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A REVOLUTIONARY APPROACH TO COMPOSITE CONSTRUCTION AND FLIGHT MANAGEMENT SYSTEMS FOR SMALL, GENERAL AVIATION AIRPLANES

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Abstract

The design studies for two composite general aviation airplanes are presented. The main consideration for both of the designs was to avoid the typical "metal replacement" philosophy that has hindered the widespread use of composites in general aviation aircraft. The first design is for a low wing aircraft based on the Smith Aircraft Corporation GT-3 Global Trainer. The second aircraft is a composite version of the Cessna 152. The project was conducted as a graduate level design class under the auspices of the KU/NASA/USRA Advanced Design Program in aeronautics. This paper will present the results obtained from the Fall semester of 1991 and the Spring semester of 1992.

Nomenclature

CRT	Cathode Ray Tube
GPS	Global Positioning System
HUD	Heads Up Display
KU	University of Kansas
LCD	Liquid Crystal Display
RTM	Resin Transfer Molding
USRA	Universities Space Research Association

Introduction

For the 1991-1992 academic year, the Advanced Design Program at the University of Kansas concentrated on two main subjects. The first is in the area of composite construction. The second is in the area of improving flight management and control systems.

Most existing composite aircraft structures have been designed by using the "metal-replacement" philosophy. As a result, many mechanical fasteners are required , which drive up the weight and cost while also introducing delamination problems. Sad examples of the "state-of-the-art" are: Beech Starship I, Boeing-Bell V-22, McDD AV-8B, and the Boeing A-6 re-wing program, all of which outweigh aluminum equivalents.

The project for the Advanced Design Program at the University of Kansas will be to develop methods in which conventional mechanical fasteners (bolts, rivets, screws, etc.) can be eliminated in the construction of all-composite aircraft. These techniques will then be applied to two different aircraft. The two aircraft chosen were the Smith Aircraft Corporation GT-3 Global Trainer and the Cessna 152. These two aircraft were chosen because information was readily available to the design teams, and they represent what can be considered to be typical configurations for low and high wing aircraft. The class produced scaled production drawings and models that show how the manufacturing process will work.

The second area of study was in the area of flight management and flight control systems. This subject was investigated only during the Fall 1991 semester. Most existing general aviation airplanes use mechanical flight controls. The handling qualities of these airplanes are often compromised by the friction and hinge moment feedback associated with such flight controls. In addition, many of these airplanes have undesirable Dutch roll and spiral mode characteristics. This increases pilot workload in conditions of turbulence and poor visibility. To remedy these problems, a de-coupled flight control system was investigated. Such a system has been shown to be very easy to fly. The results of the study included functional diagrams and drawings describing such a system. In addition, a complete list of component weights, geometries, power consumption, and cost data was generated.

Another problem with existing general aviation airplanes is that pilots are required to be familiar with all navigation systems on board as well as with all FAA rules with regard to air traffic control. This has made the current pilot environment extremely user-unfriendly. To relieve these problems, a very user-friendly flight management system was developed. This system should be able to allow a low-time pilot to fly safely in the air traffic control system without the need for extensive training. This type of system was investigated in the 1990 academic year at the University of Kansas, and this study was a continuation of that work.

Advanced Flight Management/Control Systems

The purpose of this section is to present the main results from the advanced flight management and control study. This study was conducted only during the Fall 1991 semester.

Advanced Flight Control System

The Advanced Primary Flight Control System (APFCS) is a decoupled flight control system. Decoupled flight controls force the response of the airplane to be a function of only one input variable. This system is very different from conventional flight control systems which often require some combination of two or more pilot inputs to achieve a constant response. For example, to climb at a constant rate requires that the pilot pull back on the stick (or wheel) and add thrust through the throttle. To perform a steady level turn requires that the pilot pull the stick to the side to bank the airplane, pull back on the stick to maintain altitude, and add thrust through the throttle to maintain a constant airspeed. The purpose of the decoupled flight control system is to reduce pilot workload by eliminating the coupling of control inputs necessary to produce steady-state responses from the airplane. The three motion variables that are controlled by the pilot through the APFCS are:

- vertical speed
- airspeed
- heading rate

The APFCS couples the appropriate direct control signals and performs iterations until the response of the airplane matches the signal input given by the pilot. This system has proven easy to fly and is a promising solution to increasing safety in general aviation.

The system described above requires the use of a fly-by-wire flight control system. Two main considerations of such a system are the actuation method and the computer hardware that are required.

Actuation Method

For system redundancy and to allow for smaller, less powerful (and presumably less expensive) actuators, multiple servo tabs are used for each control surface. The selected values are as follows:

- Aileron 6
- Elevator 6
- Rudder 4

The forces for each actuator were calculated and an extensive search was made to find a suitable actuator. The Nash DL 1020 linear actuator was chosen. For parts commonality, the same actuator is used for all control surfaces. The installation of the actuator into an aileron is shown in Figure 1. The installation of the actuator is similar for the other control surfaces.[1]

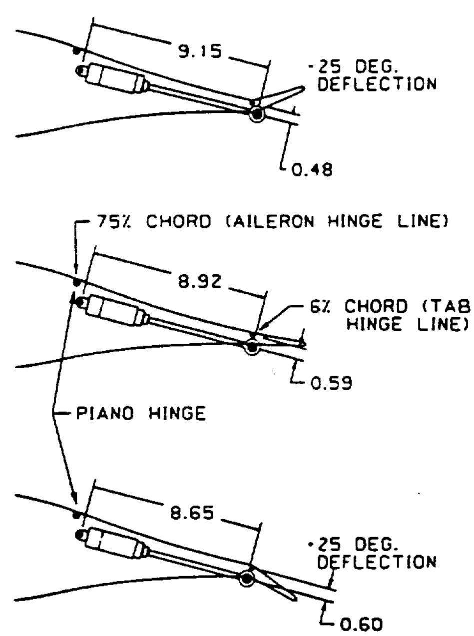

Fig. 1 Installation of aileron actuators

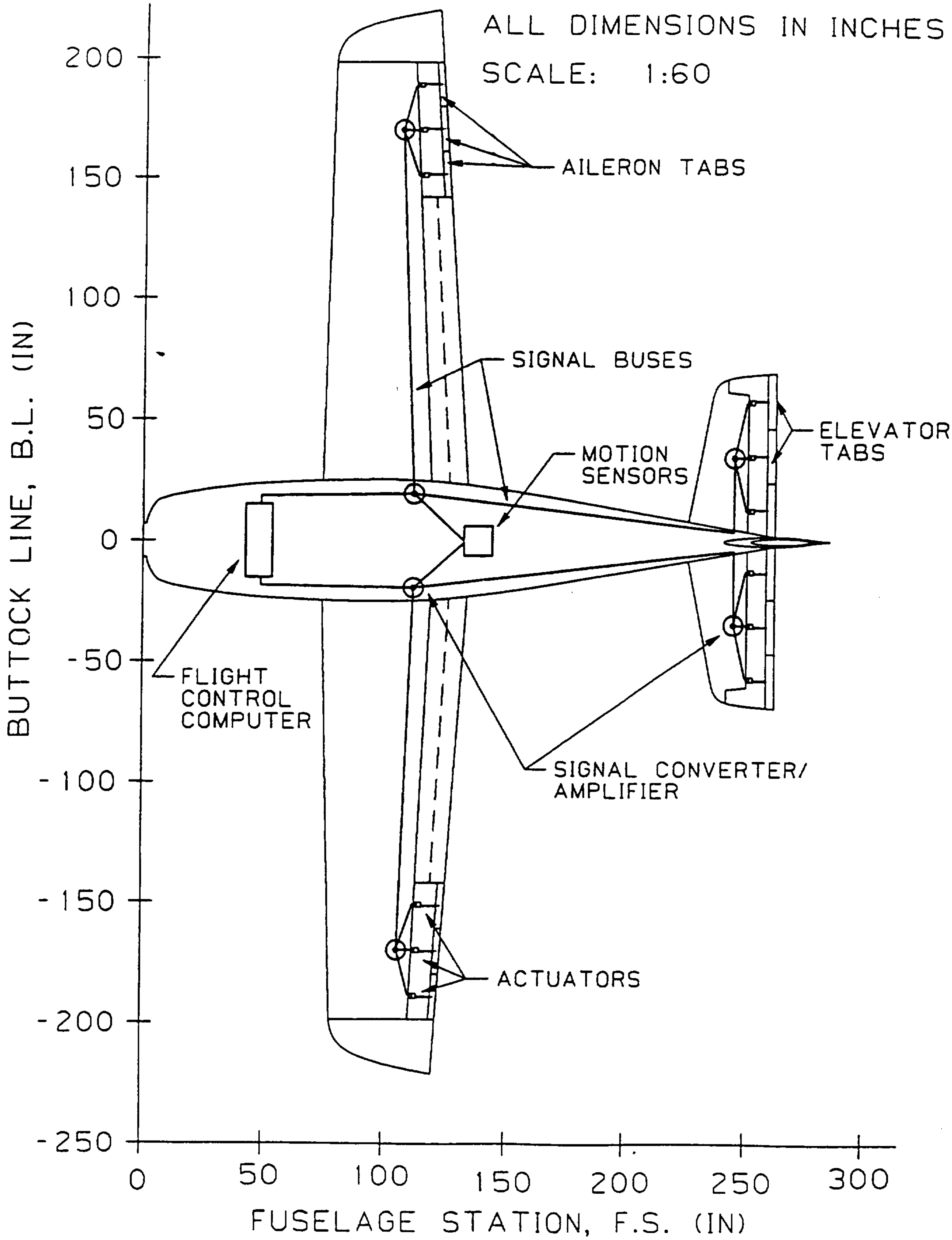

Fig. 2 Flight control system general layout (top view)

The other required equipment and the associated costs are given in Table 1. The installation of these systems is shown in Figure 2.

Table 1 Total system costs for the APFCS

Component	**Cost (US $ 1991)**
Actuators	$ 3,200
Rate transducers	18,255
Vertical gyroscopes	15,540
Computers	30,000
Batteries	316
Total	$ 67,311

Advanced Flight Management System

The main objective of the flight management study was to determine the feasibility of a very user-friendly system developed at the University of Kansas during the 1990-91 academic year.[2] The system is designed to allow an inexperienced pilot to fly anywhere in virtually any weather. To do this requires Category II landing minimums. It was determined that GPS with Selective Availability turned off would give sufficient accuracy for Category II landings.

To effectively inform the pilot, it was decided to use a Heads Up Display (HUD). This will allow the pilot to continually look outside the aircraft instead of having to monitor instruments inside the cockpit. This will give the pilot greater time to see and avoid other aircraft, thus increasing safety. An LCD HUD with a display size of 24 x 6 inches was chosen because it is lighter and requires less power than a conventional CRT HUD.

To insure a safe airplane, designers conducted a failure analysis to determine the minimum number of components required for redundancy. An acceptable failure rate was assumed to be 1 in 10^6 flight hours for non-flight-crucial systems and 1 in 10^9 for flight-crucial systems. The failure analysis was conducted for two different scenarios. The first was called the not-too-distant future system and the other was a more technologically demanding system. The main difference between the two systems is that the not-too-distant future system uses existing components and the futuristic system uses much more integration. The listing of the required components for the not-too-distant future system is given in Table 2.

Table 2 Required components for the advanced flight management system

Component	**Weight (lbs)**	**Power (watts)**	**Volume (in^3)**	**Retail price (91 $ US)**	**Number needed for redundancy**
Nav. computer/ memory/ data base	8.5	103.6	272	23,572	3
MFD	7.7		335	22,500	
TCAS II	40.5	206	1558	127,533	2
Airdata computer	2.74	4.2	192	6465	3
Flight computer	23.1	83.0	962	30,000	3
HUD	24.0	200	1200	16,000	
GPS	1.6	5.0	49	2,610	3
FCI	5.0		88	14,905	
TAS indicator	0.94		40	120	2
Altimeter	1.1		41	220	2
Totals including backups	228.0	1,199	9,245	496,752	

From Table 2 it can be seen that this system requires a large amount of power, volume, weight, and cost. Considering the nature of the airplane (a light general aviation trainer), such a system is not feasible using existing technology. A reduction of the weight and cost by 50% was determined to be the upper bound of the advantage that can be obtained by using the futuristic system. This results in a system that will weigh on the order of 100 pounds and cost in the neighborhood of $250,000, still too expensive for a light trainer. However, such a system could be used in larger aircraft such as corporate or commercial transports.

Composite Structure Design

The purpose of this section is to present the results of the composite construction and manufacturing study. This study was conducted during both the Fall and Spring semesters. The main objective of the Fall semester was to find ways in which all mechanical fasteners could be eliminated from the structure. For a representative aircraft, the Smith Aircraft Corporation GT-3 Global Trainer was used. The main objective of the Spring semester was to try to incorporate these ideas into a design, and to compare the resulting structure with an aluminum design. The airplane chosen for the Spring semester was the Cessna 152.

Composite Manufacturing Technique

The importance of concurrent engineering has been increasingly evident in recent years. This is even more the case with composite structures. If the designer does not consider manufacturing from the start, it is quite possible that the resulting product will be both overweight and over cost. For this reason, an extensive search of the various manufacturing methods available was made. The method that seemed to have the most promise was Resin Transfer Molding or RTM, a process in which dry fibers are placed in a double-sided mold. The resin is injected into the dry fiber at a constant rate so that all of the fibers are exposed to the resin. The process is shown schematically in Figure 3.

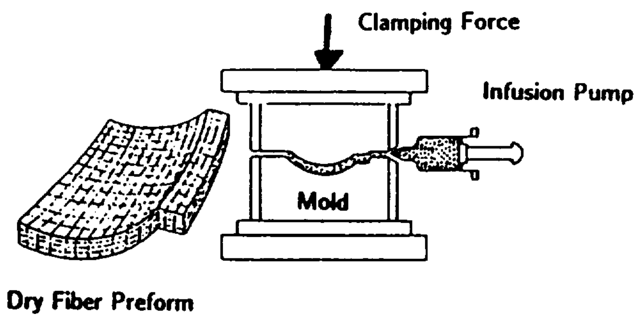

Fig. 3 Fundamentals of Resin Transfer Molding

The main advantage of RTM is that the resulting part has a controlled surface on all or most surfaces. This will significantly reduce the amount of refitting required when all of the components of the airplane are joined together. Another advantage is that the materials are cheaper than conventional pre-preg materials. This is because the resin is injected into the fibers by the partmaker instead of by the company selling the service to the manufacturer. No freezers are required to store the materials, and the part is in near net shape after being released from the mold, further reducing costs.

The main disadvantage of this process is that twice the usual number of molds is required. This would make the process difficult for a start-up company to use due to the large initial capital investment. Finally, the technology is not yet perfected. Despite these disadvantages, it was felt that the advantages far outweigh the disadvantages and that in a few years the technology will be ideal for making composite parts.

Wing

The GT-3 wing is designed to emphasize the elimination of mechanical fasteners. At the locations of mechanical fasteners, the composite needs to be built up because an interruption of the composite fibers weakens its structural integrity. This buildup around the fasteners increases the weight of the composite, which is unacceptable. Another design driver in the wing design is ease of removal and replacement for the purposes of repairability and maintainability. The wing designs were conceptualized with these factors in mind:

- slide-on wing
- key-way joint
- conventional pin joint

The slide-on wing concept will be used for the GT-3 trainer. The slide-on wing consists of a "stub" type fixture extending from the fuselage. The stub is integral to the fuselage/carry-through structure. The stub is designed to act as an inner layer of skin attached to the inboard portion of the wing. However, the wing will be assembled and then slid on this stub and attached with adhesive. This adhesive bond will then act as an interlaminar bond allowing the stub to act as a layer of skin. The stub will extend to buttock line 68 to allow for attachment of the fixed landing gear to the stub structure. The stub will be shaped as the outer skin of the inboard wing to allow for a tight fit as the wing is slid over the stub. In the chordwise direction, the stub will extend aft to approximately 0.70 chord where it will be rounded to an oval-type shape (Figure 4).

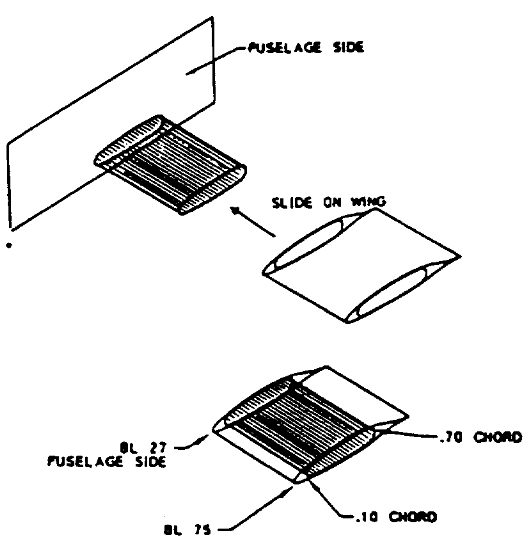

Fig. 4 Slide-on wing concept

The advantages of using the slide-on stub joint to attach the wing include:

- ease of assembly
- joint/structure synergism
- landing gear mounting synergism
- repairability

The assembly of the wing onto the stub consists primarily of sliding the wing on, attaching the landing gear, and applying the adhesive to hold the wing on. The stub will not be symmetrical; thus, there should not be any problems with mounting the wing upside down. The actual application of the adhesive is to be investigated further. Synergism is achieved when the stub is used both for mounting the wing and for wing strength. The stub is an integral part of the structure of the inboard portion of the wing. The landing gear mounting presents another advantage to using the stub. Because the stub extends to the landing gear attachment, the stub can be used synergistically as part of the landing gear attachment. Some of the actual structural strength required for the landing gear attachment and the inboard portion of it already exist in the stub.

Some of the disadvantages of using the slide-on stub joint include:

- difficulty of wing removal
- tolerances

Adhesives must be used to attach the wing because of the assumption that the stub will act as part of the wing skin. Thus the bond between the wing and the stub must be viewed as an interlaminar bond. This also assumes that the tolerances between the stub and the wing skin are very small (a similar metal joint requires approximately 0.0006-0.0012 inches).[6] This exact tolerance could present an accuracy problem during manufacturing.

Another concept that was developed was called the key-way joint. This joint allows the wing to slide on parallel to the x-direction of the aircraft. This concept is shown in Figure 5.

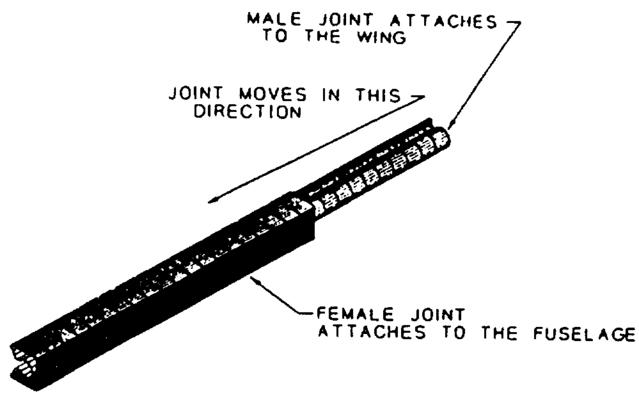

Fig. 5 Key-way joint concept

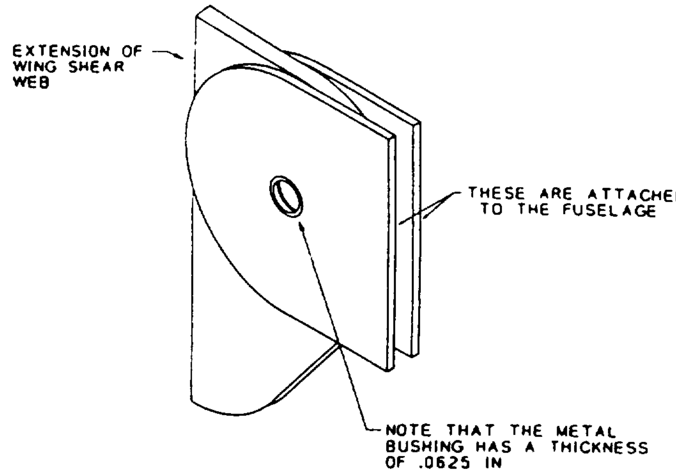

Fig. 6 Configuration of the pin joint

The advantage to this joint is that it is not required to take as much load as the slide-on wing does. This is because all of the bending loads are taken out by the unique shape of the joint. Some adhesive will still be required to prevent the wing from sliding off. The main disadvantages are its very complex shape and, like the slide-on wing, the extremely narrow tolerances required to prevent any movement. A model was built using fiberglass and epoxy resin to gain further insight into the merits of the joint. During the course of many assemblies and disassemblies, the joint became worn and became more and more loose-fitting. Clearly this would not be allowable for an actual installation, so a remedy to this problem must be found.

The final wing-to-body joint that was investigated was a conventional pin joint. While the pin violated the principle of no mechanical fasteners, it was required for the composite wing design for the Cessna 152. This is because the 152 uses a strutted high wing. By using a strut, Cessna was able to eliminate the bending moments at the root, and thus very little carry-through structure was required. To ensure that the bending moment remained zero, it was necessary to use a conventional pin joint. The configurations are shown in Figure 6.

Structural Layout for the GT-3 Wing. A primary design goal of this design is to eliminate the use of mechanical fasteners. To accomplish this goal, the decision was made to develop a design that would distribute the loads and stresses more evenly throughout the wing as opposed to channeling each load into a specific structural member. The ultimate manifestation of this concept is the monocoque wing. The pure monocoque wing, with no internal ribs, spars, or stiffeners, represents a limiting structure which designers can approach in an attempt to obtain thin, hollow wings with low fabrication and assembly costs. Since the skin is the only structural element, all loads on the wing will be distributed throughout the skin. This concept is not feasible using conventional metal fabrication because of the high weight that would be required to provide the necessary structural stiffness. Even using high-modulus graphite composites, the concept is impractical. For virtually any material, ribs are required to hold the aerodynamic contour of the wing and to prevent the wing from flattening out, which would result in structural instability. A rib is also required to distribute the landing gear loads into the skin. Spanwise stiffeners are desirable to reduce the panel width of the skin in compression, thus raising the buckling strength of the skin.

The structural item that can be eliminated is the spar. The web of a spar concentrates the shear created by the wing lift into a few finite points along the chord of the wing. The spars can be eliminated along with the concentrated loads associated with them, allowing the leading and trailing edges of the wing to serve a structural function.

Structural Layout for the 152 Wing. Due to the configuration of the Cessna 152, a no-spar wing as previously discussed is not possible. This is due to the large cutout required for the doors. There simply is not enough room to distribute the loads. For this reason the composite wing for the 152 uses conventional shear webs placed at the same locations as the standard 152. These shear webs channel the forces into bulkheads in the fuselage on both sides of the door. The composite wing differs from the conventional wing in that the upper skin between the shear webs acts as the spar cap. Figure 7 is an exploded view of the wing showing the shear webs and the required ribs.

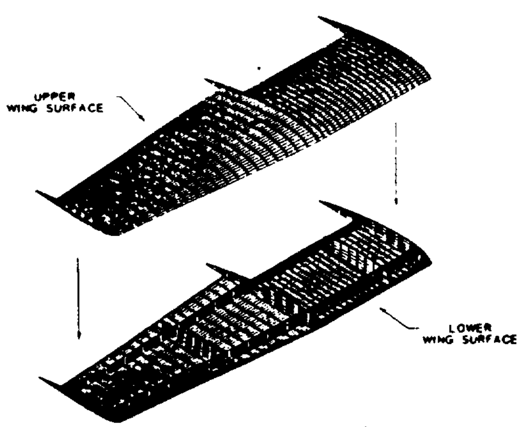

Fig. 7 Exploded view of composite 152 wing

Fuselage

The purpose of this section is to present the concept chosen for construction of the fuselage of the Smith GT-3 Global Trainer and the composite 152.

Several fuselage construction concepts were investigated before deciding on a construction technique:

- one-piece construction-wing and body
- one-piece fuselage
- two-piece fuselage
  - front/back
  - side/side
  - top/bottom

A top/bottom concept was chosen for the construction of the GT-3 and the composite 152 fuselage. It has several advantages over the other ideas. A manufacturer can lay up the bottom half of the airplane at room temperature or in an autoclave and then install most or all of the systems without having to crawl inside the fuselage. The idea is to put the bottom half on "sawhorses" and have excellent access all around the fuselage, saving equipment installation man-hours. The top half can be set over the entire assembly to see if all the systems and equipment fit inside. Then, the top can be lifted off and installation can continue, or the two halves can be bonded together. The two-piece fuselage will have pieces that will be easier to manufacture and work with than a one-piece fuselage.

A complex curve or a stair-step may be required for the joint along the aft end of the fuselage, which could increase the complexity of the manufacturing process.

Current examples of the top/bottom construction include:

- Smith GT-3 Trainer
- Wheeler Express
- Fitzgerald Cozair

Wheeler actually purchased and built a Glasair before they designed the Express and decided against the left and right half concept. An additional benefit of this concept is that small, non-load bearing structures could be taped in to run the flight controls. Figure 8 shows how the top/bottom construction technique is implemented on the composite 152.

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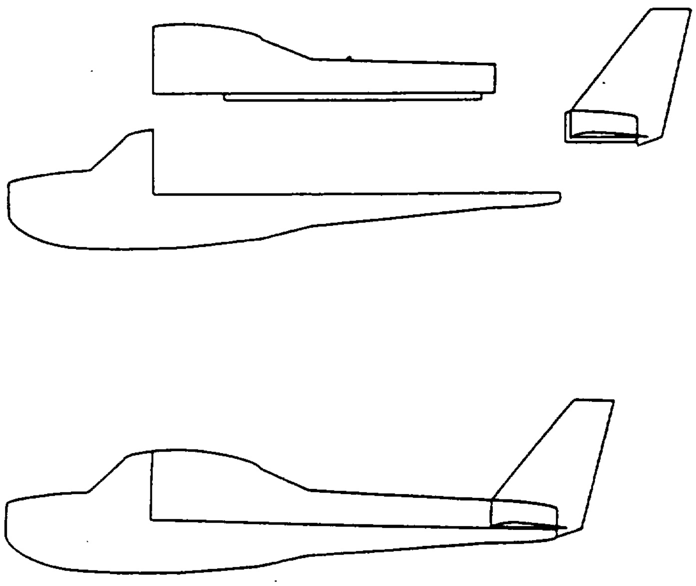

Fig. 8 Demonstration of top/bottom construction

The empennage could be designed so that it fits inside grooves in the bottom half of the fuselage. Then, the top half could fit over a section of the empennage, "locking" it in place. This is also shown in Figure 8.

The components of the wing-body joint are the wing joint and the fuselage carry-through structure. The wing-body joint attaches the wing to the fuselage and also transfers the lifting loads from the wing to the fuselage structure.

The design criteria for the wing-body joint follow:

- even distribution of loads
- no mechanical fasteners
- secure attachment of wing to fuselage
- repairability and replaceability

Joint Concepts. Several joint concepts were developed during the preliminary design phase of this task. The three most promising concepts were the stub slide-on joint, key-way joint, and one-piece wing.

An attachment mechanism must be determined for each of these joint types. Residual clips and adhesives are some of the attachment mechanisms available. A residual clip joint is one in which one piece must "snap" into place. That part can be removed by collapsing the joint with a special tool.

Hot-melt adhesive is suggested as the attachment mechanism for the stub slide-on type joint. The wing is attached to the fuselage by sliding it onto a stub that is part of the fuselage. By using an adhesive that melts at a temperature below the cure temperature of the wing and fuselage, but above the maximum operating temperature of the airplane, the wing can be removed without damaging other airplane components. The stub is itself the carry-through structure.

Carry-through Structure. The design of the carry-through structure uncovered several problems with the design of the Smith GT-3. Currently, the Smith GT-3 uses two spars to carry the wing loads. The leading spar is located at 0.45 chord, and the trailing spar is located at 0.70 chord. The leading spar carries most of the load, and the trailing spar simply acts as a mount for the trailing edge devices. The wing leading spar runs through the cockpit directly below and behind the pilot's back. In the case of a crash which broke the spar, the spar would drive up through the back of the seat, severely damaging the pilot's spine. With the loads concentrated on one spar, the likelihood of the spar's breaking is increased. This design was considered unacceptable.

Since the pilot seat location and the aerodynamic shape of the airplane were not items which the group was allowed to alter, the carry-through structure must be located behind 0.45 chord. Since the structure will still be located behind and beneath the pilot's back, the design driver for the carry-through structure was crashworthiness. The two main methods used to achieve this objective are:

- distribution of the loads
- controlled failure design

By distributing the loads over a larger area, the likelihood of the structure's breaking is diminished. Additionally, the carry-through structure was designed so that, in the case of a crash, the wing would fail before the carry-through structure. Since the structure is designed in this manner, the fracture location is moved away from the pilot and passengers.

The maximum loading placed on the carry-through structure occur in the one-wheel landing cased. The loads are:

bending	834,000 in-lbs
shear	22,400 lb
torsion	113,000 in-lbs

Conceptual Design. A tube-type design was chosen for the carry-through structure. Use of a box or tube carry-through structure rather than a two-spar structure was shown to save weight while maintaining the required load-carrying capability. Additionally, the tube structure lends itself more easily to the use of the stub slide-on joint and the no-spar wing concepts.

The actual shape of the structure will follow the internal contour of the wing airfoil shape. The structure will be rounded at the leading and trailing edges. The shape will be approximately an ellipse. Once the structure penetrates the fuselage skin, the leading edge will curve back from the leading edge to 0.45 chord to fit around the pilot seats. This cutout significantly reduces the torsional strength of the structure, but has little effect on the shear or bending strengths. To recover some of the torsional strength lost, stiffeners will be added along the 0.45 chord location in the carry-through structure. Additional stiffeners will be added for support of the wing structure, the fuel tanks and the control runs. In addition to the stiffeners, the fuselage structure will add torsional stiffness to the carry-through structure.

By over-designing the strength of the structure and adding stiffeners to further improve the strength, the designers have chosen not to take full advantage of the weight savings possible over a conventionally designed tube structure. However, the pilot's safety in the event of a crash is greatly improved.

Empennage

Though the empennage was discussed previously, the details of its attachment will be discussed in this section. The empennage is clamped in place by both the upper and lower fuselage skins and by two bulkheads located where the front and rear spars of the horizontal tail intersect the fuselage. At these points a clamped joint is used. The clamps used for this joint do not require holes drilled in the composite. Thus, the full strength of the composite can be expected. A cross-section of this joint is shown in Figure 9.

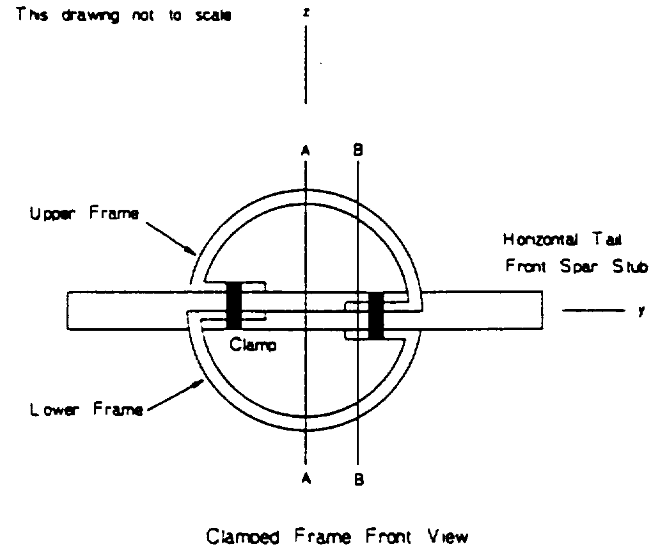

Fig. 9 Clamped joint concept

Landing Gear

Composite landing gears have been used for many years in general aviation aircraft, so design of the gear legs is not all that difficult. However, one of the main problems with landing gear design is finding a way which will introduce the fairly large point loads into the structure. For composite design, distributed loads are much easier to accommodate. One possible solution to this problem is the concept shown in Figure 10.

In this concept, the cross at the top of the landing gear strut is designed to take out all the landing gear loads. This also would eliminate the need for a drag brace, reducing drag.

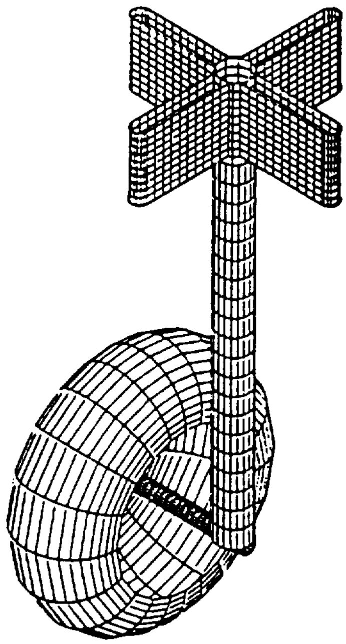

Fig. 10 Landing gear attachment concept

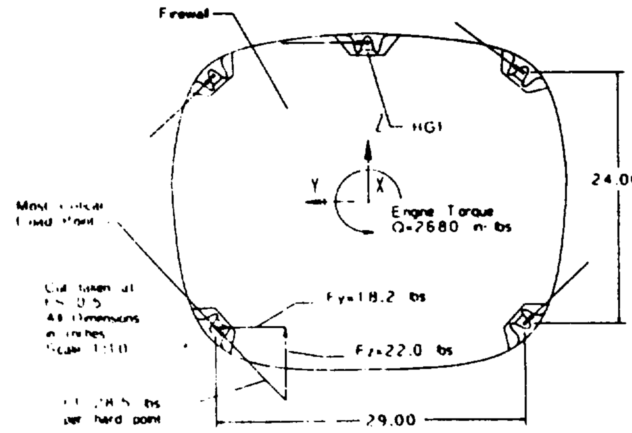

Fig. 11 Engine mount concept

Engine Mount

The engine mount for the composite 152 also posed the problem of how to introduce a point load into a composite structure. A "bathtub" type fitting was developed (Figure 11) at five different locations around the firewall. The engine mount uses the same metal structure that the standard 152 uses.

Conclusions

By using novel techniques of composite construction, designers may avoid the problem of bolts and screws in composite structures. Table 3 makes a comparison of the structural weights for a composite and a conventional aluminum 152.

Table 3 Comparison of composite and conventional structural weights

Component	Composite	Aluminum
Wing	206	216
Fuselage	138	231
Empennage	28	31
Landing Gear	80	96

Table 3 shows that the differences in weight, with the exception of the fuselage, are generally not significant. This indicates that, considering the assumptions required for preliminary design of the composite aircraft, there is no significant advantage from a weight standpoint to either material.

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