C-130 HERCULES COMPOSITE FLAPS FATIGUE TEST PROGRAM

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SUMMARY: The C130 Fatigue Test Program was a task undertaken by Hawker de Havilland to satisfy the Federal Aviation Authority certification requirements. This involved a coupon fatigue test program to quantify the fatigue threshold for the Hexcel T650/F584 material used in the design of the flaps and a component fatigue test program to demonstrate that the flaps design has satisfactory structural performance. Damage that could be expected from manufacture and service was also considered in both test programs, this included barely visible and visible impact damage.

The coupon fatigue test program determined that the material fatigue threshold occurred at a nominal strain of 3400 $\mu\varepsilon$ being above the allowable design strain. The component fatigue test, with the inclusion of impact damage at two structurally critical sites, was completed without incident and with no damage growth. All testing was completed by December 1997 and LMAS received final type certification for the C-130J Hercules transport aircraft from the FAA on 9th September 1998.

KEYWORDS: C-130 Flaps, Certification, Fatigue and Impact Damage.

INTRODUCTION

On the 9th September 1998 Lockheed Martin Aeronautical Systems (LMAS) received final type certification for the C-130J Hercules transport aircraft from the Federal Aviation Administration (FAA). Hawker de Havilland (HdH) won a competitive contract from LMAS to redesign, test and manufacture the C-130 Hercules centre and outboard flaps in early 1995. The redesign was necessary to achieve satisfactory performance in a severe acoustic-operating environment caused by the engine propeller wash and exhaust. The redesign maximised the use of carbon fibre reinforced plastic (CFRP) material and optimised the structural configuration to resist high cycle fatigue and support air and inertial loading.

The structural configuration is a conventional ‘multi-rib’ design being quite similar to its metal predecessor. The front and rear spar, ribs and skins are made up of carbon fibre solid laminates, which are predominately quasi-isotropic throughout. Fig. 1 presents the configuration of the centre wing flap.

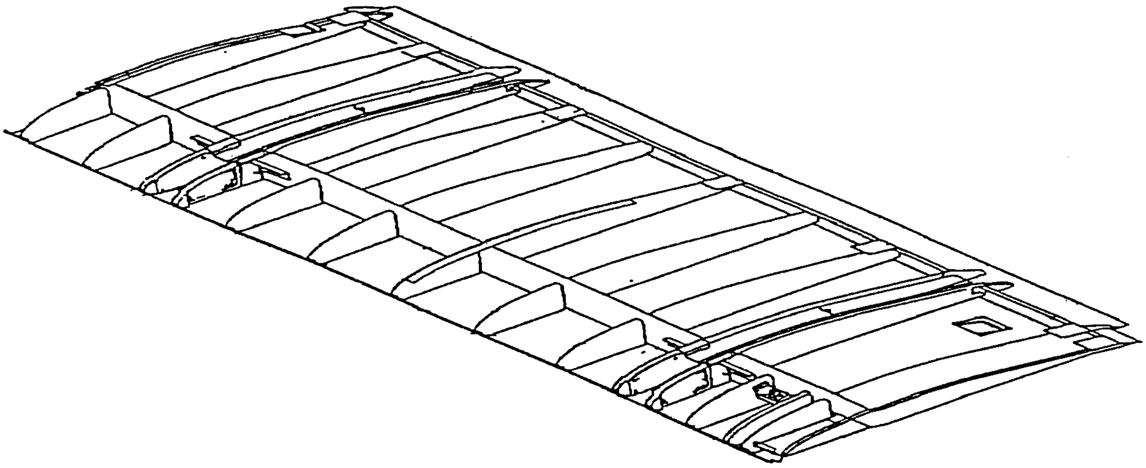

Fig 1: Structural Configuration of Centre Wing Flap

As part of the overall C-130J type certification extensive structural qualification testing was performed. This included static testing of the centre and outer flaps, main spar and rib components, lightning strike of the flap skin and flight-testing. The static testing considered the possible structural performance degradation resulting from the environment (hot wet conditions) and impact damage that could arise during manufacturing, maintenance and service. However to demonstrate full compliance to FAA regulations, in particular Federal Airworthiness Regulation (FAR) 25.571(b) 'Damage Tolerance Evaluation', a fatigue test program was required. This test program involved testing at the coupon level, along with a full-scale substructural test article representing a critical region of the flaps.

This paper outlines the methodology used to assess the fatigue performance of the composite flaps with induced damage, that could possibly arise from manufacture and service, at two structurally critical sites. The aims of the program were twofold:

1. To determine the fatigue threshold for the material, with barely visible impact damage (BVID), that was used in the design and
2. To demonstrate that the composite flaps meet the FAA's fatigue requirements.

COUPON FATIGUE TEST PROGRAM

Hexcel T650/F584 carbon epoxy material is used in the manufacture of the composite flaps. The majority of the parts in the flap structure consist of quasi-isotropic lay-up configurations; consequently a quasi-isotropic laminate was used to quantify the fatigue characteristics of the carbon epoxy material.

A total of twenty tests were performed at the coupon level. Each coupon was nominally 152 mm (6 inch) long by 102 mm (4 inch) wide, consisting of 24 plies with the following laminate configuration: $[(0/90), (\pm 45)]_{6S}$. Every coupon was impacted with BVID at the coupon centre using a 20 mm (0.8 inch) diameter tup and support conditions similar to test document NASA 1142, except a 102-mm (4-inch) square window was used.

Damage was considered barely visible when the depth of the impact site was a minimum of 0.25-mm (0.010-inch), which required an energy of 37 Joules (27 ft-lbs). This type of impact resulted in an average damage size through the thickness of the coupon of 38.1-mm (1.5-inch). Each coupon then had four strain gauges bonded, two back-to-back sets to monitor bending effects, located at 25 mm (1 inch) from the edge, width-wise, and 76 mm (3 inch) from the edge, length-wise.

Five coupons were statically loaded in compression until failure to determine the average failure load for the laminate with induced damage. From these static test results, three load levels were calculated and the remaining coupons were tested using constant amplitude cycling with an R ratio of 10 and a frequency of 5 Hz. To ensure statistical confidence in the results, five coupons were fatigue tested at each load level. Each coupon was supported to prevent buckling, in both the static and fatigue tests; these anti-buckling supports were designed not to inhibit the growth of the BVID site in each coupon.

In both the static and fatigue tests all coupons failed in a similar manner. During the fatigue tests the following similarities were observed:

1. During the initial stages of cycling, the surface of the coupon at the impact site was observed to be protruding outwards as the coupon was compressed.
2. Once initiation of the damage growth was visually detected it was found that the protrusion would grow across the full width of the specimen.
3. Upon initiation the damage growth rate appeared to be quite rapid.

Fig. 2: Typical Coupon Test Installation

Fig. 2 presents the typical test setup for each coupon and Fig. 3 presents a through transmission ultrasonic (TTU) C-scan of a coupon with BVID before and after testing, including a sectional view of the damaged region.

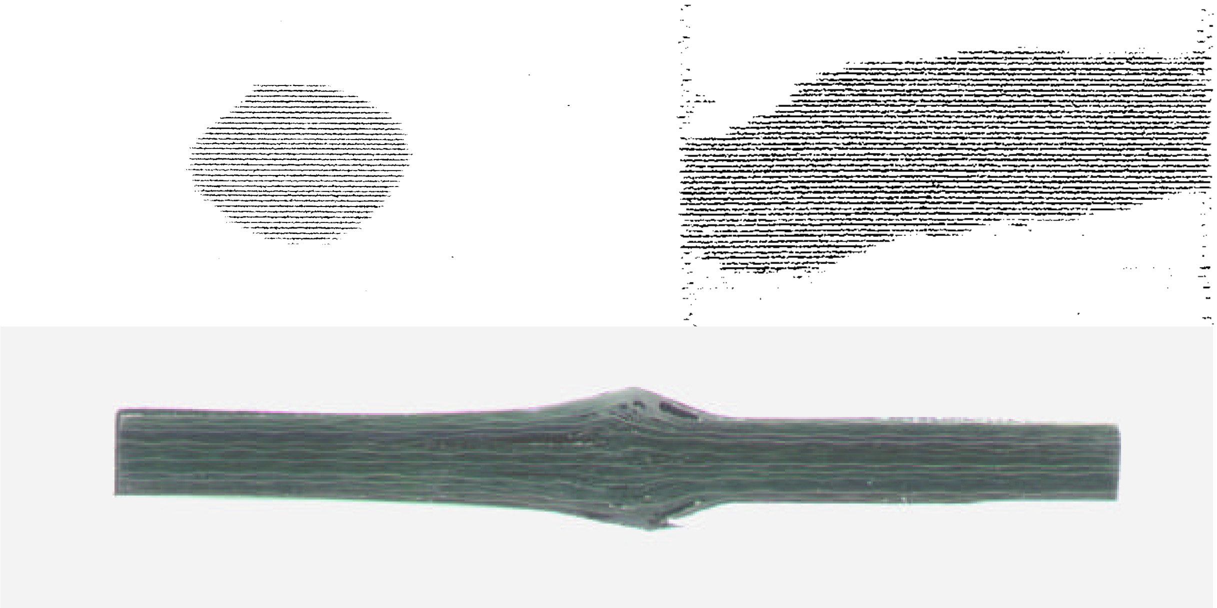

Fig. 3: TTU C-scan of a typical coupon before and after test & sectional view of damage site

Fig. 4 presents the results of the coupon fatigue test program. The aim of this program was to develop the fatigue life curve and determine the strain level corresponding to the fatigue threshold (defined as one million cycles by LMAS) for the Hexcel T650/F584 material. It can be seen in the figure that a nominal strain of ~3400 $\mu\varepsilon$ corresponds to the fatigue threshold of one million cycles.

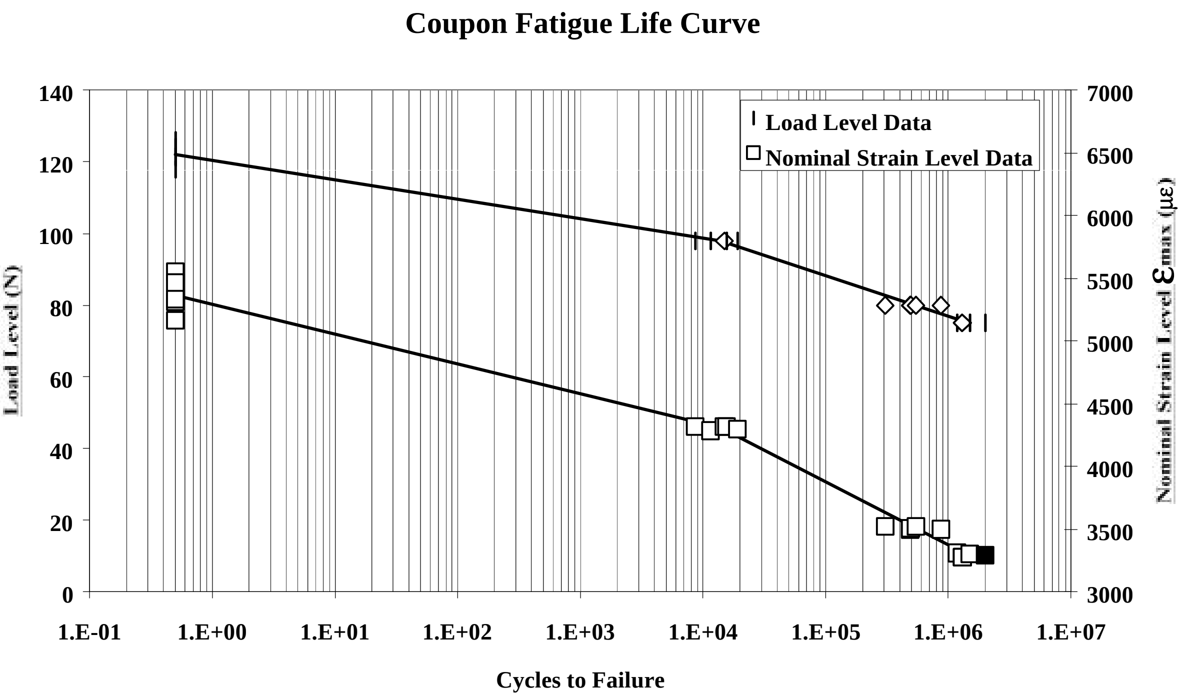

Fig. 4: Hexcel T650/F584 Material Coupon Fatigue Life Curve

FULL-SCALE SUB-STRUCTURAL FATIGUE TEST PROGRAM

A full-scale sub-structural test article representing the most critical region of the composite flaps was used to demonstrate adequate fatigue life and static structural performance of the design. Finite Element Analysis (FEA) of the flap design determined the structurally critical region to be the most inboard main spar cutout of the outer wing flap. Representative flap structure was incorporated into the test article including nose ribs, aft ribs, upper skin and lower skin in an effort to replicate the flap's structural behaviour around the cutout.

Consideration was also given to how the test article should be loaded. Originally it was intended to load the test article as a cantilever beam however unless the load was applied through the shear centre of the spar unfavourable twisting, not representative of actual flap structural behaviour, would result. Consequently this was aborted due to the possible instability that could occur during the test. The final solution was a four-point bend test configuration that could be tailored to minimise the twist of the spar (fig. 5). In this configuration the test article is simply supported at the spar end lugs and at the end of the *torsional* members forward of the nose ribs. The load was applied directly above the nose ribs, any twist would be restrained by the stiffness of the torsional members.

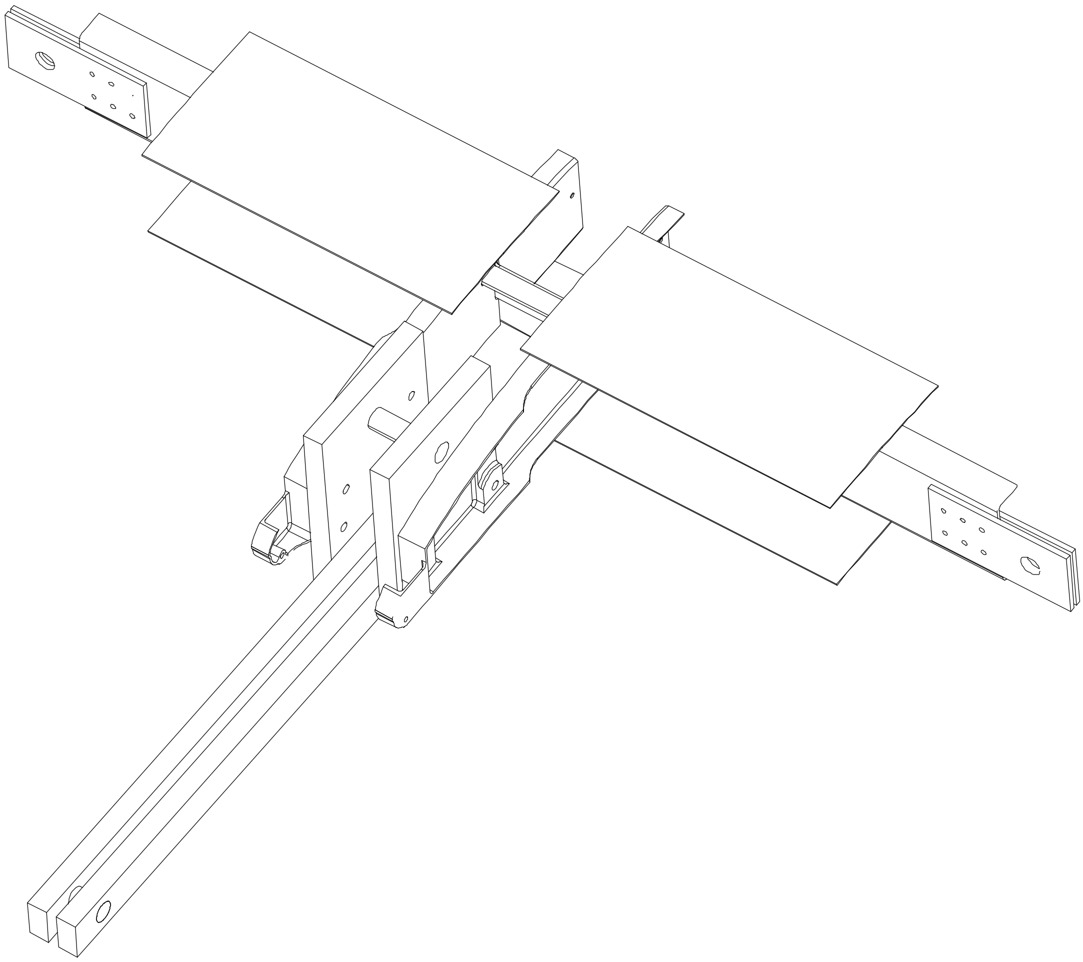

Fig. 5: Spar Sub-Component Fatigue Test Article

The test article was impacted with the same tup used for the coupons to produce BVID and visible impact damage (VID) at two predetermined sites prior to testing. For both impacts a 6-mm (0.25-inch) compressed board and steel reaction surface was used to support the back face. BVID was impacted adjacent to the spar web cutout corner, which exhibited the lowest margin of safety from the FEA. An energy of 8 Joules (6 ft-lbs) was required which resulted in a damage size through the thickness of the spar web of 11-mm (0.45-inch) in diameter. The reasoning for BVID at this location was that barely visible damage could possibly occur during handling and assembly. VID was impacted at a location along the upper spar cap flange where the maximum bending cap strain occurred as predicted by the FEA. An energy of 136 Joules (100 ft-lbs) was required resulting in a damage size through the thickness of the spar cap of 25-mm (1-inch) in diameter.

Under four point bending the test article underwent: -

1. Spectrum fatigue for the equivalent of one lifetime followed by a static test to ultimate load to validate the structural performance of the BVID site.
2. A contact pulse echo ultrasonic (A-scan) on the VID site.
3. Further spectrum fatigue for the equivalent of three inspection intervals followed by a static test to limit load to validate the structural performance of the VID site.
4. A-scan of the VID site after the static test.

Fatigue testing of the two damage sites was performed sequentially because the strain fields required at the two sites were unfortunately not coincident for the corresponding loads. Since testing was conducted under room temperature ambient conditions, a load enhancement factor of 1.19 was used to increase the static loads to account for any possible material degradation that would result from elevated temperatures and humid conditions. Fig. 6 presents the test article in the Instron testing machine.

Fig. 6: Test Article Installation

Testing of the spar sub-component was completed successfully without incident. Pathology was performed on the two impact sites and it was found that the VID damage site had not grown in size during and at the completion of testing. The BVID site did exhibit growth indicating that the damage size was now 19 mm (0.75 inch) as compared to the original damage size of 11-mm (0.45-inch). However it was shown, with the assistance of the coupon fatigue life curve, that this damage growth was attributed to the overloading of the BVID site during the VID fatigue test and therefore was not a cause for concern.

IMPACT DAMAGE DEVELOPMENT WORK

Extensive development work was carried out to determine the correct energy levels required, with the corresponding support conditions, to produce consistent BVID. For all impacts a 20-mm (0.8-inch) diameter tup was used. Varying types of support conditions were used for impacting the coupons this involved using different materials to support the non-impact surface and impacting over an open window. It was determined that the impact energy was a function of the laminate thickness and the support conditions. Also the size of the damage was a function of the impact depth irrespective of the support conditions and energy used to achieve it. Therefore depth of impact should be used as a basis to quantify impact damage rather than energy.

In order to facilitate the certification process however it was agreed to use a known test standard for the support conditions; consequently the National Aeronautics and Space Administration (NASA) reference publication 1142 was used. This standard is designed to produce compression after impact specimens and comprised of clamping each coupon about its periphery and impacting over an open window. The coupons used in the fatigue test program were smaller in size; thus the impact test apparatus was modified to suit.

CONCLUSIONS

The coupon fatigue test results showed that the strain level corresponding to the endurance limit for the material with BVID was above the allowable strains used in the design. Also non-destructive inspection of the sub-component test article indicated no measurable damage growth at the impact sites. Consequently the test program successfully met the FAA requirements demonstrating that the C-130 flap design is insensitive to fatigue and has excellent damage tolerance capability.

REFERENCES

1. NASA 1142, NASA/ Aircraft Industry Standard Specification for Graphite Fiber/ Toughened Thermoset Resin Composite Material, 1985.