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NOVEMBER 1972 J. AIRCRAFT VOL. 9, NO. 11

Design and Test of a Boron/Epoxy Reinforced Airframe

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A design investigation is conducted under a NASA contract for stiffening the air frame of the CH-54B Skycrane[R] using boron/epoxy reinforced aluminum stringers. It is shown that the reinforcement will prevent air frame resonance with appreciable weight savings over conventional aluminum construction. Thermal expansion is investigated and not found to be a problem. Tapered joints using a fiber glass insert are investigated and are shown to reduce the adhesive bond load transfer stresses to well within acceptable levels. Static load tests are conducted on reinforced stringers and skin/stringer panels. These tests show that the reinforced stringer has the required stiffness and strength and that while bond strength is the limiting factor, the panel strength in shear and compression exceeds that of the all-aluminum construction. Fatigue tests are conducted for in flight and ground-air-ground vibratory loadings. The results of the fatigue tests are presented and show that the boron/epoxy reinforced stringers meet the required fatigue loadings with a life factor of four. It is concluded that the boron/epoxy reinforced stringers are effective in reducing weight for airframe stiffening, and have more than adequate strength for the structural integrity of the CH-54B.

Introduction

BORON/EPOXY reinforced aluminum stringers offer large weight savings and permit use of conventional fastening. The structural design of large helicopter airframes involves both strength and stiffness. The stiffness requirements arise from the necessity of tuning the air frame to prevent amplification of the rotor vibratory forces. Thus, after providing the strength requirements for flight and ground conditions, it is often necessary to add additional material to increase the natural frequency of the airframe.

The original CH-54 Skycrane airframe, as shown in Fig. 1, was found to be in partial resonance with the main rotor cyclic forces under particular combinations of slung cable length and load. As shown in Fig. 1, the tail cone region was reinforced to increase the vertical bending stiffness. The method of reinforcement, as shown in Fig. 2, was to use thick aluminum skins on the top and bottom of the tail cone shell. This reinforcement added 160 lb to the basic airframe structural weight.

A preliminary analysis showed that bonding uniaxial layers of boron/epoxy strips to 7075-T6 aluminum stringers would save 130 lb and achieve the same stiffness requirements. In addition, as shown in Fig. 3, the use of reinforced aluminum stringers permits a conventional rivet attachment to the aircraft outer skins so that minimum modification and conventional tooling would be required to save the 130 lb in stiffening material.

As a result, a program was conducted under NASA Contract NAS1-10459 to design and evaluate the strength characteristics of the boron/epoxy reinforced stringers for the CH-54B helicopter. This phase of the effort consists of design analysis of the tail cone, developing fabrication techniques, and evaluating static and fatigue strength data.

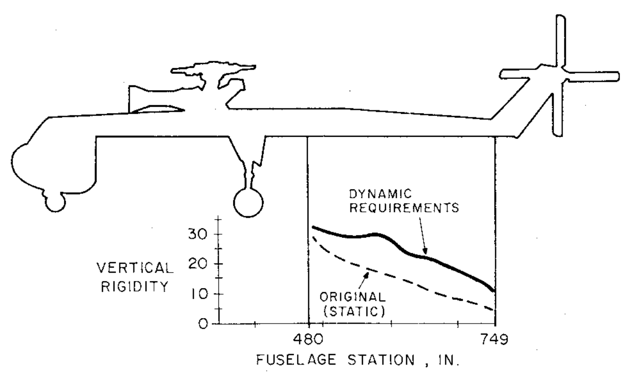

Fig. 1 CH-54 Skycrane Helicopter.

Presented as Paper 72-392 at the AIAA/ASME/SAE 13th Structures, Structural Dynamics, and Materials Conference, San Antonio, Texas, April 10–12, 1972; submitted April 18, 1972; revision received August 21, 1972.

Index categories: Aircraft Structural Materials; Structure-Composite Materials (Including Coatings); VTOL Aircraft Dal sign.

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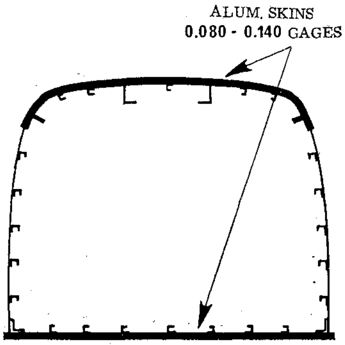

Fig. 2 Aluminum reinforcement to CH-54

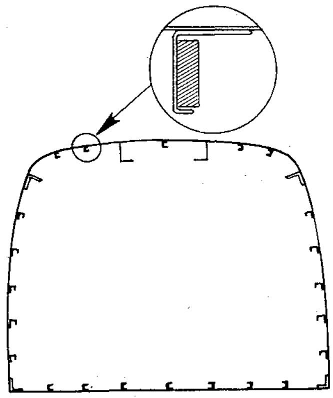

Fig. 3 Boron/Epoxy reinforced stringers.

Subsequent efforts will consist of fabricating a boron/epoxy reinforced stringer tail cone, conducting vibration and flight tests, and finally conducting a field service evaluation.

Structural Design

The structural integrity of the tail cone is maintained with or without the boron/epoxy reinforcement. Thermal expansion is not found to be a problem. Tapering the boron/epoxy reinforcement with fiber glass inserts solves the problem of load introduction to the stringers.

The boron/epoxy reinforced stringer arrangement, as shown in Fig. 4, was analyzed with and without the boron/epoxy reinforcement, and the structural integrity was maintained in all conditions. The analysis showed that modifications to assure safety were minor, and that structural integrity could be accomplished.

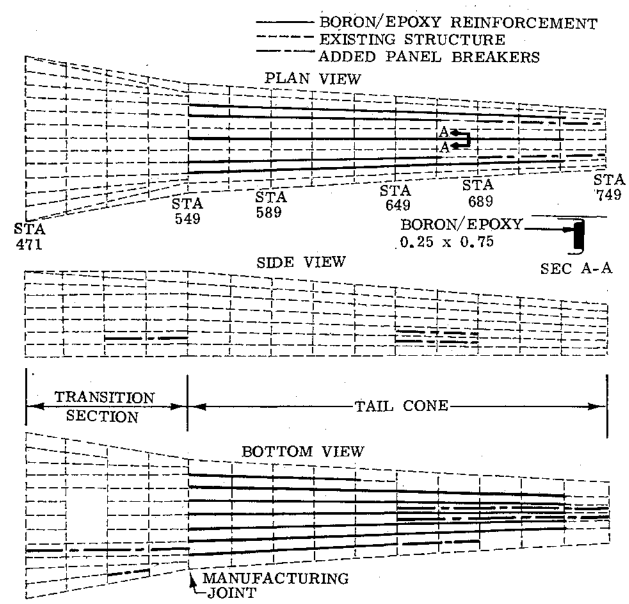

Fig. 4 CH-5B tail cone stringer modifications.

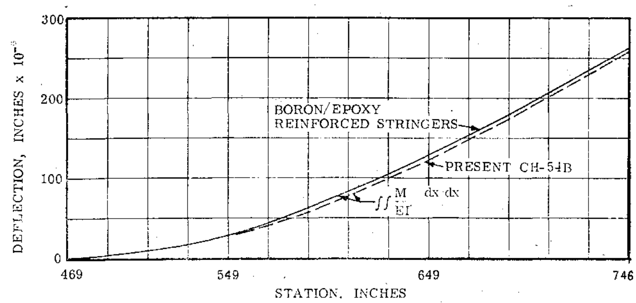

Fig. 5 CH-54B fuselage vertical deflection.

The boron/epoxy reinforced fuselage vertical stiffness was evaluated analytically and verified through test to assure it met the required characteristics of the current CH-54B. The verification is shown in Fig. 5.

The boron/epoxy (4 mils fibers in 3M's PR 279 matrix) is first layed up and cured. The boron/epoxy laminate strip is then bonded to the 7075-T6 aluminum stringer, using AF 126-2 film adhesive at 250° F. The film adhesive is 3–5 mils thick at final curing. The coefficient of expansion of the boron/epoxy is determined experimentally to be 2.14×10^{-6} in. in degrees F, whereas that of the aluminum is 13.0×10^{-6} in. in degrees F. Thus the critical condition is at the lower bound of the operating temperature range, being −65° F. An analytical evaluation (Fig. 6) showed that the induced loadings were well within the allowable load for the skin/stringer combination. The subsequent temperature testing showed excellent correlation with anticipated stresses as shown in Fig. 7.

In designing the boron/epoxy taper joint, various criteria had to be met. The taper had to be short enough to maintain the required tail cone stiffness yet be long enough to achieve low values of adhesive shear stress and basic stringer stresses. A computerized Sikorsky-developed program for the analysis and optimum design of bonded tapered joints was used to define the joint geometry. The method of analysis is a linear elastic step closed-form solution, and considers the nonlinear taper of the joint. The data input included the design-allowable adhesive shear stress and adherent direct stresses such that the geometry of the taper would result in a satisfactory stress field.

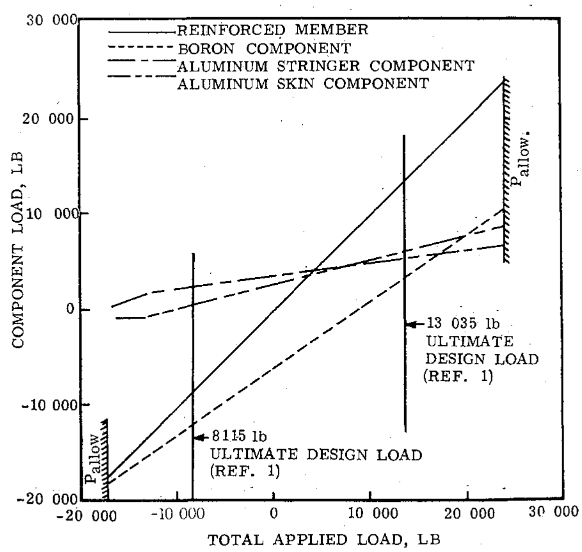

Fig. 6 Boron/epoxy reinforced stringer load vs total applied load for a 0.050-in. aluminum stringer at −65° F.

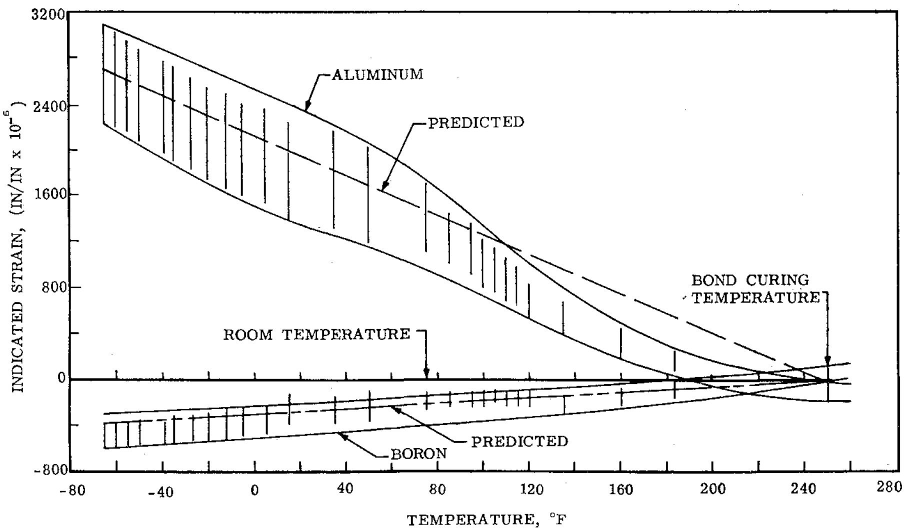

Fig. 7 Calculated and test results of induced thermal strains in boron/epoxy reinforced stringers.

To reduce the high-peak shear stresses still remaining at the end of the joint, two layers of 0° fiber glass/epoxy (1002-S) were introduced over the first two inches of the joint between the boron and aluminum, as illustrated in Fig. 8. This had the effect of introducing a "soft" insert at the joint end, thereby reducing the sudden discontinuity in stiffness. The taper designs include practical constraints, for instance, the minimum taper thickness and step size must be integer multiples of ply thickness.

The ply layup of the joints is shown in Fig. 8. The fiber glass/epoxy insert was investigated, since it seemed desirable to introduce the load as gradually as practical.

The analysis showed that fiber glass/epoxy inserts would reduce the peak shear stress to well within the limits of the adhesive strength (see Figs. 9 and 10). The design for the

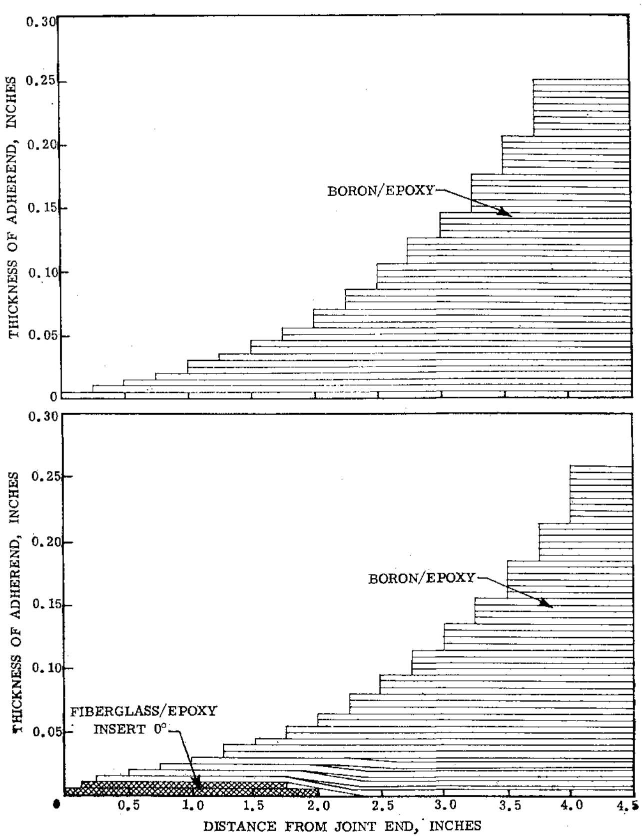

Fig. 8 4-in. tapered joint geometry.

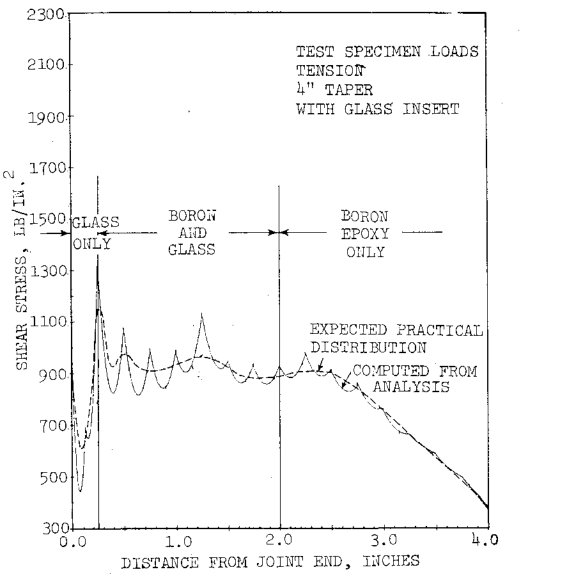

Fig. 9 Adhesive shear stress distribution in 4-in. tapered tensile joint—with glass insert.

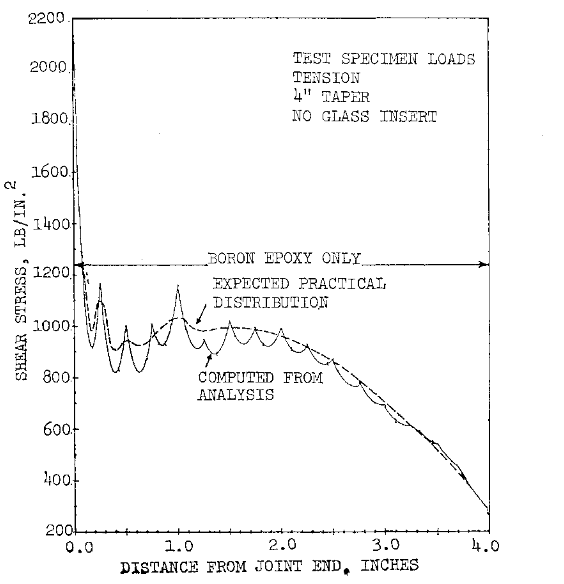

Fig. 10 Adhesive shear stress distribution in 4-in. tapered tensile joint—no glass insert.

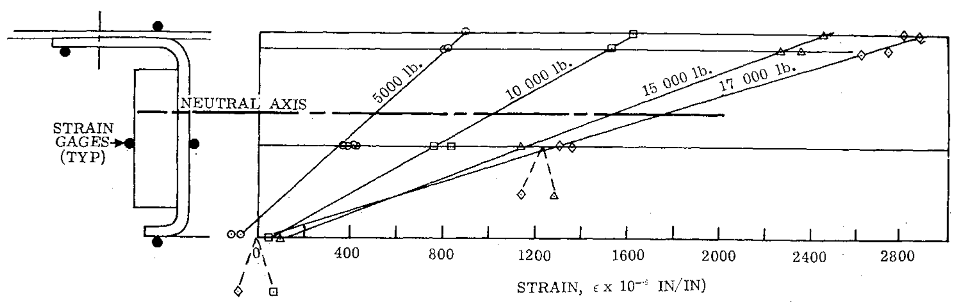

Fig. 11 Tensile load vs strain.

tapered ends therefore utilized the insert to improve the strength capability. The other design problems of static and fatigue strength were checked experimentally.

Structural Tests

Static and fatigue strength properties are found to be more than ample for the CH-54B design. The static testing consisted of tensile tests of boron/epoxy reinforced stringers with skin attached. The strains in the boron/epoxy stringer were recorded and are shown in Fig. 11.

The load into the stringer/skin combination was increased, and at about 17,000 lb the bond failed. A comparative test was made on an unreinforced stringer/skin and showed less strength. However, as shown in Fig. 12, the reinforced stringer is stronger than the nonreinforced, and both are greater than the ultimate strength required at the tapered end. Shear and compression tests were made with reinforced and non-reinforced stringers. The failed reinforced structures are shown in Figs. 13 and 14.

Both the current production aluminum and boron/epoxy reinforced shear panels experienced skin shear failures at the edge rivet holes and at the point of load introduction. The failure mode and load magnitude for both types of panels were essentially the same. The average failing load for the conventional aluminum shear panel was 25,500 lb whereas that predicted by analysis was 28,800 lb.

The two conventional design compression panels failed at loads of 23,300 and 22,900 lb with failure resulting from local crippling near the midpoint of the nonreinforced stringers. The two boron/epoxy reinforced stringer panels failed at loads of 34,500 and 29,500 lb, with failure resulting from local crippling of the reinforced stringer at the tapered end of the boron/epoxy reinforcement.

The predicted compression loads for the nonreinforced assemblies were 25,500 lb and 29,400 lb, respectively. The failure mode of the reinforced panel was predicted to be in the aluminum stringer at the termination of the boron/epoxy reinforcement, thereby permitting the use of conventional analytical formulas.

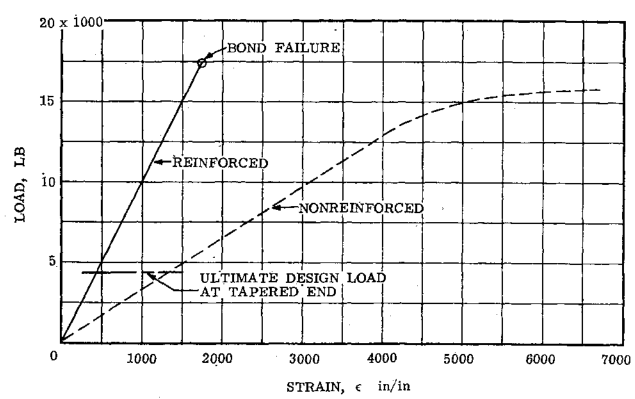

Fig. 12 Tensile load vs strain for reinforced and nonreinforced stringers.

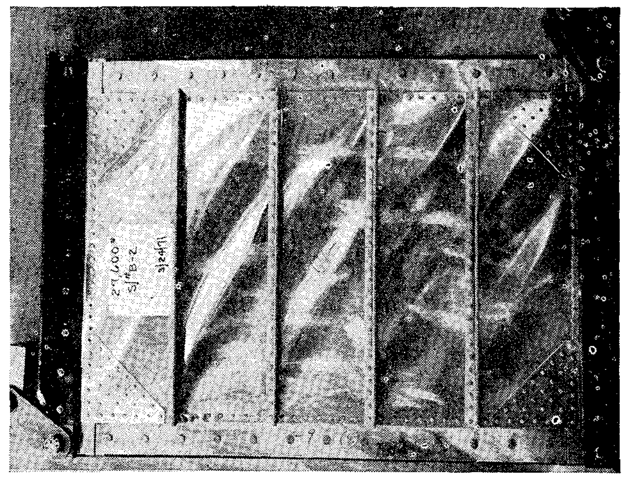

Fig. 13 Shear failure of boron/epoxy reinforced stringer test panel.

The fatigue design criterion for the air frame is that the boron/epoxy reinforced stringer have a life not less than four times the anticipated usage, which is approximately fifteen years of operation. The CH-54B flies 600–700 hr per year, so that this fifteen years encompasses 10,000 hr of life.

The fatigue stresses consist of two groups: The low stress/high cyclic stresses are ± 1750 psi, but occur only for a short duration of the flight regime and result in 364,000 cycles in a 10,000-hr total flying time. The high-stress low cycle is the result of a ground-air-ground cycling, and results in only 23,800 cycles for the 10,000 hr of flight.

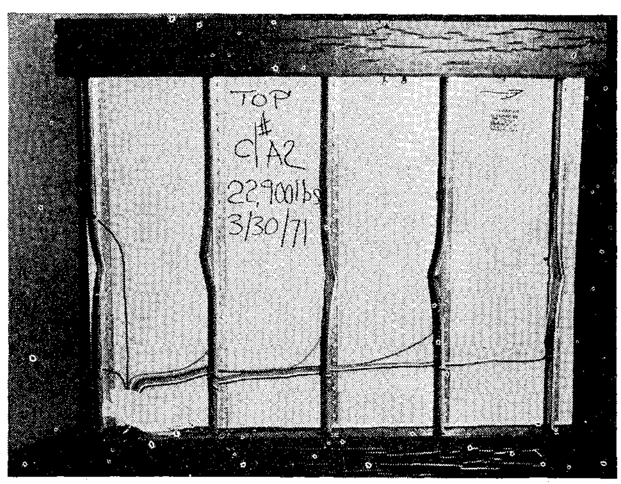

Fig. 14 Compression failure of nonreinforced test panel.

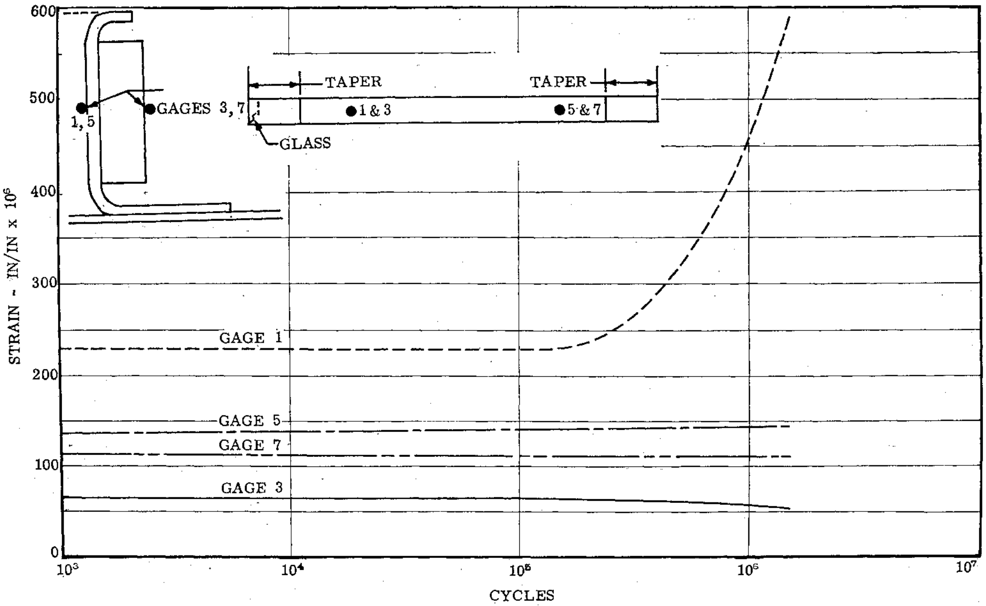

Fig. 15 Measured vibratory strain vs cycles for boron/epoxy reinforced stringer.

Table 1 Fatigue test results

Test no.	Boron/ epoxy reinforced	Clips at mid-point	Load schedule	Applied test cycles $\times 10^{-6}$	Remarks
1	no	yes	A	0.175	Test stopped after reaching required cycles
2	no	yes	B	0.365	Test stopped after reaching required cycles
3	no	yes	A	0.175	Test stopped after reaching required cycles
4	yes	no	A	0.159	Cracked stringer through attachment bolt hole
	yes	no	B	1.541	Test stopped at 1.5×10^6 cycles
6	yes	yes	C	0.175	Test stopped at required cycles
7	yes	yes	D	1.500	Test stopped at required cycles
8	yes	yes	C	0.127	Cracked stringer through attachment bolt hole
9	yes	yes	D	1.500	Test stopped at required cycles

All fatigue testing was done for an R value (minimum to maximum stress) of 0.10. Nine specimens were tested for four load schedules. The load schedules C and D represent the high stress/low cycle and low stress/high cycle, respectively. Schedules A and B are accelerated schedules of the previously mentioned conditions. A summary of the tests is shown in Table 1. As noted, the effect of holes from clips was tested.

The mode of failure noted on two of the nine test specimens was a gradual bond degradation wherein the strain in the stringers increased as the boron/epoxy became ineffective. However, it should be noted that the remaining combination carried the vibratory loads well into the range where the boron/epoxy became ineffective. The results of one of the tests are shown in Fig. 15. The results were that all boron/epoxy specimens exceed the factor of four on design life of 10,000 hr (4.1–7.3) with no strain deviation occurring (Fig. 16).

Summary

The boron/epoxy reinforcement stringers are effective in reducing weight for air frame stiffening, and have more than adequate strength for the structural integrity of the CH-54B.

By properly designing the tapered ends of the boron/epoxy stringers, the strength characteristics were more than adequate for the CH-54B structural design. The method of stiffening can save 130 lb in the air frame structure. The type of construction is such that it is readily adaptable to current aluminum construction, since conventional tooling and rivet attachments can be used.

The static strength properties of the bonded boron/epoxy reinforced stringer are equal to the normal construction. The fatigue strength is more than adequate for the CH-54B design, and further development in bonding is needed if greater fatigue strength is required.

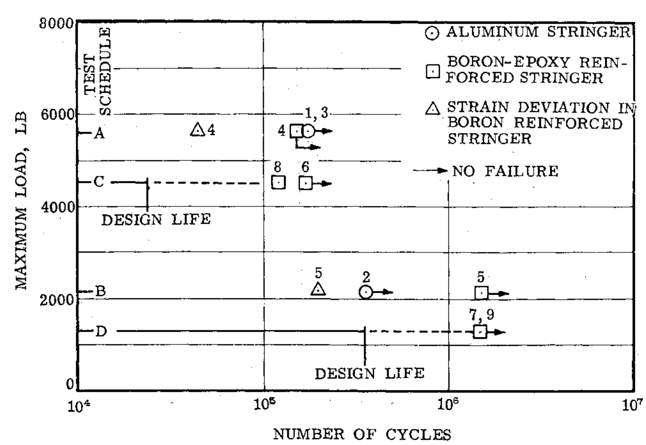

Fig. 16 Load/cycle test results for boron/epoxy reinforced stringers.