JOURNAL OF AIRCRAFT
Vol. 33, No. 3, May–June 1996

Sailplane Carry-Through Structures Made with Composite Materials

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The carry-through structure, which joins and transmits loads between aircraft wings and fuselage, is a box-and-beam configuration made from composite materials in the RP series of all-composite sailplanes. Increases in the size and weight of these aircraft increased the complexity of their carry-through structures. RP-1 has an interference-fit, box-and-beam configuration that was repeated in RP-2, but it failed during static testing because of peeling of the box capstrips at about 95% of design load. Because of this failure, the RP-2 carry through was redesigned with clearance between the box and beam and with pins transferring the bending loads: this redesign was adopted and modified for RP-3. The RP-1, RP-2, and RP-3 carry throughs and associated flight-worthiness tests are presented here and their implications for aircraft design with composite materials are discussed.

I. Introduction

THE carry-through structure is traditionally the heaviest structural component in a sailplane because it transmits the largest loads in the aircraft that are the result of wing bending, torsional, and shear forces that carry through to the fuselage. Wing-root bending moments tend to be very large in sailplanes because of their long, slender wings. Sailplanes also require dismountable wings that can be quickly and easily reassembled. For these reasons, the design of sailplane carry throughs has been crucial to overall sailplane performance,[1] and a challenging problem involving operations, structures, materials, and aerodynamics.

Figure 1 shows conventional sailplane carry-through structures. A wooden carry through is shown with heavy, bulky steel reinforcements, and is typical of classical sailplanes. The most common free-floating carry-through structure for certified sailplanes made of fiberglass composite materials is also shown in Fig. 1, and is compared to its contemporary variation with two tongues next to each other and slightly offset spars, which is typical of recent designs of high-performance, open-class sailplanes. The simpler fork-and-tongue configuration decreases assembly time and takes advantage of the anisotropic properties of specifically graphite-reinforced-epoxy composites. At the end of each spar tongue is a guide pin that fits into a rod-end bearing in the root rib of the other wing and transmits bending loads between the wings. This pin also provides guidance during final assembly. These designs are free floating because only wing bending loads are transmitted by the carry-through structure and pins. Additional locking pins are usually located in the shear web to transmit rolling torsional forces and to locate the wings in position on the fuselage. Also, two torsion pins are provided in the leading and trailing edge to transmit pitching and yawing torsional moments and loads between the fuselage and wing. These designs trade weight savings for reliable serviceability. Assembly and disassembly is

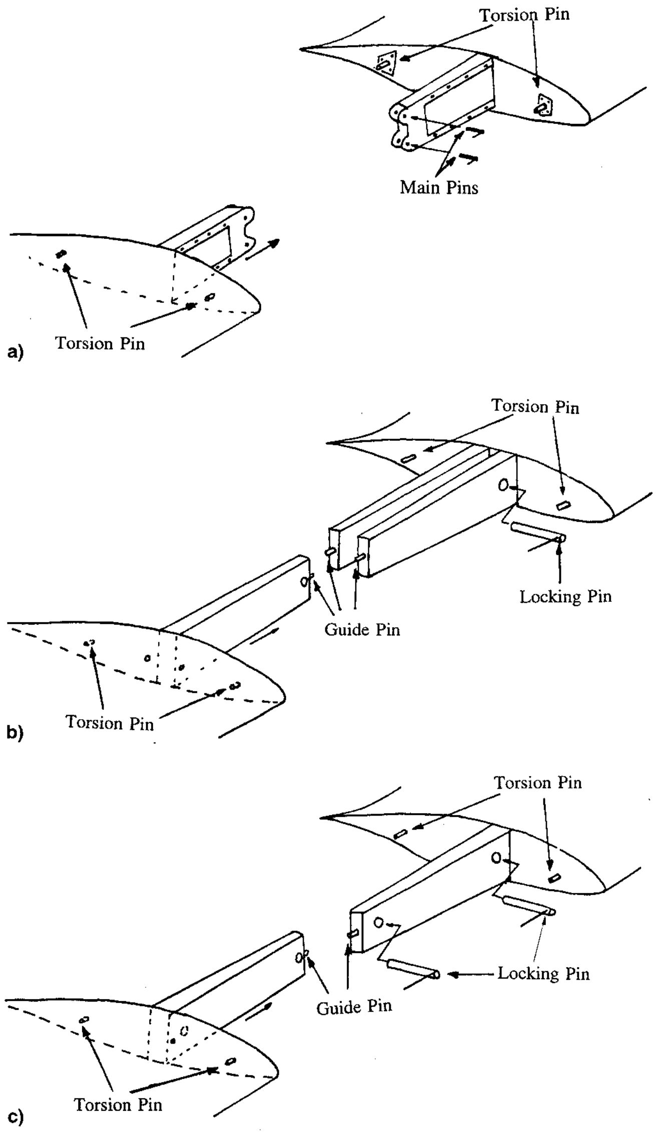

Fig. 1 Carry-through structures of conventional sailplanes: a) traditional wooden (ca. 1950), b) fiberglass composite materials (ca. 1972), and c) graphite-reinforced-epoxy composite materials (ca. 1988).

Received Oct. 24, 1994; revision received Dec. 21, 1995; accepted for publication Dec. 21, 1995.

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straightforward and accomplished safely in about 15 min by a three-person crew.

This article presents a history of RP-series carry throughs made from fiber-reinforced-epoxy composites, and places emphasis on lessons learned with the RP-2 carry through and on the RP-3 design. The following section presents a brief history of RP-series aircraft and Sec. III outlines the design motivations for the RP-1 carry-through structure. Section IV presents initial and redesigned RP-2 carry throughs with emphasis placed on the knowledge gained from static and flight tests. Section V follows with a description of the RP-3 carry-through structure and the combination of test results that support its flight worthiness. This article closes with remarks on advantages and limitations of the box-and-beam approach to composite carry throughs for sailplane applications.

II. History of the RP-Series Aircraft

The design of carry throughs and associated engineering practice have evolved as the RP series progressed from lightweight solo gliders to dual sailplanes. The first aircraft RP-1 was a single-pilot, open-cockpit, lightweight glider and featured an all-composite Kevlar® and carbon fiber structure. It first flew in 1980 and was donated after 60 flight hours to the Empire State Aerosciences Museum for display as the first student-built, all-composite glider in the U.S. RP-2 is a single-pilot, all-composite sailplane that featured an enclosed cockpit and first flew in 1985. The RP-3 aircraft is almost six times the weight of RP-1 and features side-by-side seating, and a significant increase in complexity from both RP-1 and RP-2. Table 1 provides salient data about these three sailplanes produced in the Rensselaer Composite Aircraft Studio since 1976. This studio evolved from a research project into an undergraduate design course integrated into the engineering curriculum that has given students practical experience, knowledge of aircraft, and understanding for engineering aircraft with composite materials. Its main objective has been education, and these aircraft were designed and built by over 1000 undergraduate and graduate students from mechanical engineering, aeronautical engineering, physics, chemistry, applied physics, computer science and materials engineering as part of their Rensselaer experience. It is within this context that the RP-series carry throughs were designed, tested, and fabricated.

III. RP-1 Carry Through

RP-1 was designed to foot-launch. The carry-through structure represents a significant fraction of the 115-lb empty weight of RP-1, and so emphasis was placed in its design on lightweight, simplicity, and separability so that its wings could be removed for storage and transport, in addition to load transmission. The optimum carry through for this configuration was chosen[2] to be the interference-fit, box-and-beam design shown in Fig. 2. This design features no bulkheads and is based on strict separation of load paths where the carry through transmits only wing bending loads, while the pitching and yaw torsional loads are transmitted through the four torsion pins located at the leading and trailing edge of the wing–root rib. In addition, one pin holds the box in the beam and carries only a connection load. The RP-1 was successfully static tested to

Table 1 Aircraft features

Feature	RP-1	RP-2	RP-3
Maximum takeoff weight, lb	270	450	1000
Empty weight, lb	115	270	650
Aspect ratio	11	16	17
Length, ft	18.9	21.6	23.6
Height, ft	4.2	4.1	3.9
Wingspan, ft	37.8	44.2	54.0
Wing area, ft^3	129	120	180
Maximum glide ratio, mph	20:1 (32)	28:1 (40)	33:1 (53)
Minimum sink rate, ft/s	2.0	1.7	2.1
Wing loading, lb/ft^3	2.0	3.8	5.5
Stall speed, mph	22	29	42
Occupancy	1 (open)	1 (enclosed)	2 (enclosed)

Dimensions	RP-1 [in]	RP-2 [in]
A	16.00	19.50
B	5.44	6.625
C	2.40	6.50
D	8.00	8.50
E	26.56	21.50

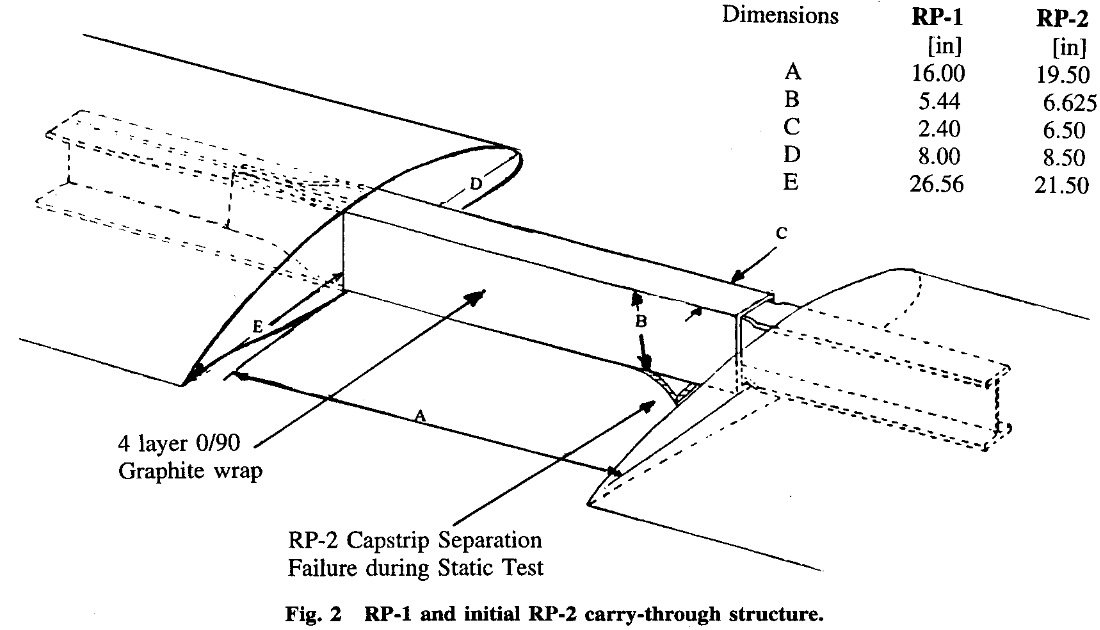

Fig. 2 RP-1 and initial RP-2 carry-through structure.

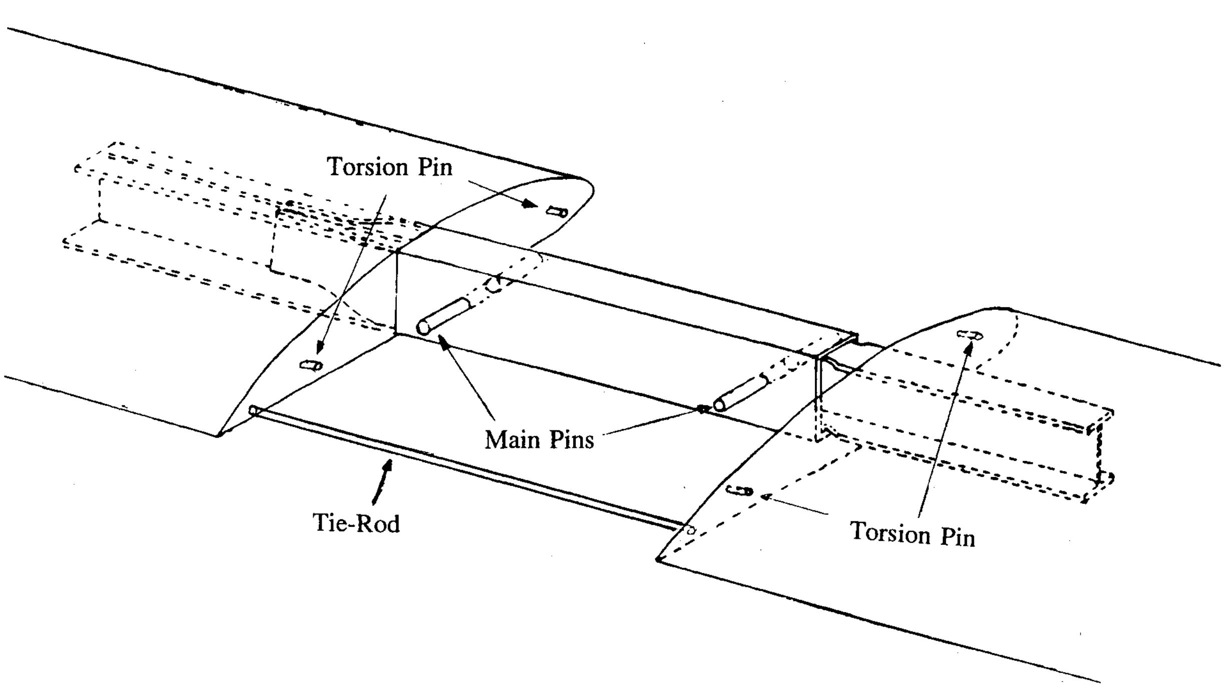

Fig. 3 Cutaway diagram of RP-3 carry-through assembly.

a 4-g static load limit prior to obtaining an Airworthiness Certificate and flying in the experimental aircraft category.

IV. RP-2 Carry Through

After a successful flight of RP-1, the RP-2 carry through was designed by copying the RP-1 configuration with minor changes that included the addition of swivel bearings for the torsion pins and the relocation of torsion pins closer to the carry through to accommodate the primary fuselage structure. This box-and-beam, interference-fit concept was again chosen for its lightweight appropriateness for the low design loads in RP-2, and because of the experience gained in design and fabrication of the RP-1 structure.

Two static tests were performed on the RP-2. First, pure bending was tested with the airplane loaded to 4 g with 1680 lb of dead weight that was distributed in 10-lb sand bags to simulate the elliptic aerodynamic-lift distribution. This loading resulted in a slight permanent set that drooped the wingtips about 0.28 in. after unloading. This test demonstrated structural integrity of the box and beam in pure bending.

The second test was a bending–twist test for 4-g loading. This test again required a total load of 1680 lb, but weights were placed to match both bending and torsion forces because of aerodynamic loads in a dive pullout. When the load reached about 840 lb, the rear torsion pins slipped from the fuselage bushing and resulted in a small forward rotation of the wings. Loading was continued and the carry-through structure failed at 95% of the anticipated maximum test load. Figure 2 shows details of the capstrip that peeled off the box structure. Initial failure analysis focused on wing–pin slippage, as this slippage would have stressed the sides of the box with torsion loads that were designed to be transmitted through the torsion pins. The actual loading during the test was not considered during the design of the box, and failure may have been because of the shear flow that exceeded design specifications and caused the secondary bond and graphite wraps to fail at the discontinuity at the box corners: this mechanism would have resulted in the observed peeling of the capstrips. However, further damage occurred when the wings collapsed after the carry through broke, and it could not be established if this was either the root cause or the sole failure mechanism. Failure could also have been because of damage during assembly, stress concentration at the tip of the beam, or a combination of these and the pull-out mechanism described previously. Although the specific failure mechanism could not be isolated, failure analysis provided both insights into this carry-through design and opportunities for improvement, as discussed next.

After the static-test failure, the RP-2 carry through was redesigned with the clearance-fit, two-pin concept shown in Fig. 3. This redesign was chosen for its similarity to the interference-box-and-beam concept and because it offered two structural advantages: 1) there is clearance between box and beam, and so nondesign, complex loading is not possible; and 2) the loads carried in the shear web are transferred by the pins rather than having to travel from shear webs into capstrips and back into the shear web. A tie-rod was also added to prevent deflection that allowed slippage of the wing–root torsion pins. Static tests for pure bending and bending–twist were repeated and maximum loads were successfully carried. RP-2 now has over 20 flight hours.

V. RP-3 Carry Through

This section presents the RP-3 carry through, the approach to its design, its strategy for transmission of loads, and the functions of carry-through components, including the box-and-beam structures, tie-rod, wing torsion pins, and carry-through-bulkhead bolts. Design features that avoid the possible failure mechanisms found with RP-2 are described.

Figure 4 shows the assembled RP-3 carry through. Design objectives were similar to those for the RP-1 and RP-2 carry throughs, which include lightweight, separability, and simplicity, although there are substantial differences in load-carrying capacity. The RP-3 carry through was designed to avoid the possible mechanisms identified during failure analysis of the RP-2 carry through, and these were addressed as follows: carry-through components were dimensioned and fit to ensure clearance between the box and beam throughout the flight envelope, gussets were added at the discontinuous joint between capstrips and shear webs in the box and beam to provide a load path to carry shear flows and provide reinforcement for hidden bonds, the tension rod was added at 85% of chord to carry forward moments at high angles of attack and to provide sufficient stiffness to prevent slippage of wing–root torsion pins, and a procedure was developed to prevent prying by the beam on the box during assembly. The two torsion pins, which are located at 10 and 80% chord on each root rib and transmit the torsional loads from the root rib to the secondary bulkheads, were disengaged during the RP-2 breakage.

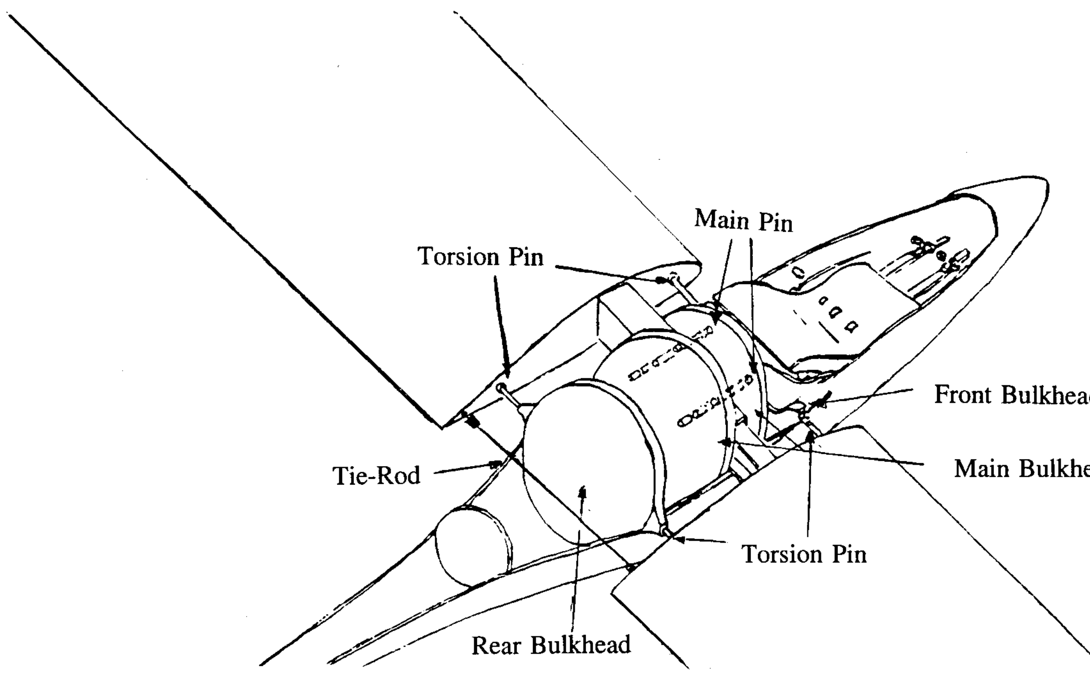

Fig. 4 Redesigned RP-2 and RP-3 carry-through structure.

The RP-3 wings transmit aerodynamic loads to the root as follows[3]: wing skins combine with three shear webs (front, main, and rear) to create a torsion box for transmission of torsional loads to a structural root rib. Figure 4 shows the internal structure in the vicinity of the carry through. The fibers in the capstrip run continuously from the wing into the box-and-beam structures. These capstrips are discussed later and transmit bending loads to the box-and-beam components, which in turn convey these to the fuselage through the bolts to the main bulkheads. The beam is an extension of the left wing main shear web and capstrip, and is connected to the box component and the two main bulkheads with the two carry-through-bulkhead bolts. The RP-3 structure was tested at loads of 6-*g* solo flight and 4-*g* dual flight, both at a never-to-exceed speed of 134 kn. Distributions of bending moment and shear force in RP-3 wings, which were obtained from aerodynamic load distributions, calculated from solutions of inviscid-flow equations with boundary-layer corrections. The wing–root bending moment and maximum shear are 28,000 ft-lb and 2450 lb, respectively, which is more than five and three times higher than for RP-1 and RP-2, respectively. For the RP-3 carry-through structure, a factor of safety of 3 was applied, which is twice that required currently for CFR 14 Part 23 certification.

The main design constraint for wing capstrips is the transmission of the bending moment because of aerodynamic lifting and rolling forces. Bending moment decreases with distance from the wing root, and so capstrips were tapered uniformly from 52 to 3 layers of unidirectional graphite preimpregnated fabric (Fiberite 1048) between the root and tip.

The carry-through-bulkhead bolts were separated by the maximum available distance of 30 in., which was limited by fuselage diameter. The maximum wing–root shear and bending moment result in shear forces on the bolt of 12,000 lb and 1-in.-diam ASI 4130 pins were used and heat treated to an ultimate tensile strength of 140 ksi. These were fit into bushings made of identical material that were bonded with epoxy resin into the bulkhead, the beam, and the box.

The clearance between the box and beam was obtained by summing deflections of wing bending, beam bending, box bending, and deflection of all aforementioned bushings in their epoxy seats. During normal loading the box and beam deflect in the same direction, and so clearance was diminished only by the difference in deflections, which was calculated to be less than 0.008 in.: this calculation was validated by deflection and strain measurements obtained with a full-scale model of the beam carry through, which compared within 10% of calculated values and is adequate for the safety factors applied here. Bushings in epoxy seats were measured in test specimens to deflect less than 0.015 in. The net of all deflections was a reduction in clearance of 0.023 in., because of 6-*g* aerodynamic loading within an actual gap of 0.375 in. between box-and-beam structures as discussed next.

The stress distribution around the bulkhead bolts required reinforcing plates to diffuse loads into the shear web of the box. Cyclic tests confirmed stress distributions on the reinforcing plates divided equally into two bushings. Bushing damage was apparent at 21,000 cycles and failure occurred at 48,000 cycles under cyclic 6000-lb loading. Strain-gauge measurements confirmed the diffusion of stresses into the reinforcing plate and capstrips.

Shear flow was calculated and confirmed by the aforementioned beam test. Shear flows around the box and beam required gussets to reinforce the bond between capstrips and shear webs in the carry through. The bond between capstrip and shear webs is a secondary bond, and alone would have been insufficient to transmit the shear flow. The box was wrapped with six layers of 45-deg bidirectional graphite cloth around the box exterior, and one partial wrap of 45-deg graphite cloth on the inside at the corners. The beam has three graphite flanges within the beam structure, and two final wraps of 45-deg bidirectional graphite cloth over the beam exterior.

A tie-rod was incorporated at the rear of the wing to stiffen the wing–fuselage junction and carry aerodynamic loads that pull the wing upstream at high angles of attack. Each end of the tie-rod is attached to a steel plate bonded to wooden blocks that disperse the load into wing skins and webs through graphite flanges. The tie-rod was designed for maximum lift in dive pullout, which causes a 2400-lb axial load on the tie-rod. The stiffness of this rod, which prevents deflections that might result in pullout of the rear torsion pins as experienced by RP-2, is the critical constraint, and a threaded rod of 0.375 in. diameter made from ASI 4130 aircraft grade steel with a tensile strength of 140 ksi was used. Fatigue analysis estimated a life of 100,000 and 1,000,000 cycles under 6- and 3-*g* oscillating loading, respectively, for this tie-rod.

Tolerances within the carry through were 1/16 in. for composite parts, which makes manufacturing difficult with the methods used for RP-3. All parts, with the exception of the capstrips, were layed up by hand and room temperature cured under vacuum.[4] Warping of vacuum tables, bonding of complex assemblies, and inaccuracies from construction by students, all contributed to the difficulties in maintaining design tolerances in the carry through. For example, clearance between the capstrips of the box and beam reduced from the design value of 0.75 in. to about 0.375 in., and this is adequate as discussed earlier.

The box component is closed on five sides and there is no access inside the carry through after assembly. Both the inspection and fitting of the carry through are difficult. While epoxy resin was used to bond the bushings in the bulkhead, the box and the beam cured with the wings and fuselage aligned at prescribed angles of fuselage-to-wing incidence and dihedral, feeler gauges were used to maintain clearances inside the carry through. Actual clearances cannot be measured. During field assembly, the beam carry through is positioned using the torsion pins for support, and then the box is aligned and slid over it without excessive relative movement, and the main wing pins installed: care is taken to avoid prying damage, as may have occurred during RP-2 assembly.

VI. Concluding Remarks

The box-and-beam concept was chosen for the RP-1 carry through and then used on RP-2 and RP-3 aircraft. Implementation of this design became progressively more difficult with increasing takeoff gross weight. The failure of the RP-2 carry through, its successful redesign, and the resulting engineering required for the RP-3 carry through provided many Rensselaer undergraduates with an education in engineering practices with composite materials, and experience with the complex design factors typical of the aircraft industry.

Acknowledgments

The authors are grateful for the efforts of the Sailplane Advisory Committee, especially the technical contributions of S. S. Sternstein, O. Bauchau, R. Loewy, H. Hagerup, A. Lemnios, and Volker Paedelt. In addition, the authors thank the many students who contributed to the RP-series aircraft and enriched the aircraft design community here at Rensselaer.

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