Structural Fiber Glass Aircraft Component-Program Results

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Several components were built with an external configuration similar to the horizontal stabilizer of the T2A Trainer aircraft. The program encompassed three phases: materials selection and processing, structural component design, and structural tests. Design included an analysis to obtain the best practical arrangement of the basic materials and also considered the production processes from both a cost and an ease-of-construction basis. The relatively low modulus of elasticity of most Fiber Glass compositions dictated a sandwich construction to meet the stiffness requirements of an aircraft lifting surface. The sandwich chosen was an integrally woven, corrugated core material in which the core is a physical part of the face sheets and not just bonded to them. Design data were developed for selected sandwich composites using edgewise compression and panel shear tests. The fabrication problems encountered were in the areas of accurate tooling and in maintaining the proper resin-to-glass ratio. Practicability is demonstrated by the structural efficiency and performance of the Fiber Glass stabilizers as compared with the T2A metal stabilizers, making use of the results from static, fatigue, and vibration tests.

Introduction

REQUIREMENTS now exist for a simple, lightweight, low-cost airplane that has low radar echo characteristics and that requires a minimum of logistic support. Reinforced plastic structures possess potential in this application, especially since the advent of developments such as 994-"S" glass and High Tensile Strength (HTS) finish.

The objective of this program was to show the practicability of a glass-fiber-reinforced plastic (GFRP) structure for aircraft use. It was reasoned that practicability of a GFRP structure could most rapidly and definitely be demonstrated by designing, fabricating, and testing a number of specimens of a representative aircraft component and comparing the weight, workmanship, strength, stiffness, cost, and other factors for these components with similar existing metal components. In this connection, a contract was awarded to North American Aviation, Inc. (NAA) to design and fabricate four GFRP stabilizers for the T-2A (T2J-1) airplane. The examination and structural tests of these stabilizers were performed by the Aeronautical Structures Laboratory (ASL) of the Naval Air Engineering Center (NAEC), Philadelphia, Pa. In order to have a basis of comparison, the NAEC procured four metal stabilizers on which tests were performed identical to those on the GFRP stabilizers.

The program was timed to provide confidence and initial design data for the Counter Insurgency (COIN) aircraft proposal program. To provide initial design data and the required confidence to consider building a complete airplane of GFRP prior to evaluation of industry proposals required a quickly executed program of greatest value. The program encompassed four phases: materials selection and processing, stabilizer design, stabilizer fabrication, and stabilizer testing. The problem areas and results of the testing phase are discussed in this paper.

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I. Materials Selection and Coupon Tests

Materials Formulations and Processing

Knowledge of the design requirements coupled with material properties was necessary to initiate optimization of potential candidate-material systems. Structural optimization techniques indicated the strength-to-weight advantages of sandwich-type construction, providing an initial starting point. The following variables were studied with the intent of achieving the maximum strength-to-weight relation while employing low-cost tooling and fabrication techniques.

The balanced strength of the 181 fabric in both the warp and fill directions minimized the selective orientation of plies necessary to achieve balanced mechanical properties. Excellent drapability of the long shaft-satin harness weave around extremely complex curvatures was also a significant advantage. Therefore, 181 fabric was chosen as the best type.

Unidirectional material exhibited remarkable mechanical properties; however, the major objection to these materials on this program was the learning time required for handling and processing unidirectional materials in large lay-ups. The use of unidirectional material does offer significant advantages with further processing development.

From a combination of glasses and glass finishes, 994-"S" glass with HTS finish was selected as the best for this program. This selection was based primarily on the increased modulus obtainable with the 994-"S" glass.

A choice of Epoxy 828 or its equivalent was made from several systems based on the wealth of mechanical properties data available coupled with ease of fabrication on low-cost tools with moderate cure schedules.

With the selection of epoxy resins as the optimum resin system for mechanical properties, a compatible catalyst system, consisting of an eutectic mixture of meta-phenylenediamine (Apco 320, RP-7A, Hardener "Z," etc.), was chosen for ease of handling, degree of cross-linking, decreased toxicity, moderate temperature requirements (200°–250°F) for complete reaction to achieve good mechanical properties in the final polymeric structure, and excellent strength retention up to 200°F.

Two basic sandwich-core materials were evaluated in this program. Glass-fabric honeycomb (MIL-C-8973, type I-B) was evaluated early in the program. Although aluminum honeycomb is a lighter core material than glass-fabric honeycomb core, the aluminum core was not used because of its radar reflectivity properties. The glass-fabric honeycomb core was eventually eliminated from the program because of its low facing-to-core bond area, the fact that it cannot be used with the wet vacuum-bag lay-up processing, and the requirement for the use of an adhesive system for a satisfactory structural sandwich.

The Raypan fluted core was finally selected as the core material to be used in this program. Therefore, most of the coupon tests of sandwich material were performed using some form of the Raypan core material. The greater efficiency of the triangular fluted core over the rectangular fluted core was shown during these coupon tests. The triangular fluted core in most of the high-axial-load applications was more efficient than the honeycomb core, primarily because the Raypan core material supports its share of the axial load. The major advantage of the Raypan sandwich over the honeycomb sandwich is the fact that the core is integrally woven to the faces, thus preventing facing-to-core bond failures. The Raypan core is also convenient for use with the wet vacuum-bag lay-up process selected for this program.

The coupon test program included both solid laminate and sandwich coupons to provide all of the necessary mechanical properties data. The configuration of the various coupons and the fabrication processing are shown in Table 1. The mechanical properties data obtained from these coupon tests and the various test methods used are shown in Table 2. The test results of Table 2 illustrate the superior mechanical properties obtainable with the new 994-"S" glass HTS fabric over the conventionally finished "E" glass-fabric materials regardless of the conditions investigated.

II. Structural Configuration

After the decision was made to construct a GFRP stabilizer, it became necessary to determine the best type of construction for the particular mechanical properties of the material. A box-beam optimization computer program was used to compare the following types of construction: 1) honeycomb sandwich—multispar, 2) solid skin—multispar, 3) stiffened panel—multirib, and 4) corrugated sandwich—multispar.

In order to arrive at a realistic comparison, the optimization program was run several times using various fixed spar spacings and realistic minimums for skin gages, facing thicknesses, and sandwich-core depths. For any practical configuration, the optimization program indicated a multispar type of construction with no preference between the honeycomb or the corrugated sandwich.

An examination of the mechanical properties of GFRP reveals several reasons for the choice of the multispar sandwich construction, which was shown to be optimum by the computer programs. The modulus of elasticity of GFRP varies roughly from one-third to one-half that of aluminum. Higher-modulus GFRP materials have been developed for special purposes, but these materials were not considered useful for a structure subjected to various loads in various directions. The low modulus associated with GFRP causes a severe loss of stiffness if the same type of construction is used for the GFRP component as for the metal component. To relieve this problem, the obvious choice is to use a sandwich construction, which can greatly increase the stiffness without a corresponding weight increase. Another mechanical property of GFRP which indicated the choice of sandwich construction was the linearity of the stress-strain curve. This linear characteristic is another factor tending to limit buckling of the skin panels at high loads. Faced with the fact that the skin panels must remain stable and be constructed of a low-modulus material, the use of sandwich construction was inescapable.

Several detail design problems were encountered as outlined below:

1) Main fuselage fitting. This area was the highest loaded area in the surfaces and the most difficult area in which to determine loads. Since the fuselage support fitting location could not be changed, a metal fitting was necessary for the main fuselage fitting on the stabilizer. A fan-shaped fitting, which was attached to the surfaces over a fairly large area, was devised. There were two reasons for this shape. One was the fact that the load was already distributed in the surface, and the other was the low bearing strength properties of GFRP.

Table 1 Coupon and element test specimen configuration[a]

Specimen no.	Type of test specimen	Material: Glass	Material: Weave	Material: Finish	Precured face sheets: One side	Precured face sheets: Both sides	No. of plies	Foam core insert density	Core config.	Cure cycle
1	Solid laminate	E	181	Volan "A"	...	...	12	...	...	180°F, 1 hr 250°F, ½ hr 325°F, 2 hr
2	Solid laminate	E	181	Volan "A"	...	...	12	...	...	180°F, 1 hr 250°F, ½ hr 325°F, 2 hr
3	Solid laminate	E	181	Volan "A"	...	...	12	...	...	180°F, 1 hr 250°F, ½ hr 325°F, 2 hr
4	Solid laminate	S	181	HTS	...	...	12	...	...	180°F, 1 hr 250°F, ½ hr 325°F, 2 hr
5	Solid laminate	S	181	HTS	...	...	12	...	...	180°F, 1 hr 250°F, ½ hr 325°F, 2 hr
6	Solid laminate	S	181	HTS	...	...	12	...	...	180°F, 1 hr 250°F, ½ hr 325°F, 2 hr
7	Sandwich	S	181	HTS	Yes	No	2 each face	4	NA-302-2	180°F, 1 hr 225°F, 6 hr
8	Sandwich	S	181	HTS	Yes	No	2 each face	4	NA-302-2	180°F, 1 hr 225°F, 6 hr
9	Sandwich	S	181	HTS	Yes	No	2 each face	4	NA-302-2	180°F, 1 hr 225°F, 6 hr

[a] The following information applies to all panels: resin system = Epon 828 + 17 pts Apco 320 + 2 pts Z-6040; cure pressure = 12.5 ps, vacuum bag.

Table 2 Coupon and element and mechanical properties

Specimen no.[a]	Test method 1101 (FTM-STD-406) Machine speed, 0.250 in./min Tensile strength, psi × 10^{-3} (conditioning)				Test method 1042 (FTM-STD-406) Machine speed, 0.250 in./min Interlaminar shear (unsupported) in psi (conditioning)				Test method 1042 (FTM-STD-406) Machine speed, 0.250 in./min Interlaminar shear (supported) in psi (conditioning)				Test method 1021 (FTM-STD-406) Machine speed, 0.250 in./min Edgewise compression in psi × 10^{-3} (conditioning)			
	1 (Dry)	2 (Wet)	3 (+165)	4 (−65)	1 (Dry)	2 (Wet)	3 (+165)	4 (−65)	1 (Dry)	2 (Wet)	3 (+165)	4 (−65)	1 (Dry)	2 (Wet)	3 (+165)	4 (−65)
"E" glass laminate																
1	70.5	59.6	58.2	75.1	816	772	695	967	2158	1876	1872	1889	32.6	36.5	32.4	41.8
2	67.7	53.9	51.3	70.2	843	1084	590	1015	1898	1831	1613	1554	36.2	36.4	35.1	45.1
3	67.7	59.6	55.9	70.5	1095	736	706	1132	2100	1632	1826	2780	38.2	38.0	38.0	...
Average	68.6	57.7	55.2	72.0	918	864	664	1071	2053	1780	1770	2074	35.8	37.1	35.1	43.5
"S" glass laminate																
4	102.1	88.8	87.5	109.4	1845	1910	1680	3409	3630	3799	3307	3367	64.9	66.8	58.5	60.6
5	101.2	94.5	90.5	110.2	1680	1614	1925	2903	3510	3981	3407	3843	71.1	64.9	46.9	83.9
6	108.2	97.0	88.5	118.5	2327	1551	2080	...	4045	3815	2661	...	63.2	63.5	48.4	62.9
Average	103.8	93.4	88.9	112.3	1924	1692	1862	3156	3725	3865	3125	3605	66.4	65.1	51.2	69.1

Specimen no.[a]	Test method (R5.2.3) MIL-STD-401 Machine speed, 0.025 in./min Flatwise tensile in psi (conditioning)				Test method (R 5.1.4) MIL-STD-401 Machine speed, 0.05 in./min Flatwise compression in psi (conditioning)				Test method (R 5.2.1) MIL-STD-401 Machine speed, 0.05 in./min Edgewise compression in psi × 10^{-3} (conditioning)				No spec. method applicae Machine speed, 0.25 in./min Lengthwise tensile in psi × 10^{-3b} (conditioning)			
	1 (Dry)	2 (Wet)	3 (+165)	4 (−65)	1 (Dry)	2 (Wet)	3 (+165)	4 (−65)	1 (Dry)	2 (Wet)	3 (+165)	4 (−65)	1 (Dry)	2 (Wet)	3 (+165)	4 (−65)
"S" glass RDI core; sandwich																
7	411.2	...	410.0	437	493.7	451.6	424.9	604.3	43.8	34.0	32.8	46.5	106.4	...	...	...
8	468.7	...	445.0	438	516.6	446.5	540.7	629.8	40.4	39.4	38.6	43.6	107.2	...	...	...
9	...	...	...	...	508.9	463.2	440.2	571.4	39.5	35.9	34.4	45.7	...	...	...	...
Average	439.9	...	427.8	421	506.4	453.8	468.6	601.8	41.3	36.4	35.3	45.3	106.8	...	...	...

[a] All specimens were fabricated using materials and processes as called out per NAA process specification, HA605-001: "Structural reinforced plastic, horizontal stabilizer, fabrication of," dated September 10, 1963.
[b] Flute thickness was not used in calculations.

In order to alleviate this latter problem, metal plates were bonded in the surfaces to obtain more bearing strength. These were later replaced by built-up GFRP plates, as it was found difficult to bond in the metal plates without introducing severe local problems.

2) Forward fuselage fitting. This was a pinned joint made entirely of GFRP using both woven and unidirectional material. The design of this fitting presented no problem.

3) Elevator hinge fittings. It was required that two of these be metal and the other GFRP. The two metal fittings were essentially production parts and were easily attached to the stabilizer. The outboard fitting was made of GFRP and was an integral part of the outboard rib. Both unidirectional and woven cloth were used in this construction.

4) Access doors. Although the metal stabilizer has no access doors, two structural doors were required in the GFRP stabilizer to prove their feasibility. Solid GFRP lands were built into both of the surfaces and the door to provide sufficient bearing strength to transfer the load from the surface to the door and back again.

III. Structural Fabrication

The fabrication techniques for the stabilizer were selected to satisfy several requirements of the development program. The primary consideration was to achieve the lowest-cost tooling and processing that would not unduly compromise structural reliability. The selected tooling concept had to be one that would maintain accuracy and processing control. The selection of the Epoxy 828 resin and the Apco 320 catalyst system required hand processing. With the required resin control and hand impregnation, the tools must allow for hand rub-out. An alternate to this process would be matched metal tools, which would increase the tooling expense substantially. Therefore, simple surface tooling and vacuum-bag processing were selected.

IV. Structural Test and Evaluation

The main structural factors that should be considered in such a test and evaluation program are the following:

1) General factors: *weight and performance,* workmanship, aerodynamic smoothness, growth potential, procurability, and cost.

2) Operational service factors: *vibration and damping properties*; *static strength, structural efficiency, and stiffness*; *reliability* (*fatigue strength*); shock and impact properties; fail safe; durability; vulnerability (structural).

3) Nonoperational service factors: maintainability (structural); repairability; storage, ground handling, and transport.

The four factors in italic type were investigated in this program by the use of results obtained from the tests shown in Table 3. The other 12 factors were investigated briefly by analytical studies, a survey of the literature, or by some preliminary tests performed at NAA. Both NAA and the NAEC expect to perform or sponsor work on all of these factors to obtain more definitive information. The effects of temperature and creep were not investigated in this program since the requirements pertain to a low-speed airplane.

Table 3 Test program

Jig 1
Vibration survey of metal stab. 1
Vibration survey of metal stab. 2
Vibration survey of GFR plastic stab. 2
Vibration survey of GFR plastic stab. 3
Hinge-calibration and static test of metal stab. 1
Hinge-calibration and static test of metal stab. 2
Fatigue test of metal stab. 3
Fatigue test of metal stab. 4
Jig 2
Hinge-calibration and static test of GFR plastic stab. 1
Hinge-calibration and static test of GFR plastic stab. 2
Fatigue test of GFR plastic stab. 3
Fatigue test of GFR plastic stab. 4

Weight and Performance

A comparison of the weights of the GFRP stabilizers is as follows:

Metal stabilizer No.	Metal stabilizer Wt, lb	GFRP stabilizer No.	GFRP stabilizer Wt, lb
1	59	1	93
2	59	2	69
3	60	3	68
4	59	4	69

The weight of the four metal stabilizers ranged between 59 and 60 lb. For the GFRP stabilizers, the first specimen weighed 93 lb (58% overweight compared to metal stabilizer 2). After delivery of the first GFRP stabilizer, NAA instituted a weight-reduction program with the result that the next three GFRP stabilizers (before any rework was done) weighed from 68 to 69 lb (17% overweight) and had a weight variation as consistent as for the metal stabilizers.

In this program, the designer was forced to use GFRP in an inefficient manner because of a number of restrictions. It is conceivable that elimination of some of these restrictions could eliminate the overweight of approximately 10 lb which exists, and this leads to the conclusion that, based on the results of this program, a GFRP stabilizer can be fabricated with no weight penalty over a metal structure. A recent study for a GFRP airplane yielded a gross-weight reduction of approximately 8% over the metal counterpart.

Vibration and Damping Properties

The tests for vibration and damping properties, as well as the other test reported herein, were performed at standard conditions with all stabilizers in the unpainted condition. The test of each stabilizer was performed with the stabilizer mounted on representative fuselage support fittings, which were attached to a rigid abutment. Two sets of support fittings were installed to permit the simultaneous testing of two stabilizers. The stabilizers were all left-hand stabilizer halves, mounted right side up.

As shown by the test program in Table 3, the sequence of tests for each stabilizer was as follows: vibration survey, hinge-calibration tests, preliminary run to measure hinge loads, and the static or fatigue test to failure. The elevator was installed only during the preliminary run to measure hinge loads. For either the static or fatigue test to failure, the elevator was removed and the elevator loads applied to the hinge brackets.

In the vibration survey, the stabilizers were excited by either an electromagnetic shaker or a dual-voice-coil speaker. The exciter was located at one of three locations: tip, midspan at the leading edge, or midspan at the center of the stabilizer.

In some cases, the vibration survey was performed both with and without a constant load applied to the stabilizer. The purpose of the constant load was to determine the effect on structural damping of joint slippage. A constant up-load of 300 lb was applied by means of a bungee chord wrapped around the stabilizer just inboard of the outboard hinge fitting.

The motion of the structure was monitored by 12 Endevco-type 2245 accelerometers, whose outputs were recorded on an oscillograph. Decay traces were obtained to determine damping constants at the various resonances.

The resonant frequencies and damping constants are summarized in Table 4. The damping constants correspond to the logarithmic decrement determined by the decay-rate method. With regard to resonant frequencies, examination of the information in Table 4 reveals the following:

1) A comparison of two identical stabilizers of each type shows that the two GFRP stabilizers compared with each other more closely than did the metal stabilizers.

2) In the first mode, the average resonant frequency for the GFRP stabilizers was slightly less (8%) than the average value for the metal stabilizers, but in the other two modes, the average value for the GFRP stabilizer was appreciably lower (23 and 27%, respectively).

Table 4 Comparison of resonant frequencies and damping constants[a]

Mode	Type	No load: Metal stab. no. 1	No load: Metal stab. no. 2	No load: GFR plastic stab. no. 2	No load: GFR plastic stab. no. 3	300-lb load: Metal stab. no. 2	300-lb load: GFR plastic stab. no. 3
		Resonant frequencies, cps					
1	Fundamental	17.9	21.7	18.0	18.6	19.8	18.8
		(19.8)		(18.3)			
2	Second bending	70.3	77.8	57.4	57.2	72.3	56.5
		(74.1)		(57.3)			
3	Torsional	110.2	115.9	81.7	82.6	107.2	83.1
		(113.1)		(82.2)			
		Damping constants					
1	Fundamental	0.100	0.065	0.048	0.037	0.068	0.076
		(0.083)		(0.043)			
2	Second bending	0.054	0.029	0.039	0.033	0.039	0.042
		(0.042)		(0.036)			
3	Torsional	0.034	0.019	0.036	0.027	0.120	0.075
		(0.027)		(0.032)			

[a] Values in parentheses are average values.

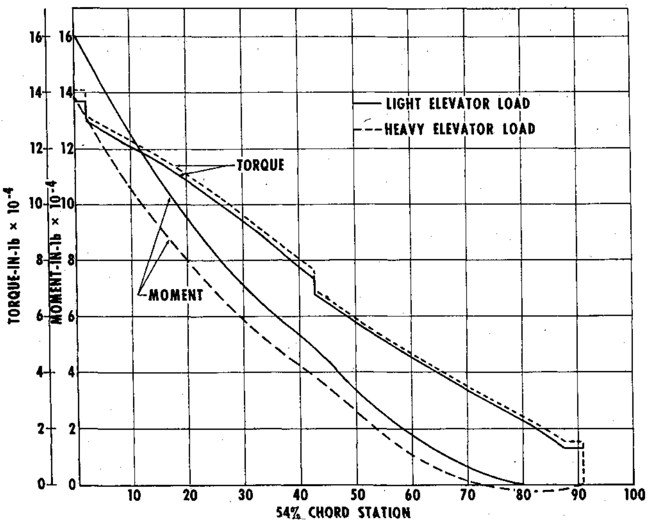

Fig. 1 Limit test bendng and torsion.

3) The addition of a constant load had a negligible effect on the natural frequency of both types.

With regard to the damping constants, an examination of the last six columns of Table 4 reveals the following:

1) Again, the GFRP stabilizers yielded more consistent results when compared with each other than did the metal stabilizers.

2) In the first two modes for the unloaded case, the average damping constant for the GFRP stabilizers was appreciably lower (48 to 14%, respectively) than the average value for the metal stabilizers; in the third mode, however, the average value for the GFRP stabilizers was appreciably higher (18%).

3) For the loaded case, the results were as follows. For the metal stabilizers, considering only values for stabilizer 2, the addition of the constant load increased the damping constant in the first two modes by 5 and 35%, respectively, and in the third mode by 530%. For the GFRP stabilizers, considering only values for stabilizer 3, the damping constants in the first two modes increased by 105 and 27%, respectively, and in the third mode by 180%. Comparing the results for the two types, the damping constant was higher for the GRFP stabilizer in the first and second modes by 12 and 8%, respectively, and in the third mode the damping constant was lower by 38%.

The preceding results indicate that the GFRP stabilizers exhibited approximately the same natural frequency in the first mode but an unfavorable trend in two cases. One case

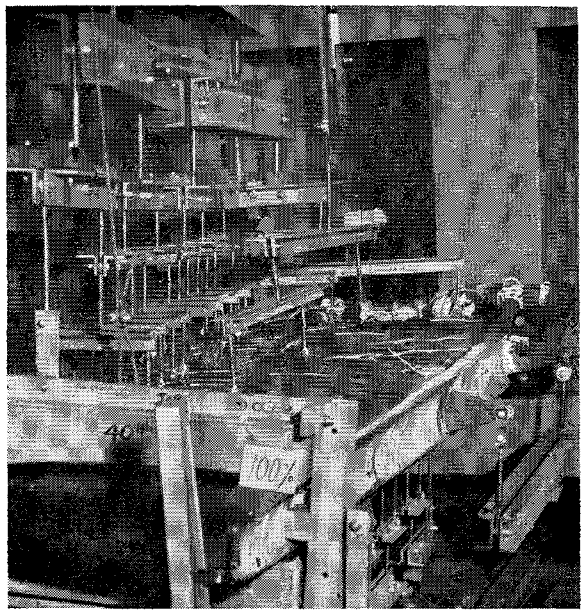

Fig. 2 Static test setup.

was the lower natural frequency in the second and third modes, and the other case was the lower damping constant in the third mode of the loaded case. However, these unfavorable values are not critical. Vibration and damping were not considered in the design concept, and, conceivably, when properly considered in a future design, vibration and damping properties could be improved if necessary. Vibration specialists do not attach much significance to the damping constants obtained in this manner.

The results of the concentrated load on damping were unexpected in two cases. It was expected that its effect would be to reduce the damping of the metal stabilizers and to have a negligible effect on the GFRP stabilizers. Both beliefs were violated. A more thorough study is required to obtain better and more conclusive data on damping.

Static Strength

These properties were determined by comparing the behavior of the GFRP and metal stabilizers under static tests. The stabilizers were mounted on an abutment as described for the vibration tests, and aerodynamic loads corresponding to NAA Condition 1235 were applied.

Condition 1235 was selected because it was critical for the GFRP stabilizer and was the failing load test condition used

Table 5 Static-test results for T-2A stabilizers

	Metal stabilizers		Glass-fiber-reinforced plastic (GFRP) stabilizers						
	Specimen no.								
Parameter	1[a]	2	1	2	3	2a	2b	2c	4a
Weight, lb[b]	59	59	93	69	68	69	73	73	69
Strength, % of metal stab. load (MSL)	98[c]	100[d]	136[e,f]	70[e]	76[d]	89[d,g]	78[d]	108[d]	124[d,h]
Strength-weight ratio compared to metal stab. 2	0.97	1.00	0.86	0.59	0.66	0.76	0.62	0.88	1.06
Tip deflection, in.[i]	4.65	4.41	3.65	4.10[j]	3.27[j]	3.20	2.43	2.62	3.10
Max. twist,[k] deg	4.70	5.4	4.60	6.55[j]	7.60[j]	7.80	8.20	7.00	7.90

[a] This was a reworked, used stabilizer.
[b] Weight of metal stabilizers was with paint removed.
[c] Failed with low elevator load (−2360-lb limit) on hinge brackets.
[d] Failed with high elevator load (−2797-lb limit) on hinge brackets.
[e] Failed with low elevator load (−2360-lb limit) on metal elevator.
[f] After a nonrepresentative repair was made, a static strength of 139% of MSL was achieved.
[g] In the second static test, after a representative repair was made, a strength of 98% of MSL was obtained; in the third static test, after another representative pair, strength of 97% of MSL was obtained.
[h] This stabilizer had previously been fatigue tested.
[i] Tip deflection of rear spar at 100% limit load.
[j] Values obtained by extrapolation to 100% limit load.
[k] Maximum twist at 100% limit load.

Table 6 Shear test panel configuration[a]

Specimen no.	Facing plies		Precured face sheets		Foam core insert density, lb./ft^3	Total load	q, lb/in.	fs, psi
	Warp dir. next to core	Warp dir. exterior ply	One side	Both sides				
10	0	None	Yes	No	4	4,600	840	21,000
11	0	None	Yes	No	4	5,100	895	23,300
12	0	None	Yes	No	4	4,590	840	21,000
13	45	0	Yes	No	4	9,750	1780	29,700
14	45	0	Yes	No	4	10,150	1855	30,900
15	45	0	Yes	No	4	9,700	1770	29,500
16	None	None	No	No	None	1,730	315	15,700
17	None	None	No	No	None	1,530	278	13,900
18	None	None	No	No	None	1,100	200	10,000
19	0	None	Yes	No	None	4,200	770	19,200
20	0	None	Yes	No	None	4,020	735	18,400
21	0	None	Yes	No	None	4,080	745	18,600
22	0	0	Yes	Yes	None	6,370	1160	19,400
23	0	0	Yes	Yes	None	6,040	1100	18,400
24	0	0	Yes	Yes	None	6,400	1170	19,500

[a] The following information applies to all panels: Material: 994-"S" glass; 181 weave, HTS finish, NA2-302-2 RDI core; Resin system: Epon 828 + 17 pts Apco 320 + 2 pts Z-6040; Cure cycle: heat 180°F 6 hr at 230°F with 12.5 psi vacuum bag pressure.

by NAA for the metal stabilizer. Condition 1235 provided a critical combination of bending and torsion. This test condition is a positive-high-angle-of-attack condition with positive buffet $V_e = 300$ knots at $h = 6000$ ft and a limit load factor of 7.5 at the airplane c.g. The test shears and moments are shown in Fig. 1. The bending and torsion values have positive signs indicating compression on the upper surface and nose-up torsion.

The setup for the static tests is shown in Fig. 2. Loads were applied through tension pads cemented to the stabilizer surfaces. The tension pads were gathered by means of levers to two pull-off points, at which locations loads were applied by hand pumps and hydraulic jacks. Loads were measured with dynamometers.

Each GFRP stabilizer was instrumented with approximately 52 channels of strain gages consisting of single gages, dual gages, and rosettes. On the metal stabilizers, strain gages were installed only on the elevator hinge fittings and only on stabilizers 1 and 2. Deflections were measured by means of dial gages and a wire deflection system. The strain-gage locations are shown in Fig. 3 and the deflection-point locations in Fig. 4. Strain and deflection measurements were recorded at progressively higher load levels, and after each load level the load was reduced to a reference load of 20% limit load to record permanent set.

The static strengths of all stabilizers are summarized in Table 5. These strengths are expressed as a percent of the metal stabilizer load (MSL) for metal stabilizer 2. Besides the original GFRP stabilizers 1, 2, and 3, Table 6 includes results for four additional GFRP stabilizers, three (2a, 2b, and 2c) that were reworks of the original static-test stabilizers, and one

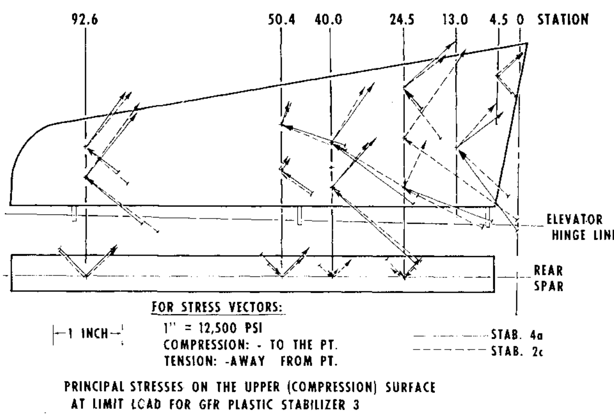

Fig. 3 Magnitude and direction of principal stresses.

(4a) that was a rework of a fatigue-test stabilizer. Because of the changes that were made in design and loading, the GFRP stabilizers that are comparable to metal stabilizer 2 are GFRP stabilizers 3–4a.

Table 3 shows that progressively higher strengths were achieved, as is normal in a development program; however, many of the failures, such as that of GFRP stabilizer 2b, were caused by unbonded or poor joints between the surfaces and the spar or rib capstrips.

In Table 7, the final improved versions of the GFRP stabilizers are compared with metal stabilizer 2. Both specific and average values are shown for the GFRP stabilizers. The static strengths of the GFRP stabilizers were, on the average, 16% higher than metal stabilizer 2.

A comparison of structural efficiency is shown by means of the strength-weight ratio. The average structural efficiency for the GFRP stabilizers was approximately the same as that for the metal stabilizers.

With regard to stiffness, the values in Table 7 show that GFRP stabilizers were, on the average, 35% stiffer in bending but 38% more flexible in torsion than metal stabilizer 2.

A comparison of the spanwise distribution of bending deflection and twist is shown in Fig. 5. It can be seen that most of the twist for the GFRP stabilizer occurred in the outer-span region where there was only one ply of cloth on each side of the Raypan core. The additional flexibility in torsion of the GFRP stabilizer is not considered to be critical because of the low speed of the airplanes under consideration; however, torsional stiffness can easily be increased by a change in the ply lay-up direction, which on these stabilizers was in the spanwise direction. The plot of load vs tip deflection and tip set in Fig. 6 shows that the GFRP stabilizers exhibited no unusual results such as creep effects.

The stress distribution for the upper (compression) surface of the GFRP stabilizers at limit load is shown in Fig. 3. The

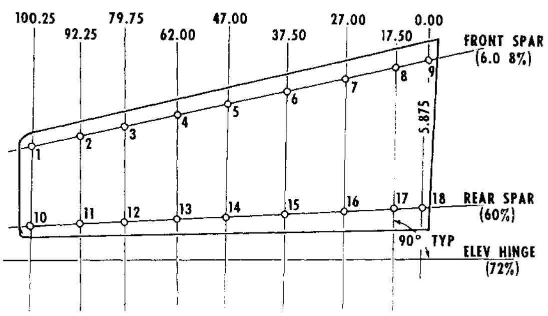

Fig. 4 Deflection-point locations.

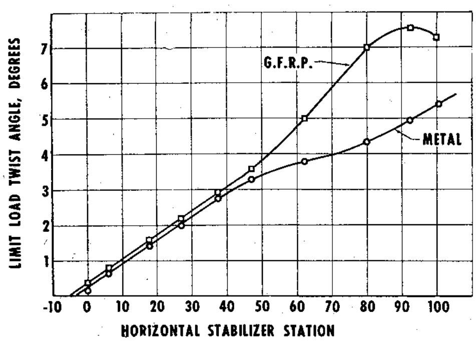

Fig. 5a Comparison of spanwise twist at limit load.

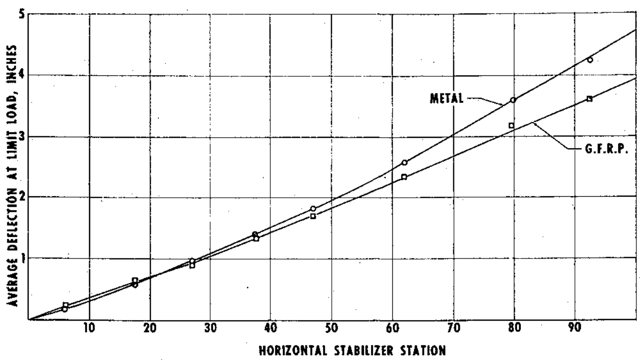

Fig. 5b Comparison of spanwise bending at limit load.

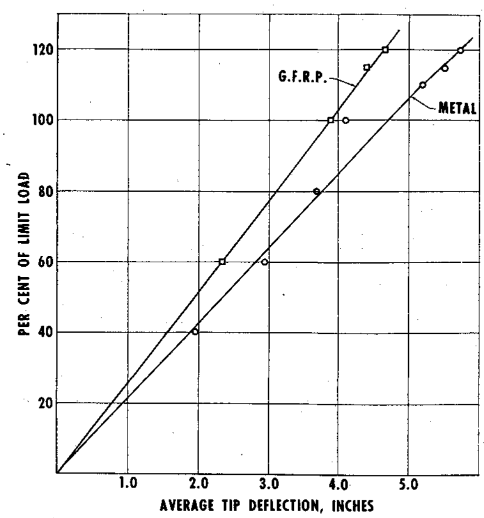

Fig. 6a Load vs tip deflection (station 100.25).

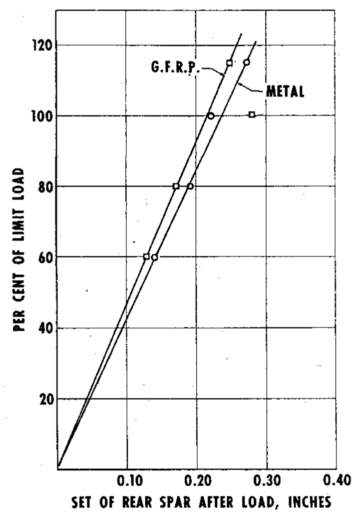

Fig. 6b Load vs set at the tip.

magnitude and direction of the principal stresses are shown by the vectors originating from, or directed to, each rosette-gage location. A modulus of elasticity of 3.5×10^6 psi was assumed in transforming the measured strain into stress. For GFRP stabilizer 2c, the maximum principal stress at limit load was 20,000 psi and the extrapolated, maximum principal stress at failure was 28,000 psi. The primary failure in this case was an adhesive band-joint failure. The general panel-buckling failure of stabilizer 4a occurred at a projected stress level of 31,800 psi. Figures 5, 7, and 8 show axial load strain-gage data from the several GFRP stabilizer tests. Points are also plotted which were calculated during the design analysis of the horizontal stabilizer. Figure 9 plots the axial load gages along the leading edge. Figure 7 plots the axial load gages along the center spar from stations 13 to 40. Figure 8 plots the axial load gages along the rear spar.

Reliability (Fatigue Strength)

Structural reliability was determined by means of a fatigue test using a spectrum-type loading. The test condition and limit loads for the fatigue test were identical to those for the static test. The load spectrum was the positive portion of spectrum A of specification MIL-A-8866[1] with one change. The change was that the cycles in the specification at the highest load level of 125% limit load were applied at the next lower level of 115% limit load. This change was made to obtain sufficient life to permit a comparison. Spectrum A is not a structural requirement for these stabilizers. It was used here because it represented the best simple spectrum available for comparison purposes.

The setup for the fatigue tests was identical to that for other static tests except that the two pulloff loads were combined into one to simplify load control during cycling. A load-control system and a programer of the fixed-sequence type were

Table 7 Comparative static strength, weight of stiffness and metal and GFRP stabilizers[a]

	Metal stabilizer		Glass-fiber-reinforced plastic (GFRP) stabilizers					
	Specimen no.							
	2		2c		4a		Average values for specimens 2a and 4a	
Parameter	Actual	Relative	Actual	Relative	Actual	Relative	Actual	Relative
Weight, lb	59	1.0	73	1.24	69	1.17	71	1.20
Strength	...	1.0	...	1.08	...	1.24	...	1.16
Strength-weight ratio	...	1.0	...	0.88	...	1.06	...	0.97
Tip deflection, in.	4.41	1.0	2.62	0.59	3.10	0.70	2.86	0.65
Max. twist, deg	5.40	1.0	7.00	1.30	7.90	1.46	7.45	1.38
Corrected strength weight ratio[b]	...	1.0	...	0.96	...	1.16	...	1.06

[a] Based on indicated values for metal stabilizer 2.
[b] Reduction of GFRP stabilizer weight of 6 lb; 4 lb overweight of metal root fitting; 2 lb for weight penalty induced by inspection doors.

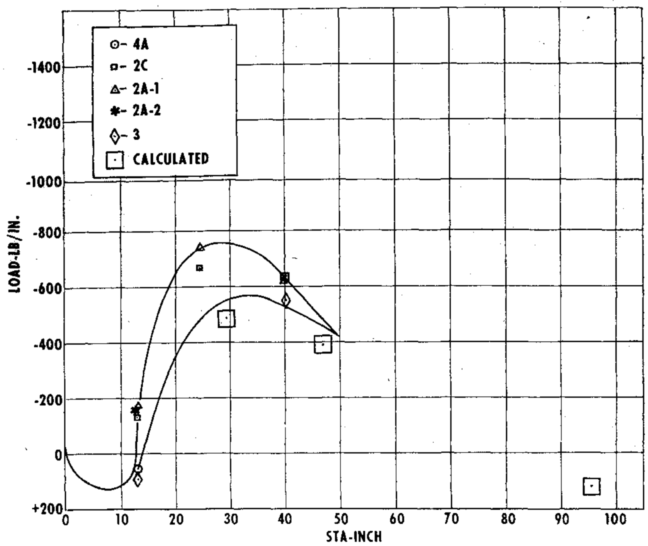

Fig. 7 Midchord spanwise skin load.

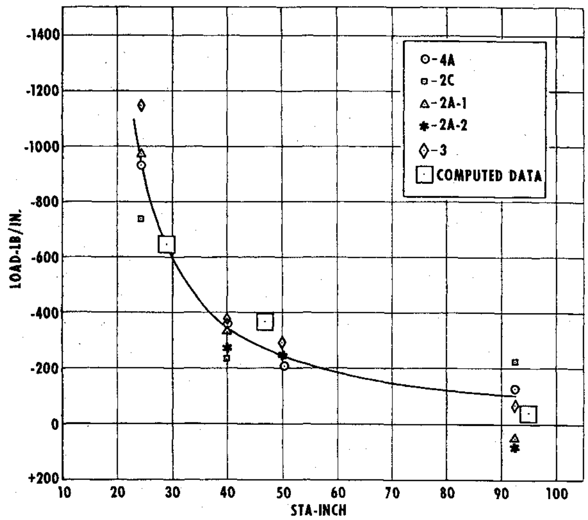

Fig. 8 Trailing edge spanwise skin load.

Table 8 Fatigue: test results

Specimen	Weight, lb	Fatigue life in 20-hr blocks	Average fatigue life in 20-hr blocks
Metal 3	60	55	46
Metal 4	59	37	
GFRP 3[a]	69	...	357
GFRP 4	69	434	
GFRP 3[b]	69	280	

[a] This specimen had previously been subjected to a static test.
[b] This specimen had previously been subjected to static and fatigue tests. Another fatigue test remains to be performed.

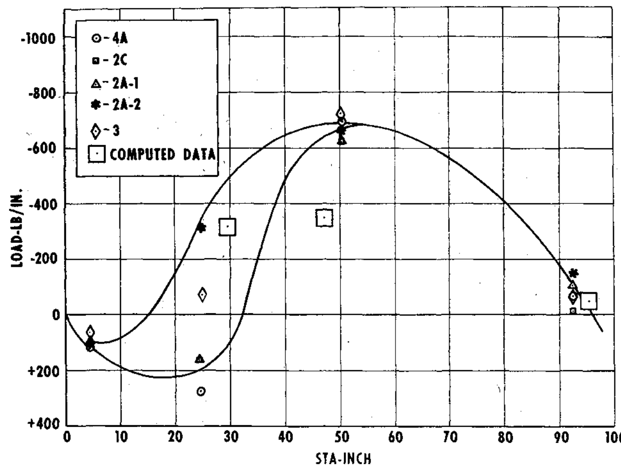

Fig. 9 Leading edge spanwise skin load.

added to load the structure automatically. Each block was equivalent to 20 hr (840 cycles) of maneuvering flight. On the GFRP stabilizers, strain readings were recorded after every block for the first three blocks. Thereafter strain readings were recorded at various larger increments. No strain measurements were taken on the metal stabilizers.

The results of the fatigue tests are shown in Table 8. GFRP stabilizer 4 withstood 434 blocks, and GFRP stabilizer 3b withstood 280 blocks, for an average life of 357 blocks. The average life for the two metal stabilizers was 46 blocks. The life of 356 blocks remains $7\frac{3}{4}$ times the average life for the metal stabilizer.

Although the preceding results indicate that GFRP structures may have good fatigue properties, much design data on materials and simulated structures, especially those fabricated with 994-"S"glass and HTS finish, are required to enable a structure to be designed with a reasonable degree of reliability. For example, it appears that this material has good structural reliability because of its high tensile-stress-to-compression-stress ratio, low notch sensitivity, and slow crack propagation; however, data are needed to define the degree to which these attributes are realized so that they can be properly considered in the design of a structure.

V. Conclusions

In this paper, results are presented of some preliminary tests and analytical studies that were directed toward examining GFRP structures with regard to the main structural factors believed to be important in structural design. These preliminary results indicate that GFRP structures are practical when compared to metal structures since they show some advantages for factors such as weight, aerodynamic smoothness, reliability, shock and impact properties, resistance to corrosion, vulnerability, and maintainability. These advantages make a low-speed GFRP airplane attractive. The main weaknesses of GFRP structures are low resistance to moisture and weathering.

One deterrent to the immediate embarkation on a GFRP airplane design is the lack of basic design data in all of the factors considered. These design data are required for simple material specimens, structural specimens, and full-scale structures. Only after sufficient design data of this nature have been accumulated can a structure be designed with a fair degree of reliability.

Reference

[1] "Airplane strength and rigidity. Reliability requirements, repeated loads, and fatigue," Specification MIL-A-8866 (May 18, 1960).