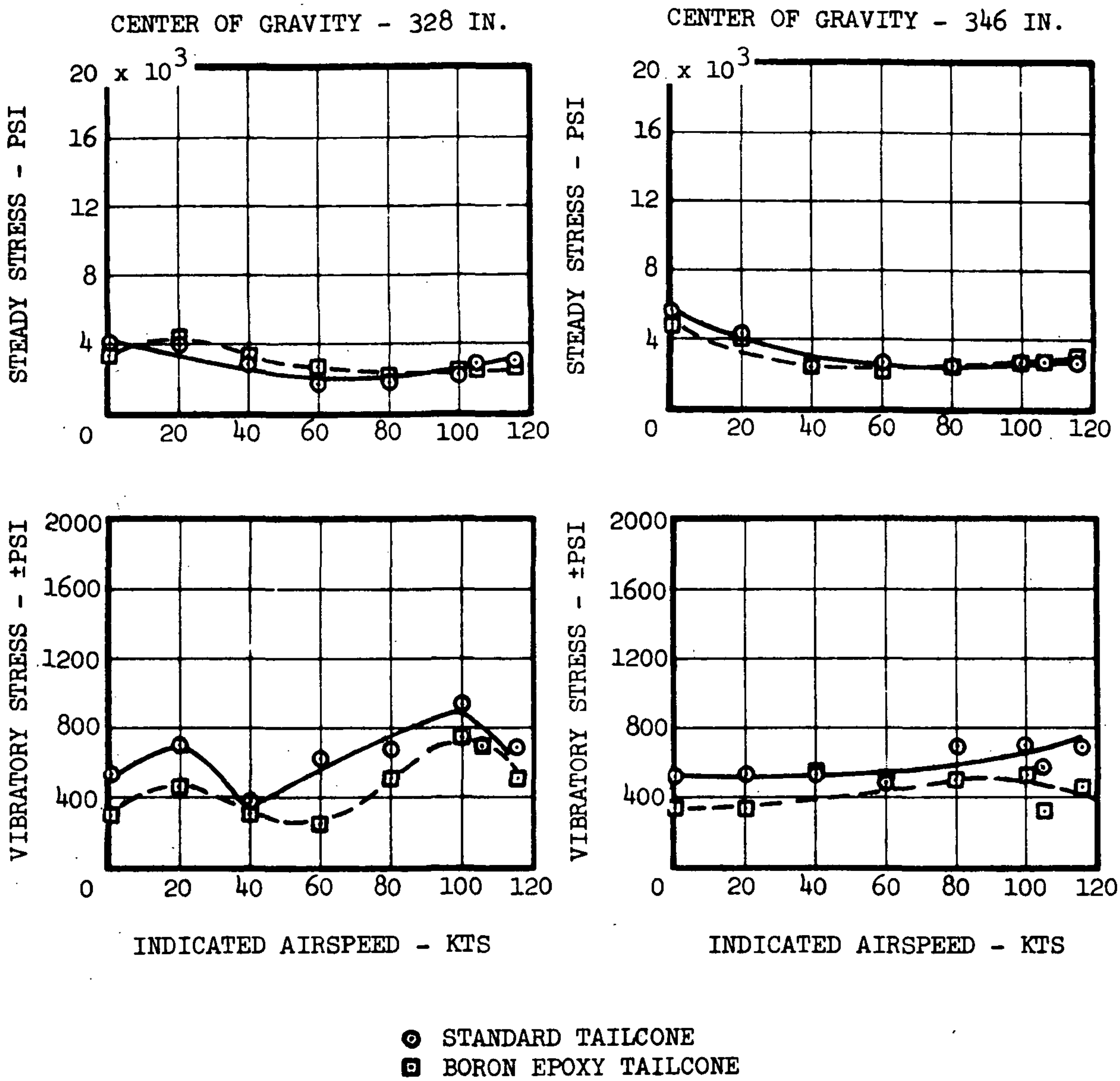


FIGURE 4-13. STRESS COMPARISONS FOR BORON/EPOXY AND PRODUCTION AIRCRAFT - STRAIN GAGE FS-7.

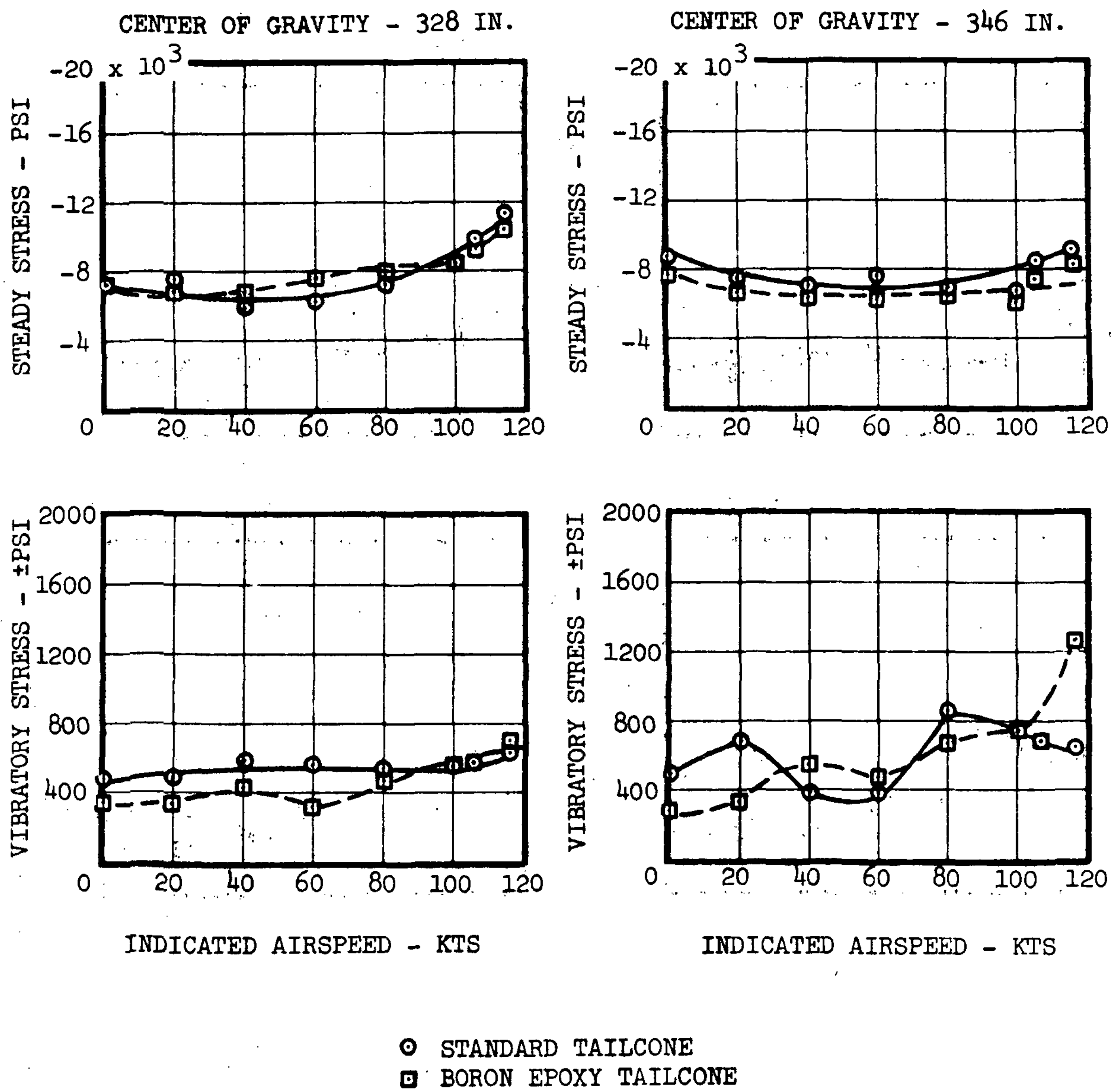


FIGURE 4-14. STRESS COMPARISONS FOR BORON/EPOXY AND PRODUCTION AIRCRAFT - STRAIN GAGE FS-8.

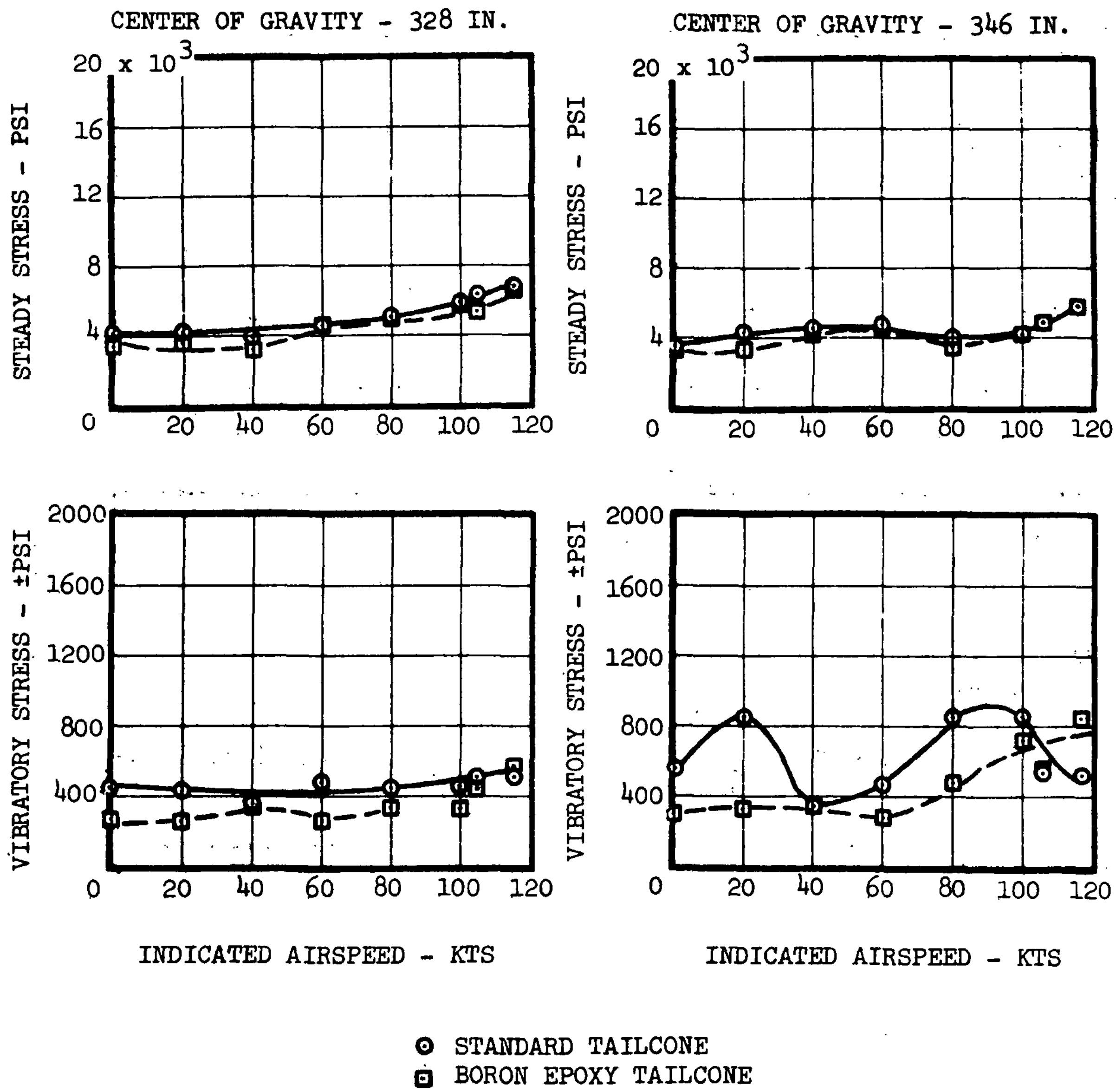


FIGURE 4-15. STRESS COMPARISONS FOR BORON/EPOXY AND PRODUCTION AIRCRAFT - STRAIN GAGE TCL-1.

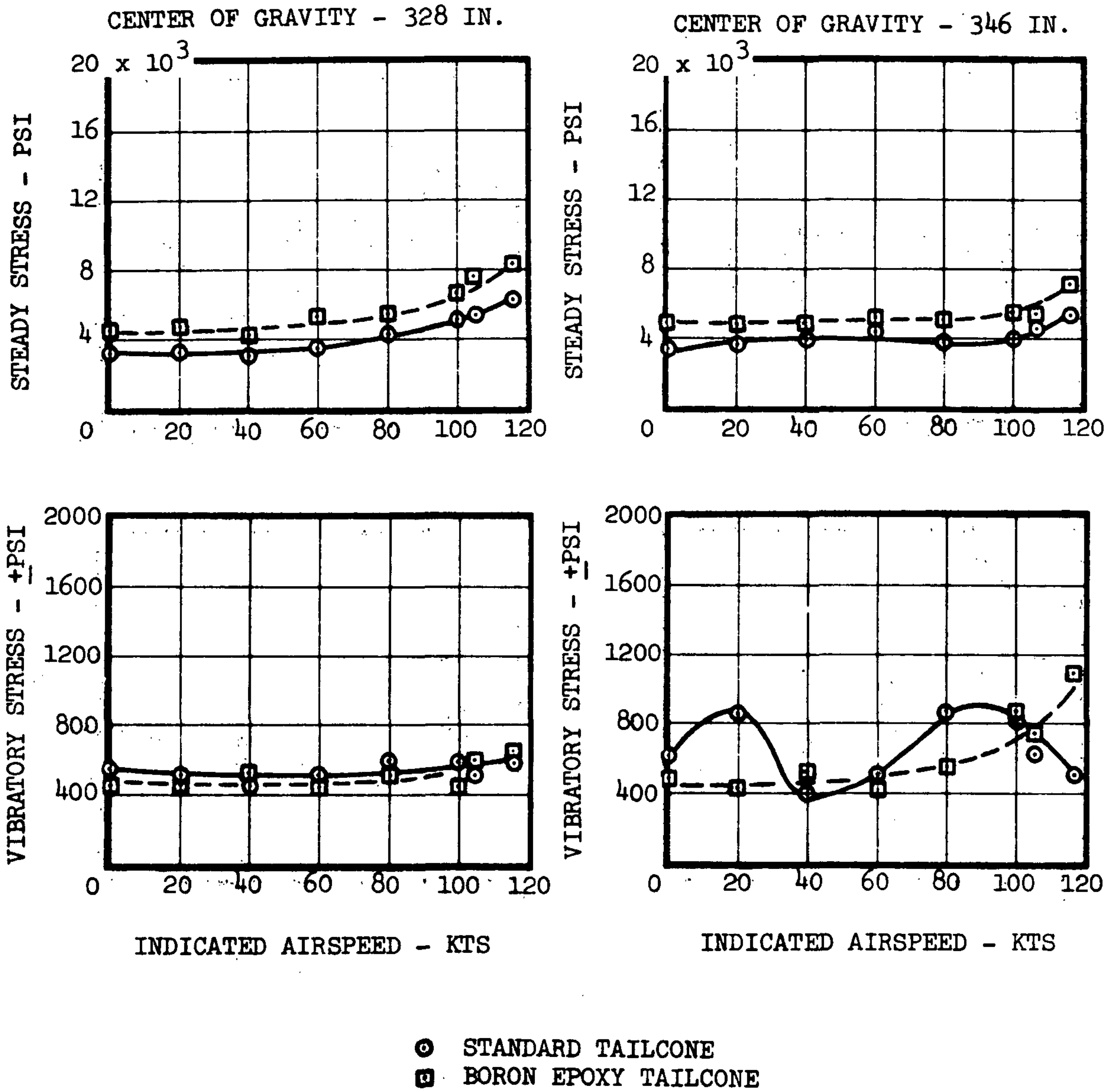


FIGURE 4-16. STRESS COMPARISONS FOR BORON/EPOXY AND PRODUCTION AIRCRAFT - STRAIN GAGE TCL-2.

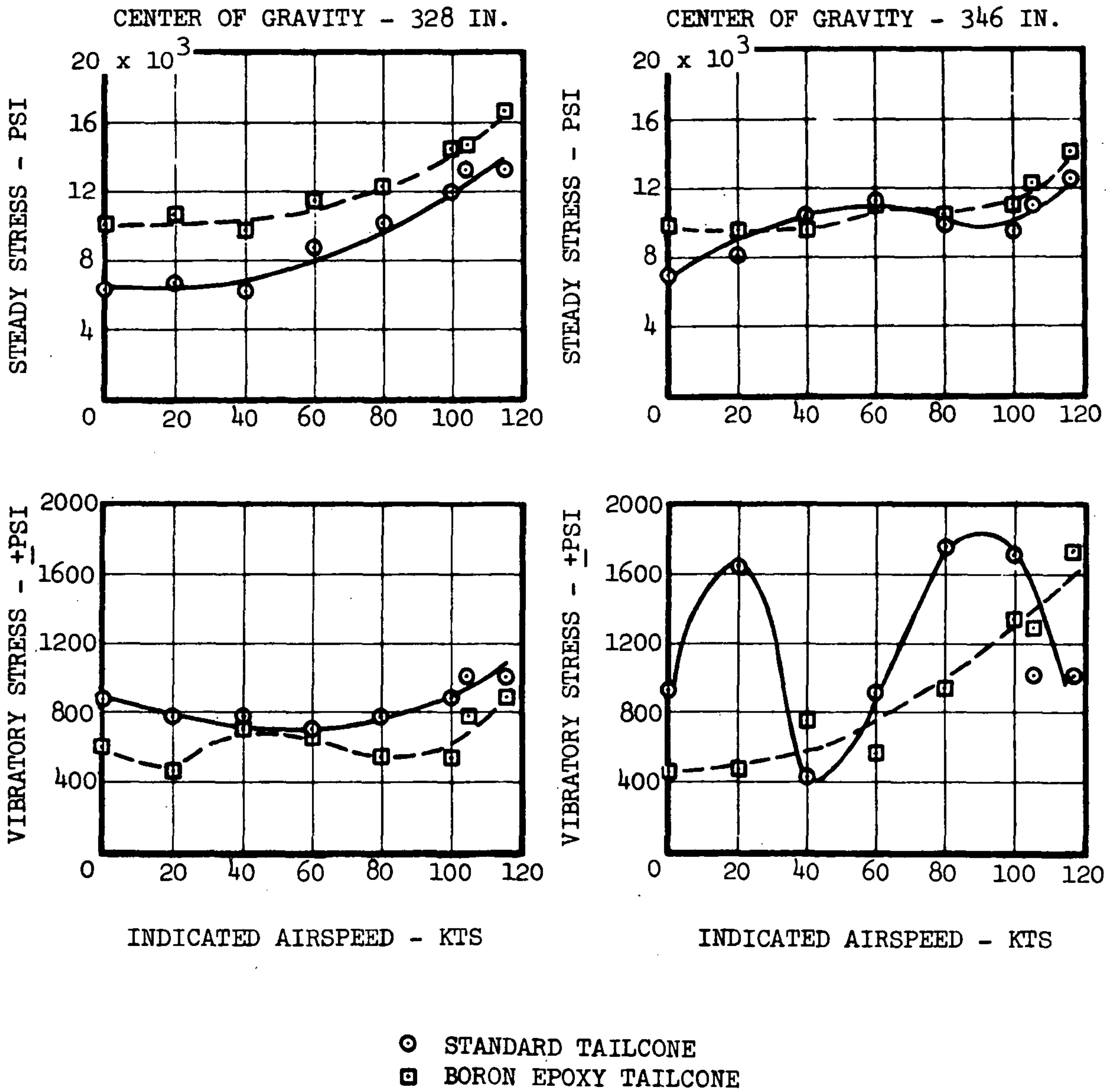


FIGURE 4-17. STRESS COMPARISONS FOR BORON/EPOXY AND PRODUCTION AIRCRAFT - STRAIN GAGE TCL-3A.

5.0 SKID GEAR DESIGN AND ANALYSIS

Objective

The objective of this study was to verify the structural capability, for flight service, of boron/epoxy skid gear tubes designed to replace the swaged aluminum members on the CH-54B aircraft.

Approach

The boron/epoxy skid gear tubes, installed on the CH-54B, were designed fabricated and proof tested under a Sikorsky funded program. The justification of the structural integrity of the composite tubes is based upon the proof load tests to which they were subjected. The end fittings were analysed by incorporating the results obtained from the proof load tests. The fitting attachments were conservatively analysed assuming a no bond condition and the bolts were designed to resist the total induced fitting loads.

Discussion

The tail bumper or skid gear consists of three struts pinned to the aircraft pylon and converging to a point through which ground loads are introduced. Two struts are of fixed length, the third contains an oleo strut plus an electromechanical retraction actuator (see Figure 5-1).

In the composite design the two aluminum fixed length links were replaced with boron/epoxy prototype tubes. Aluminum adapter fittings were designed so that the composite tubes attached to the same pylon skid gear end fitting as the production aluminum tubes which in turn facilitated interchangeability on the aircraft. These adapter or transition fittings connect the constant diameter boron/epoxy tubes to the upper production fittings and to magnesium casting "shoe" on the lower end. The geometry of this assembly is shown in Figures 5-2 and 5-3. The criteria for interchangeability and use of existing fittings penalized the composite tube design such that a weight savings of only thirty-five percent was achieved while a potential saving of seventy-nine percent is felt to be obtainable. The component weights for both the restricted and non-restricted skid gear are shown in Table 5-1. The composite tube assembly consisted of straight boron/epoxy tubes bonded and bolted at each end to the aluminum transition fittings. The boron/epoxy tubes are 43.25 inches long and of a constant inside diameter of 2.04 inches.

The composite tubes are basically six (6) plies of unidirectional boron, with two (2) plies of $\pm 45^{\circ}$ S-Glass forming the inside diameter.

One transverse ply of S-Glass was added on the outside to increase the transverse strength of the tube and to protect the boron/epoxy. Additional glass reinforcement plies at each end provided the necessary bearing strength for the bolted/bonded joint. The six (6) plies of boron at the ends were interplied with 481 E-Glass at $\pm 45^{\circ}$. The orientation of the various materials and the end fitting attachment is shown in Figure 5-2.

The critical design loading condition for the tail skid is a tail down landing with an aft center of gravity. The current production skid gear is designed to the loads shown in Figure 5-4 with the strut member loads calculated by assuming pin ended truss members. Boron/epoxy tubes were designed, fabricated, and tested to the production applied loads under a Sikorsky funded program. A company developed computer program was used in the design and analysis of the composite tubes. The orthotropic properties of the total composite system, in a direction parallel with the tube axis, are a function of the individual principle material properties of each layer and their corresponding orientation. The basic material data and tube geometry is an input into the computerized program (Reference 7-4).

Two series of tests were conducted with the composite tubes: a compression test of a boron/epoxy strut with a bolted/bonded joint; and a proof test of the boron/epoxy skid brace assembly.

In the compression test a boron/epoxy strut was strain gaged and installed in a Baldwin 100,000 pound universal test machine. The tube was loaded in compression with special care taken to assure the strut was centrally plumb in the machine. At 22,300 pounds, the bond between the end fitting and composite tube failed. The load dropped momentarily then was brought back up to 22,000 pounds. The composite tube then failed by local crushing at the bolt holes as shown in Figure 5-5. The maximum ultimate production design tube load is 9823 pounds (Reference Figure 5-4).

The proof test of the skid gear assembly is shown in Figure 5-6. During this test the transition fitting, at the lower attachment point, failed at an applied resultant load of 6600 pounds. The failing load was above the design limit load of 4450 pounds but below the design ultimate load, (Reference Figure 5-4). It was noted in this test that the individual strut loads changed from pure axial, in the undeformed condition, to a combination of axial and bending, as the assembly deformed. Strain gages on the assembly monitored the strains. Ultimate strut loads were generated by extrapolation of test data and were used in the design and analysis of the assembly end fittings. These loads are higher than the production ultimate design loads as shown in Figure 5-4. A new reinforced lower transition fitting was designed for the aircraft installation taking into account the moments as determined by test. A summary of margins of safety for the strut is shown in Table 5-2.

The composite tubes used in the skid gear assembly test were visually inspected for damage and none was detected. The bonded end fittings were carefully machined out and the new fittings bolted and bonded in place.

The bonding agent used was EC 2214 and is a room temperature bond. The skid gear tube assembly was installed on the boron reinforced tail cone at the beginning of the flight test program.

Conclusion

The structural integrity of the production skid gear assembly is maintained with the interchangeable boron/epoxy skid gear assembly.

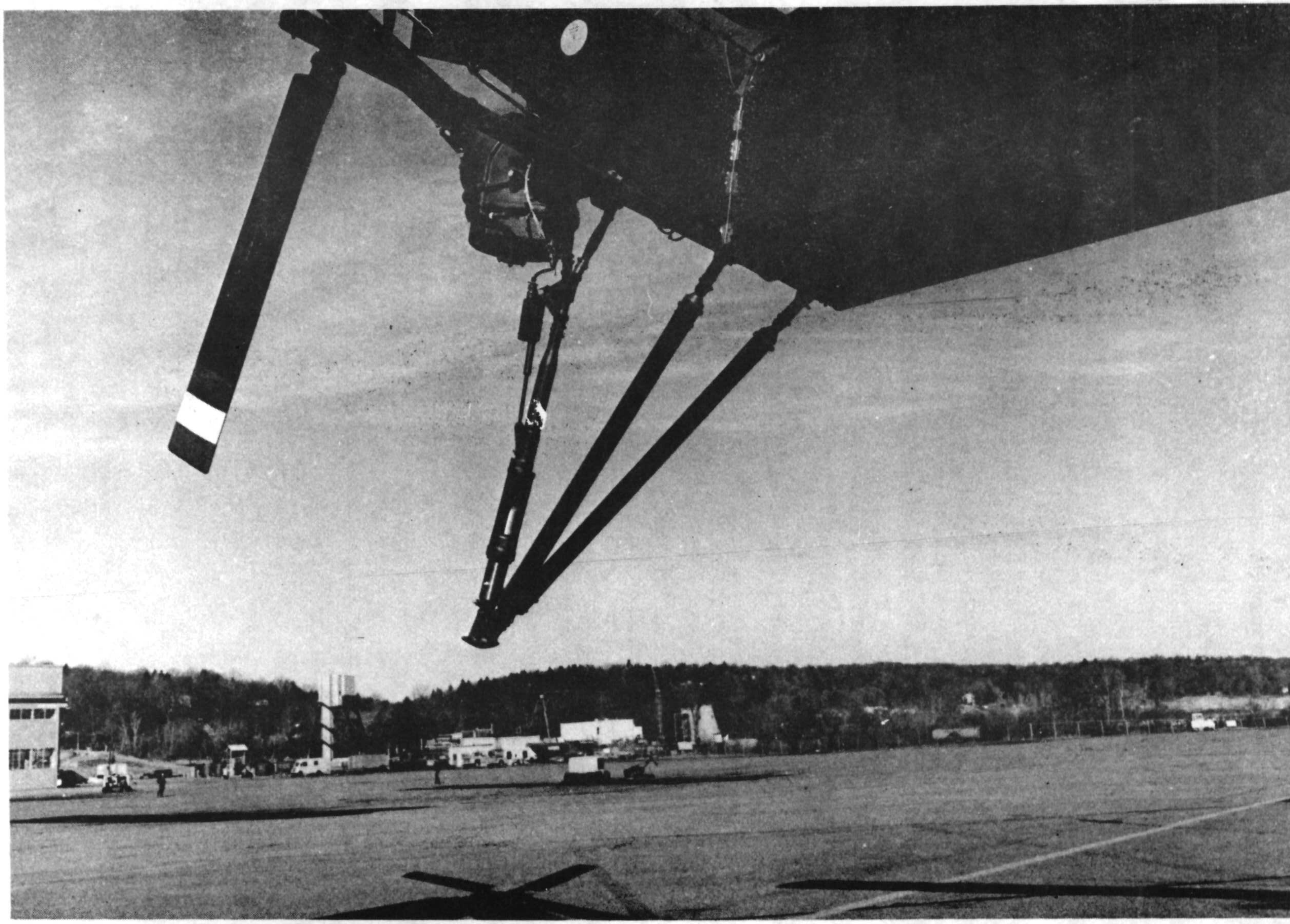


FIGURE 5-1. BORON/EPOXY SKID GEAR AIRCRAFT INSTALLATION

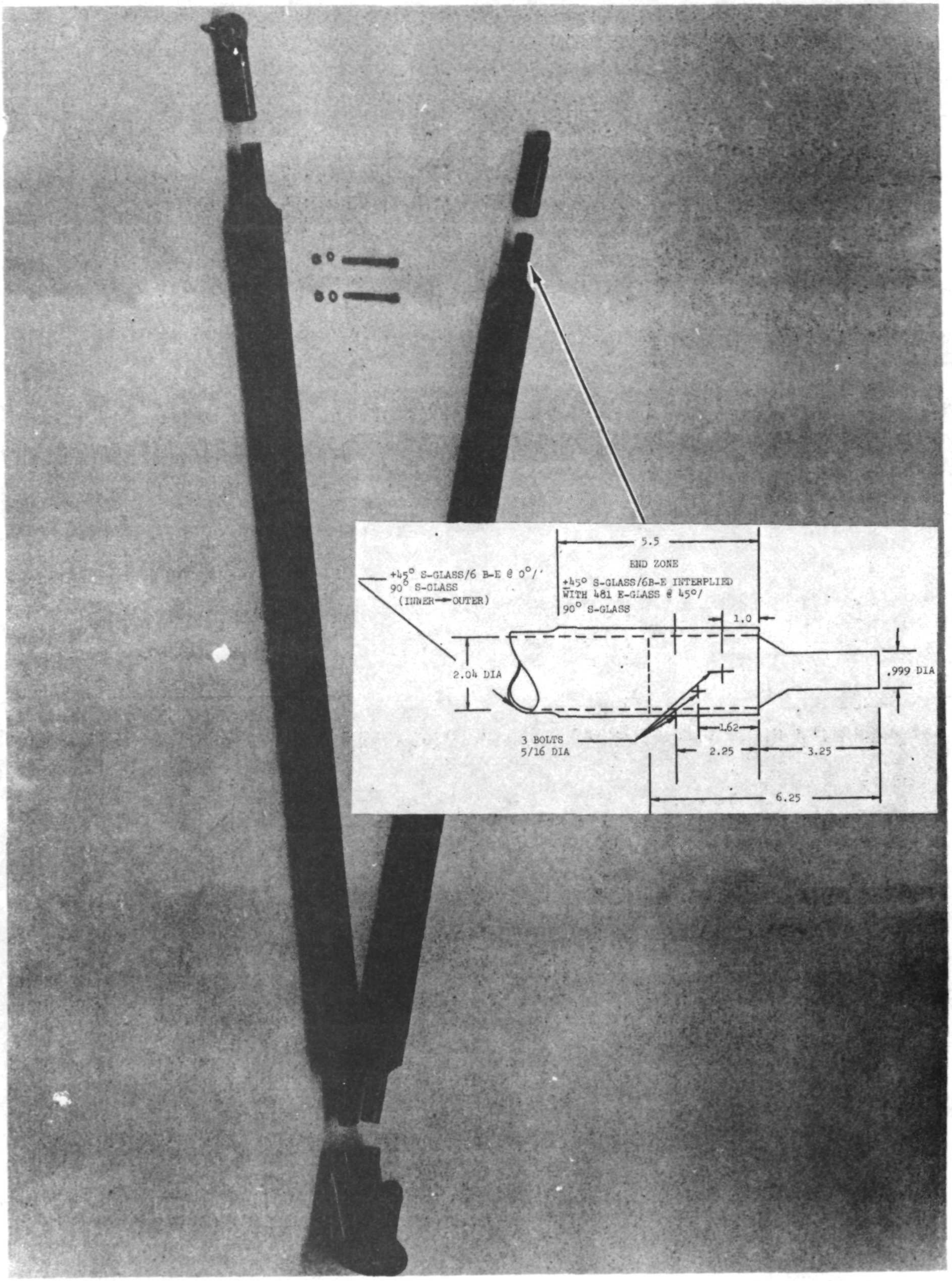


FIGURE 5-2. BORON/EPOXY SKID GEAR COMPONENTS

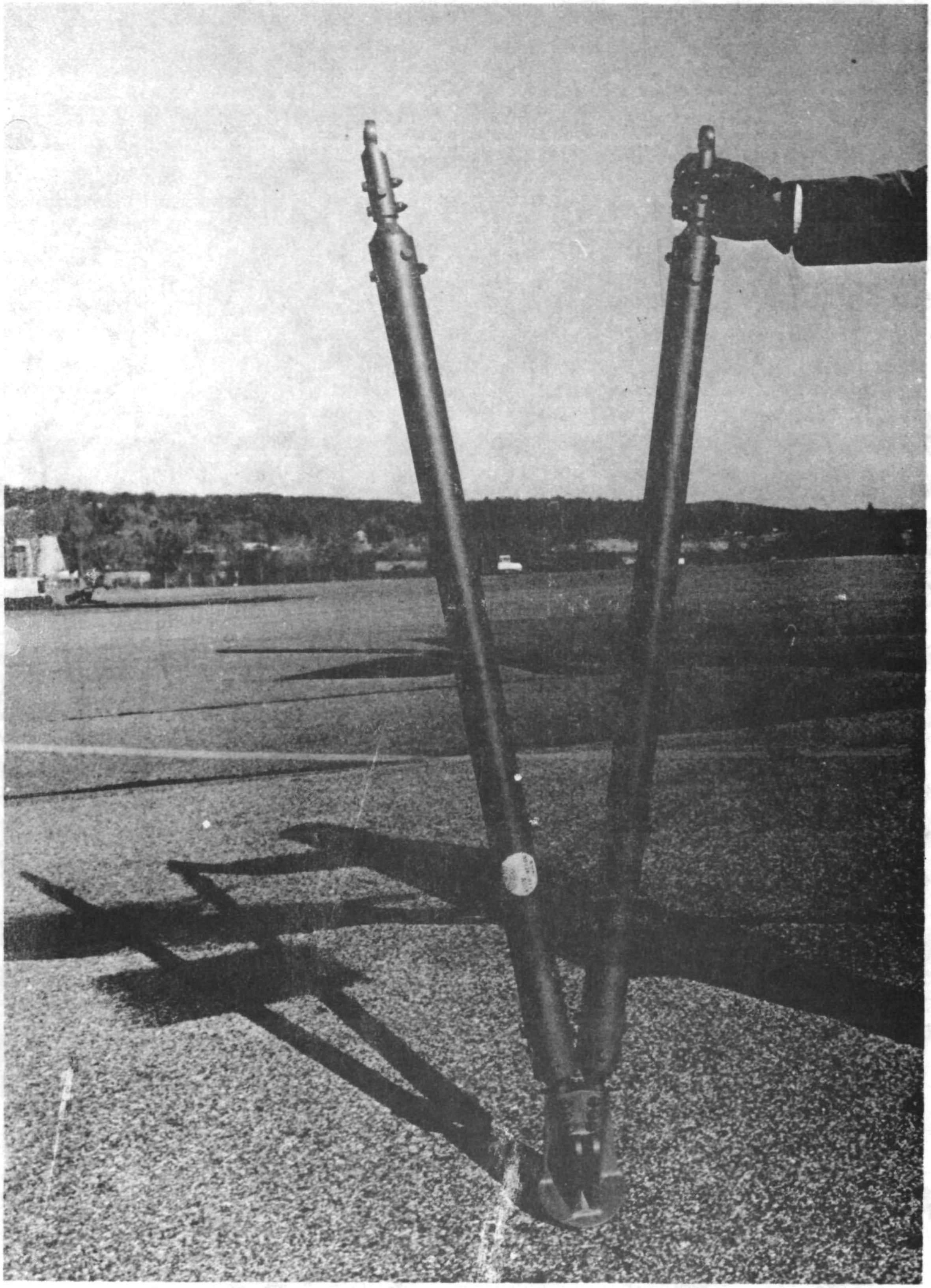
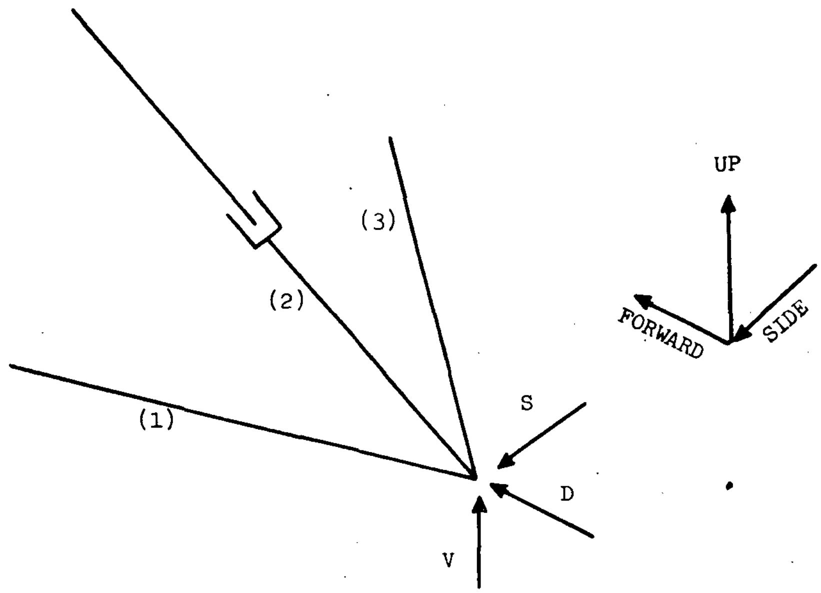


FIGURE 5-3. BORON/EPOXY SKID GEAR ASSEMBLY



APPLIED SKID GEAR LOADS

LOAD COMPONENT	ULTIMATE (POUNDS)	LIMIT (POUNDS)
V (Vertical)	6656	3868
D (Drag)	1422	860
S (Side)	3408	1986
Resultant	7520	4450

DESIGN SKID GEAR MEMBER LOADS

	Pin Ended Production Design Loads		
Members	Ultimate Strut Loads - Pounds	Limit Strut Loads - Pounds	Extrapolated Strut Test Loads - Pounds
1	-9823	-5950	-12450
2	-8731	-5280	Not Measured
3	12190	7370	14550

FIGURE 5-4 SKID GEAR LOADS

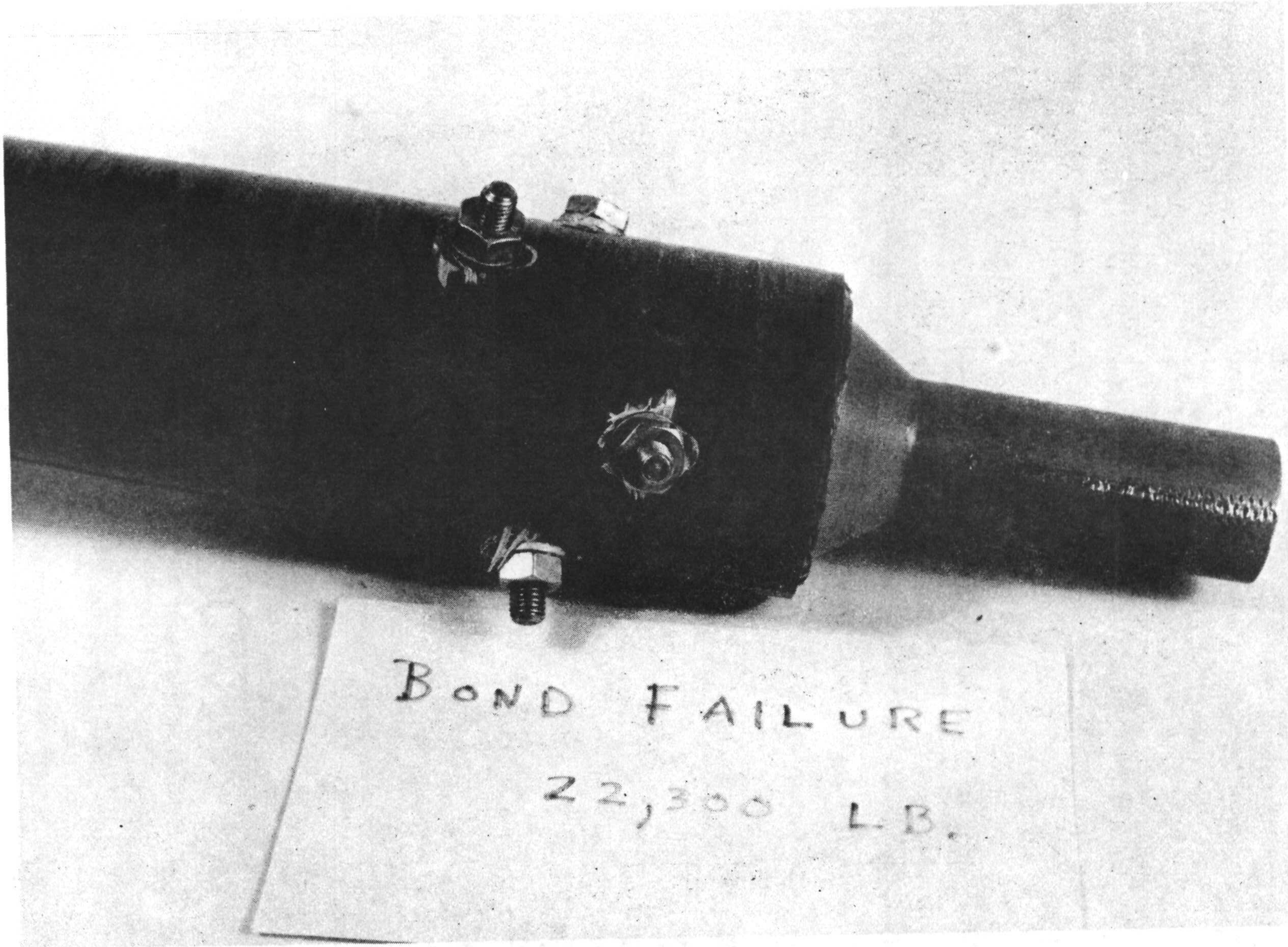


FIGURE 5-5. COMPRESSION END FITTING FAILURE IN BORON/EPOXY TUBE

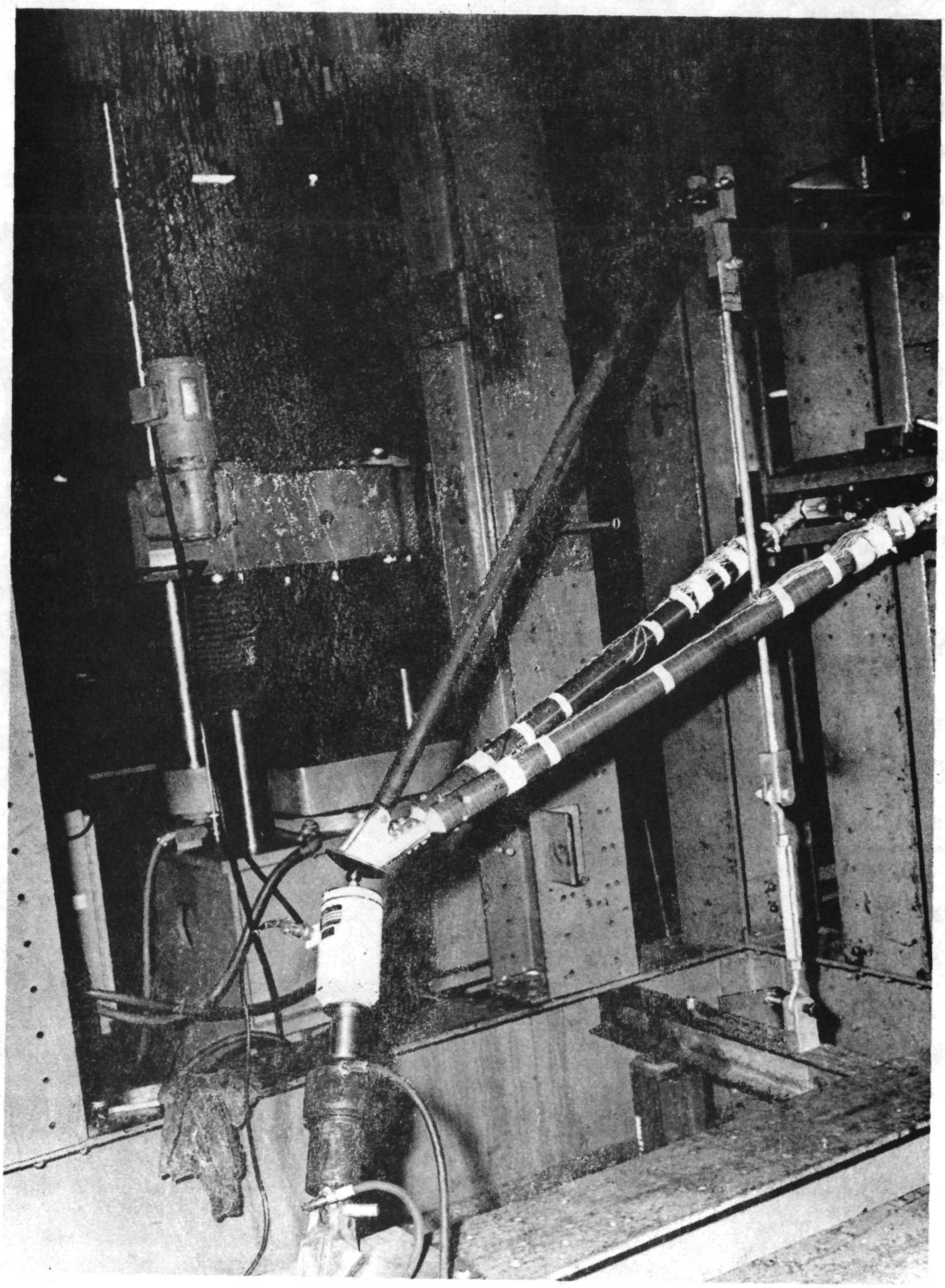
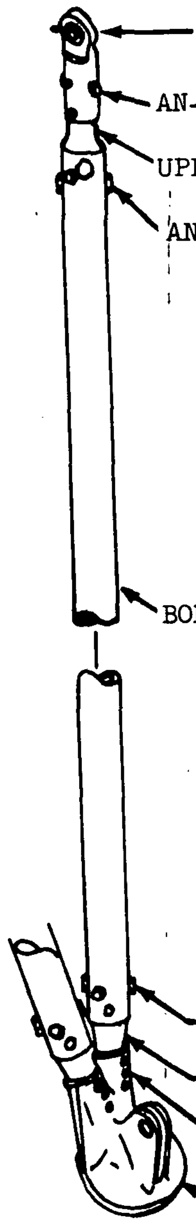


FIGURE 5-6. ASSEMBLY TEST OF SKID GEAR INSTALLATION

TABLE 5-1 COMPARATIVE WEIGHT
FOR ALUMINUM AND COMPOSITE TAIL SKID
BRACE TUBE ASSEMBLIES

ALUMINUM TUBE		INTERCHANGEABLE COMPOSITE TUBE		OPTIMUM COMPOSITE TUBE	
Tube	3.4	Tube	2.20	Tube	.7
Nuts & Bolts	.31	Nuts & Bolts	.62	Nuts & Bolts	.4
End Fittings	2.6	Adapters	.51	End Fittings	3.5
	6.31	End Fittings	2.6		4.6
			5.93		

TABLE 5-2. SUMMARY OF CRITICAL MARGINS OF SAFETY FOR THE BORON/EPOXY SKID GEAR



COMPONENT	MODE	MARGIN OF SAFETY
Rod End	Bolt Bearing	.27
Upper AN-174 Bolts	Shear	.52
Upper Fitting	Bending	.24
AN-175-24	Bearing	.28
Composite Tube		proof loaded
Lower Fitting	Bending	.24
Lower AN-174 Bolts	Bending	.10
"Shoe" Fitting	Bearing	.23

(a) REF. TABLE 5-2

6.0 SUMMARY OF CONCLUSIONS

The study, of the boron/epoxy reinforced CH54B tail cone, has proven the feasibility of committing hybrid structures to production. It has shown that this type of construction can save weight over current methods of manufacture, and can be fabricated using conventional tooling, normal production personnel and with minor modifications to an existing design.

Current ultrasonic inspection methods were found to be adequate in detecting bond deviations during fabrication. The coin tap method, recommended for field inspections, was found to be adequate in detecting disbonds.

The flight test plan, as developed and followed in this study was sufficient to provide the required information needed to evaluate the modified aircraft.

The measured stresses on the individual elements of the reinforced stringers and on the conventional structure meet the requirement of 10,000 hours of life with a factor of four. Higher stresses than predicted, however, were recorded in the ground-air-ground cycles and results in a 10,000 hour life with a factor of 1.2 on the bond of the boron/epoxy reinforced stringers.

The bond integrity should be inspected periodically though no safety of flight is envolved in the event of disbond of the stiffening boron/epoxy reinforcement strips. The tail cone was analysed for the applied loads without any boron/epoxy reinforcement.

Divergent vertical bounce could not be induced in the tail cone and although slightly more sensitive to pilot's control, the aircraft was found to be acceptable for service and field evaluation.

The structural integrity of the boron/epoxy skid gear, installed on this aircraft and made interchangeable with the production structure, was found to be adequate based upon proof load tests, load measurements and structural analysis.

7.0 REFERENCES

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