THE DEVELOPMENT OF A COMPOSITE ROOT ATTACHMENT LUG

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Abstract

The attachment of a carbon fibre reinforced epoxy fin to the aluminium alloy fuselage of a Mirage F1 aircraft requires a special root attachment fitting to be designed and manufactured if the fin is to be completely compatible with the fuselage without altering the fuselage and if as many of the existing controls as possible are to be used. The development and testing of an attachment lug at the root end of a spar cap, capable of withstanding the operational loads of a fin, are described in this paper. The best of the designs investigated proved its ability to carry the required loads and demonstrated substantial damage tolerance. Nevertheless, improvements can still be made to simplify its manufacture.

Introduction

In line with the current trend of building aircraft components from composite materials, a fin for the Mirage F1 aircraft was manufactured from carbon fibre reinforced epoxy. However, two important requirements had to be met. Firstly, the fin had to be completely compatible with the existing aluminium alloy fuselage as no alterations were permissible, and, secondly, as many as possible of the internal controls were to be retained. Both these requirements, however practical and reasonable, influenced the design of the fin considerably. The result was that a special root attachment had to be devised to cater for this. Figure 1 shows the arrangement of the root attachment as well as the primary components. The root attachment fitting bracket was designed and manufactured in accordance with established metal technology and presented few problems. However, the lug attaching the spar of the fin to the metal fitting required a novel application of composites technology. It had to go through an extensive design and development phase to meet the requirements of the relevant static and cyclic load cases. The development of the composite root attachment lug has been driven mainly by considerations of damage tolerance and extends the work conducted by Cooper and Wright (1). The design of the lug to avoid initiation and propagation of cracks as well as the testing to which the fitting was subjected are described below.

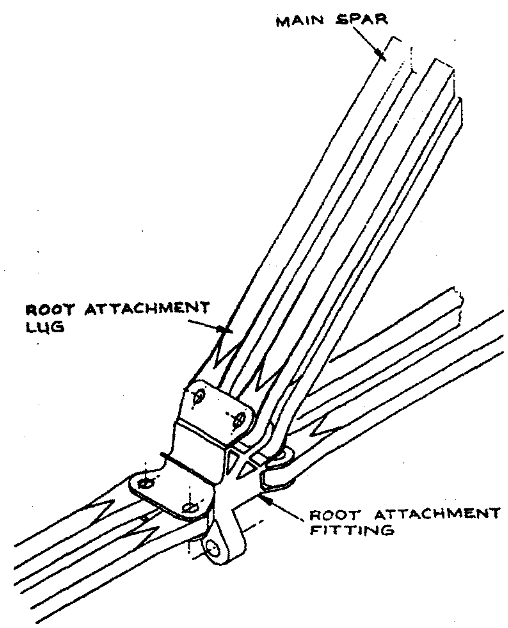

FIGURE 1: Root Attachment

Damage Considerations

Before the fin could be designed, the effects of all likely forms of damage on the root attachment and, in particular, the root attachment lug had to be investigated. Three main forms of damage were identified: damage due to over-loading and cyclic loading, damage occurring during maintenance and damage due to ballistic impact.

Damage due to Over-Loading and Cyclic Loading

This is the most serious and the most likely form of damage as it occurs each time the aircraft is used.

The intensity varies from flight to flight and is often not recorded so it important to have a design that resists this type of damage.

Damage Occurring During Maintenance

Damage due to maintenance is much less likely to occur. The fin is removed from the fuselage only when a major overhaul is performed. This would take place once every ten years or approximately after every 2000 flying hours. For all other types of maintenance the fin would not be removed, so it is unlikely that the root attachment would be damaged, particularly as it would be covered by a fairing.

Damage due to Ballistic Impact

Three types of ballistic impact can be considered:

a) bird strike;
b) small arms fire; and
c) dedicated anti-aircraft weaponry.

The possibility of a bird strike is remote as the fin presents a very small frontal area. The lug is partly shielded by the leading edge and is covered by a fairing, which provides further protection. Small arms fire will usually be directed at the aircraft from below. The root attachment would thus be shielded by the aircraft's wings and fuselage and the probability of hitting a component of this size on a rapidly moving target is small. Dedicated anti-aircraft weapons pose a greater threat. In the case of an air burst, the shock waves would impact primarily on large surfaces. This would, in turn, cause large loads on all attachments, including the root attachment lug. The damage would be caused by over-loading rather than by ballistic impact. Protection against shrapnel could be achieved by using energy absorbing materials in the fairing.

Loads Applied to the Root Attachment Fitting

The loads applied to the various forms of the root end fitting to verify the changes in the design were static tensile and compressive and reversed cyclic.

Static Loading

The static load applied to the fitting was obtained from a finite element model. From the model, the ultimate load on each lug was found to be 500 kN. The specimen is only half the width of the cap and so the ultimate load set for the specimen was 250 kN.

Cyclic Loading

No fatigue load spectra could be found for fins, so the spectrum given in MIL-A-8866 (2) for wings was modified. This was not entirely satisfactory because wings are subjected to asymmetrical loading whereas the loading on a fin is symmetrical.

Symmetrical flight limit load factors were obtained from MIL-A-8861A, Table I (3) and flight manoeuvre spectra and frequency of manoeuvre loads from Tables I and II of MIL-A-8866. If one considers only fluctuating loads, a direct transformation can be made of load cycles around 1.0g to load cycles around 0.0g. The maximum and minimum load factors for the Mirage F1 are 7.2g (n_{max}) and -3.0g (n_{min}) respectively. The percentages of the maximum and minimum symmetrical limit load factors for the Mirage F1, A*, can be calculated from the values given in Table II of MIL-A-8866, A as follows:

For positive fluctuating loads:

$$A^* = \frac{\frac{A}{100}.7.2 - 1}{7.2}.100 \qquad (1)$$

For negative fluctuating loads:

$$A^* = \frac{\frac{A}{100}.3.0 + 1}{3.0}.100 \qquad (2)$$

If the loading on the fin is symmetrical, one can assume that half the positive fluctuating loads act on one side of the fin and the other half act on the other side. The same assumption can be made for the negative fluctuating loads. Consequently, the values for the number of full cycles in 1000 flying hours given in Table II of MIL-A-8866 should be halved for symmetrical loading. By grouping some of the loads together, assuming the life of the aircraft to be 4000 hours and taking a factor of 5 on life, the following simplified load spectrum can be derived:

TABLE1: Simplified Load Spectrum for 4000 Hours

Number of Full Cycles in 4000 Flying Hours	Percentage of Maximum Limit Load on Fin	Cyclic Load (kN)
177000	21.1	35.2
96950	31.1	51.9
65550	41.1	68.5
45350	51.1	85.2
25180	61.1	101.9
15000	71.1	118.5
3000	81.1	135.2
1500	91.1	151.9
400	101.1	168.5
160	111.1	185.2

The factor of 5 on life is conservative. A factor of 4 was used in the certification of the Tornado taileron (4) which was made from carbon fibre reinforced epoxy.

Table 1 formed a basis for the fatigue loading of the fin. However, the compressive loads that could be applied to the root attachment lug would be limited by buckling. The maximum compressive load was set at 100 kN. To account for the lower risk of damage caused by compressive loads, the maximum value was used in each cycle. The modified load spectrum is shown in Table 2.

TABLE 2: Load Spectrum with Constant Peak Compression

Number of Full Cycles for 4000 hours	Tensile Load (kN)	Compressive Load (kN)
177000	35.2	-100
96950	51.9	-100
65550	68.5	-100
45350	85.2	-100
25180	101.9	-100
15000	118.5	-100
3000	135.2	-100
1500	151.9	-100
400	168.6	-100
160	185.2	-100

The effect of having a fixed minimum load of 100 kN is likely to be conservative. This load is 60 per cent of the limit in compression, so, for most cycles, the alternating load will be higher than that required in a more realistic load spectrum. In addition, it was observed from the testing of the lug that more damage was caused by tensile loads.

Evolution of the Lug Attachment

The development of the root attachment lug took place in essentially two stages:

a) a lug configuration was developed that would withstand the static ultimate load, equivalent to 1.5 times the limit load, for at least three seconds:

b) the lug was improved to be able to survive a full fatigue load spectrum and afterwards, to withstand the static ultimate load (1.5 times limit load).

First Lug Design

The initial lug design is shown in Figure 2. It features a strap for the transfer of tension loads, a compression column, a metal bush and triangular load couplers. The purpose of the load couplers was to distribute load from the compression column to the strap as well as the bush, help stabilise the interface between the bush and the compression column and facilitate a gradual thickness change between the compression column and the bush.

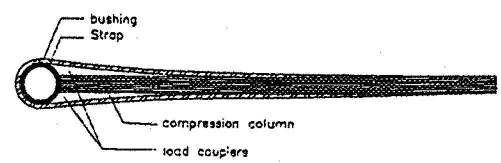

FIGURE 2: Root Attachment Lug, Initial Design

In a compression test, the adhesive bond between the strap and one of the load couplers failed. A crack then developed at the bush and propagated into the compression column. Due to the bond failure, the loading straps carried too little load. All the load was concentrated in the central region with the result that splitting occurred around the bush. It appeared that insufficient adhesive was responsible for the bond line failure. It had squeezed out during the curing process. Glass beads were subsequently added to the adhesive to ensure a minimum bond line thickness.

In another compression test, failure occurred in bearing at the interface between the compression column and the bush. Bending was also observed during compression, indicating a possible stability problem. However, this was considered a problem associated with the test specimen rather than the fitting. Buckling would probably occur at higher loads on the actual fitting as the spar cap and the skin would be supported by the web. The specimens were made shorter for subsequent compression tests.

Modifications to the Design

The debonding of the loading strap from the compression column was reduced by bolting the strap to the column. The bolts apply a transverse compressive clamping load, thereby delaying delamination. Loading plates were added to spread the clamping force. These were later tapered at their ends.

The carbon fibre reinforced epoxy doublers and the metal bush were replaced by a single metallic insert, and to reduce the risk of the compression column pulling out when under tensile load, the shape of the insert was modified so that there was a more gradual change in stiffness.

Current Design of the Root Attachment Lug

The root attachment lug consists of five main elements. These are the outer strap, the metal insert, the compression column and the crack arresting bolts and plates. Figure 3 shows these components in exploded view. The first three components are pre-manufactured and are then bonded together. The crack arresting bolts fit freely and the plates are only seated in adhesive.

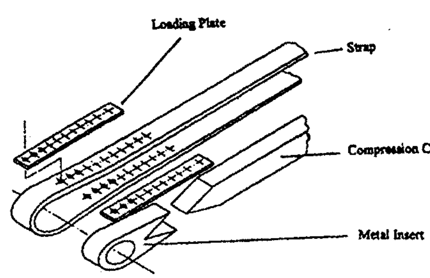

FIGURE 3: Root Attachment Lug, Current Design

The root attachment lug is the primary load introduction member for transferring the bending moment in the main spar of the fin to the root attachment fitting, which, in turn, loads the aircraft's fuselage. The construction of the lug is that it cannot transfer bending by itself, but as a load pair, the bending can be taken out as a compressive/tensile force couple. Essentially, there are two load paths in the root attachment lug. Although these paths are shared by the tensile and compressive loads, one path accounts primarily for tensile load transfer and the other for compressive load transfer. During the bending of the wing, the one side of the spar will be in tension and the other in compression. These loads will primarily be carried in the spar cap.

Load Paths

The root attachment picks up the tensile loads through the bonding interface between the wing skin and the root attachment strap. The strap transfers the load to the metal insert by means of bearing. The metal insert then bears on the attachment pins. This is the primary load path for all tensile loading. Compressive loads would introduce transverse tension, resulting in delamination, so another load path is required to accommodate compression.

The load path for compression is much simpler than that for tension. The compression load that is concentrated in the spar cap is taken directly into the metal insert by means of bearing. This is the primary load path for all compressive loads, but it is inevitable that this load path will attract tensile load as well. This is a secondary function that has become more important during the development of the attachment.

Structure of the Root Attachment Lug

The composite material used in the manufacture of the lug was Hexcel T190 F263 unidirectional carbon fibre prepreg.

As shown in Figure 4, most fibres are aligned along the length of the strap, the 0° direction, that coincides with the tensile load. Ten per cent of the fibres are aligned in the ± 45° direction. These fibres have the function of containing damage by preventing in-plane cracks from running all the way through the thickness of the strap. They take out in-plane shear loads that might be introduced by misalignment as well as transverse stresses caused by the Poisson effect. An important feature of the strap is that it is stepped at the end, but this is more relevant to the bond than to the strap itself.

The purpose of the compression column is to take all of the compressive load out of the spar and wing skin and feed it into the metal insert. As most of the load is compressive, it is desirable to have most of the fibre aligned in the direction of the load. However, compressive load can lead to the micro-buckling of fibres as well as the cracking of the matrix between the fibres caused by the Poisson effect. This cracking increases the likelihood of micro-buckling or even macro-buckling. It is important, therefore, to have sufficient fibres in the ± 45° directions to inhibit the cracking of the matrix. The compression column is, in essence, a continuation of the spar and the wing skin and this accounts for the higher than expected number of plies at ± 45° and also the lack of symmetry in the lay-up. The tapering at the tip is undesirable for compression because it causes kick-out loads on the metal insert due to the wedging effect, but this must be balanced by the requirement for a secondary load path to handle tensile loads.

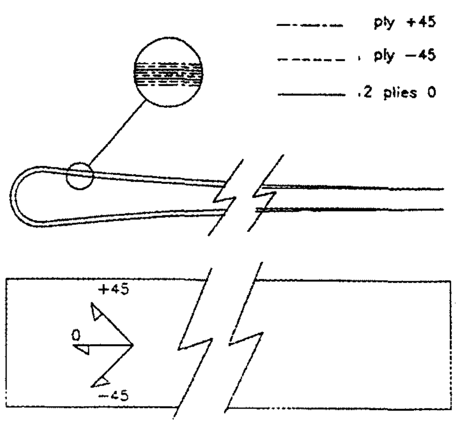

FIGURE 4: Strap Lay-up

The metal insert, shown in Figure 3, is made from 17-4 PH stainless steel. Being a high strength, isotropic material, steel has the advantage that it can resist loads in different directions equally well. However, it is heavy, but where there are constraints in geometry, the load paths are complex and the bearing loads high, it is more practical to use steel in spite of its higher weight. After investigating several different concepts, it appeared that the most effective way of introducing the loads into the composite was to use a steel insert with a large and well designed bonding area.

The use of crack arresting bolts and spreader plates contributed strongly to the increase in the damage tolerance of the lug. The propagation of cracks in the adhesive bonds and the compression column was significantly reduced.

Hysol EA 9346.2 was the adhesive used in the joints of the root attachment lug. The bond line on the strap acted as a crack arresting mechanism because the adhesive was tougher than the epoxy matrix. This was accomplished by laying up the shorter plies on the inside of the strap and the longer plies on the outside. This meant that the tips of every ply in the strap were bonded to the rest of the structure by the adhesive. If interlaminar shear failure occurred in the epoxy matrix, the strap would still be attached to the rest of the structure at its tips. The strap could thus act as a "rope" and remain effective in tension.

Tests Conducted on Current Design

Static tensile loading was applied monotonically to the root attachment lug and at a load of about 180 kN, a crack initiated in the area at the grips and propagated down towards the metal insert. The lug continued to carry the load without failing catastrophically. The crack was probably caused by the stress concentration at the grips and propagated rapidly because of the relatively low toughness of the matrix resin and the tensile kick loads in the strap that would tend to open it up.

The specimen was repaired as well as possible and three transverse bolts were inserted between the metal insert and the grips to prevent cracks originating at the grips from running down the specimen. The repair was only partly successful as it was not possible to inject adhesive into the tip of the crack. A reversed loading fatigue test was conducted on the lug, with the maximum tensile and compressive loads being 100 kN and - 100 kN respectively. After 20 000 cycles, the test was stopped. One of the wedges of the insert had debonded, although the specimen was still capable of carrying the full load.

A second fatigue test was carried out on an undamaged specimen, applying the loads given in Table 2. The load spectrum was modified in the sense that each of the ten loading steps was divided into four equal parts and then these forty load steps were applied in a random order. The specimen survived the first quarter of the spectrum without showing signs of damage. Some of the clamping bolts failed during the test but were replaced at the end of the relevant loading step. The failure of the bolts did not seem to damage the composite structure. During the final loading step, after about thirty cycles, a crack initiated at the grips, and by the end of the test had propagated to the lower clamping pad. Otherwise, the lug survived the fatigue spectrum successfully. Afterwards, the lug was loaded statically in tension up to 250 kN, 1.5 times the limit load. No further significant damage was observed.

Non-Destructive Testing

Several cracks were detected by applying dye penetrant to the root attachment lug. Cracks were located in four main areas:

a) in the strap as it wraps around the metal insert;
b) in the "V" formed by the wedges of the metal insert;
c) at the tips of the wedges in the metal insert; and
d) along the shaft.

The cracks can be seen in Figure 5. Three of the larger ones are worthy of mention. The crack, about 80 mm long, that developed in the bond line between the metal insert and the strap appears to end at the first bolt. This is an indication of the effectiveness of the bolts as crack arresters. A second crack, about 70 mm in length and originating at the base of the "V" of the metal insert, seems to have been restricted in its growth by the reduction in stiffness of the metal insert as its wedges became thinner. Another interesting crack, running from the grip plates to the spreader plates, appears only on one side of the specimen. The other side seems not to have suffered the same damage. The strap lost about thirty per cent of its bonded area as a result but the test specimen survived the full load spectrum. The effectiveness of the strap has thus been brought into question.

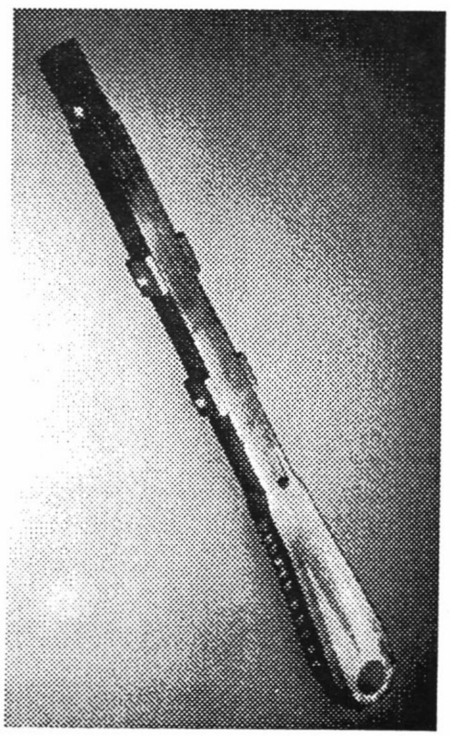

FIGURE 5: Dye Penetrant Applied to Lug

Photoelastic Analysis

Photoelastic analysis was carried out on the final design of the root attachment lug. An undamaged specimen was manufactured for this purpose. The PhotoStress® method developed by the Measurements Group, Inc. was used for the analysis. This is a full field technique for measuring surface strains to determine the stresses in a component or structure during static or dynamic testing. A strain sensitive, polymeric coating is bonded to the component and, as the loads are applied, the coating is illuminated by polarised light from a reflection polariscope. When viewed through the polariscope, the coating displays a coloured fringe pattern that reveals the strain distribution and the highly strained regions.

The photoelastic test was performed in three stages. Firstly, the fringes at zero load were recorded to measure the residual strains. Then the fringe pattern on the specimen was obtained at various tensile and compressive loads both before and after fatigue damage had been introduced.

Comparison of the respective fringe patterns showed that the strain field in the lug changed significantly after fatigue loading. The very high strain concentrations at the tips of the steel insert in both tension and compression were reduced. This is probably due to three factors: yielding of the tips of the steel insert, debonding at the interface between the tapered central column and the steel insert, and the delamination in the central column. The reduction in the strain concentrations retarded the propagation of damage in the region of the insert and had a beneficial effect on the fatigue behaviour of the root fitting. The redistribution of strain is shown in Figures 6 and 7.

Conclusions

A carbon fibre reinforced epoxy root attachment lug has been designed to withstand the operational loads expected in joining a composite fin to an aluminium alloy fuselage. The current design of the lug also demonstrated substantial damage tolerance. The crack stopping bolts played a major role in increasing the damage tolerance but they are not desirable from the points of view of manufacture, maintenance and aerodynamics. An alternative means of applying the necessary transverse clamping loads should be investigated.

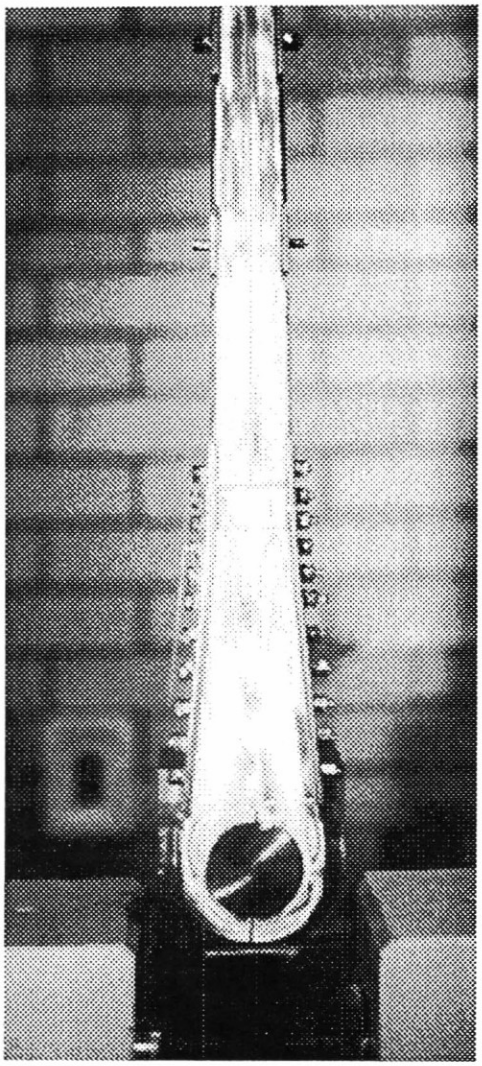

FIGURE 6: Lug with an Applied Compressive Load of -100 kN

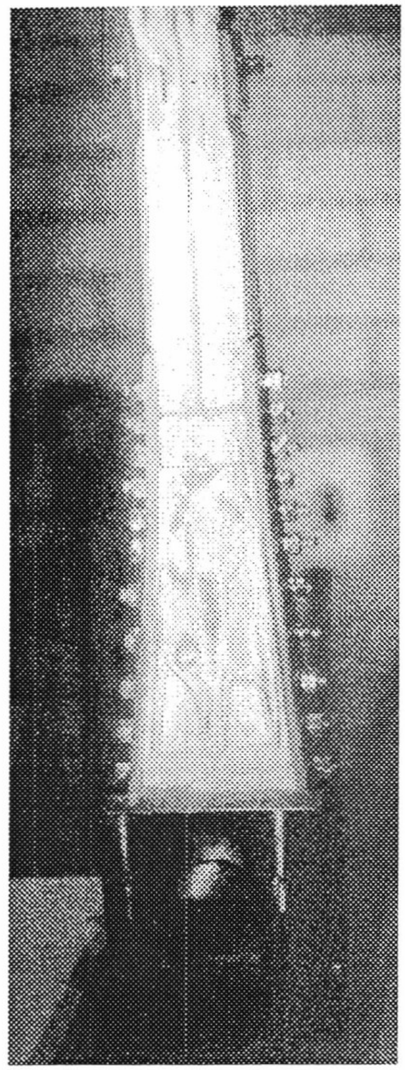

FIGURE 7: Lug After Fatigue Test: Applied Compressive Load of -100 kN

Considerable information about the strain distribution and the damage locations in the root attachment lug was obtained from the photoelastic analysis. This technique should be considered in the testing of any future designs.

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