HERCULES C-130 LIFE EXTENSION PROGRAM

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1 *Introduction*

The Hercules C-130, in production by Lockheed Martin since 1956, is a large four propeller driven transport aircraft.

More than 2,350 C-130's have been built so far, of which about 600 are operated by the US Air Force. The average age of this fleet is about 32 years. As the intended service life was only 25 years, a huge retirement wave is on the way. If the current pace of withdrawals is maintained, the fleet will begin to lose airworthiness by 2013.

Replacing all 600 aircraft is not an option, because a new C-130J costs $69 million and thus replacing the entire Hercules fleet would result in a total cost of $41.4 billion. Furthermore, Lockheed Martin will not be able to deliver 600 aircraft by 2013. That is why a life extension program, to lengthen the operational life of the current fleet is the only viable option.

2 Project definition

The Mission Need Statement (MNS) is an imperative statement which expresses what the DSE team has to perform. For this project, the following mission need statement was chosen:

"Extend the operational life of the C-130 past 2040, increasing availability rate and lowering maintenance costs."

Closely related to the MNS, the Project Objective Statement describes the approach the team took to satisfy the mission need.

"Present the US Air Force with a solution which will extend the operational life of the Hercules C-130 past 2040, by updating materials and technologies with a group of 10 students in 10 weeks time"

3 Requirements

All structural repair and replacement approaches for the primary structure should be in compliance with the top level requirements which are marked by the following list:

Structural requirements

- Structural inspection should be eliminated during the extended life and the inspection
- Complexity should be reduced (visual inspection is preferred).
- The repaired or replaced structures should be highly damage tolerant (more than original parts), considering the aggressive environment in which the airframe is operated, since there can be lots of bullets in the air.
- Corrosion and fatigue should be eliminated as life-limiting mechanisms
- The design for structures to be replaced should also be applicable to future production of this transport aircraft with a design service goal of 80 years.
- The developed life extension solutions should be at least weight neutral, but weight reduction is always preferred (not the highest priority).

Economical requirements

- The production costs of new structural replacement designs should be equal to current structural replacements.
- The operational costs are the main driver within the project (inspection and maintenance are costly and limit availability) and should be the absolute minimum

4 Problematic areas

When attempting to extend the operational life of an aircraft, the first step is to identify the areas that limit the life span. For a military aircraft such as the Hercules C-130, finding information on possible life limiting issues is a difficult and time consuming process. However, after an extensive literature study, the following problematic areas were identified.

- Fuselage
- Trailing Edge
- Outer Wing Box
- Center Wing Box
- Avionics

- Landing Gear

Since the emphasis of this project was on material and aircraft structures, avionics was discarded. This was further motivated by the fact that several avionics modernization programs are already widely available for the C-130.
Further research showed that a redesign of the landing gear would only lead to marginal improvements. It was therefore decided to discard the landing gear as well.

After this first trade-off the outlines of the life extension program were made visible.
In order to extend the life of the aircraft past 2040, the following problematic areas were offered a solution.

Fuselage
The fuselage mainly suffers from impact damage due to runway debris and enemy fire.
A basic solution that was conceived of is a so called “patch”. Essentially a sheet of Glare, it is bonded or riveted against the damaged area. This technique can also be used for the repair of fatigue cracks on the fuselage skin, although this is not yet a problem on the current C-130 fleet.

Trailing Edge
The original trailing edge suffers from corrosion, which is formed due to the combination of engine soot and water. Furthermore, fatigue is a serious issue. In order to effectively solve the corrosion and fatigue problems, new materials will have to be implemented. To facilitate maintenance, part count has to be reduced. Combining the latter two, the trailing edge will have to be completely redesigned.

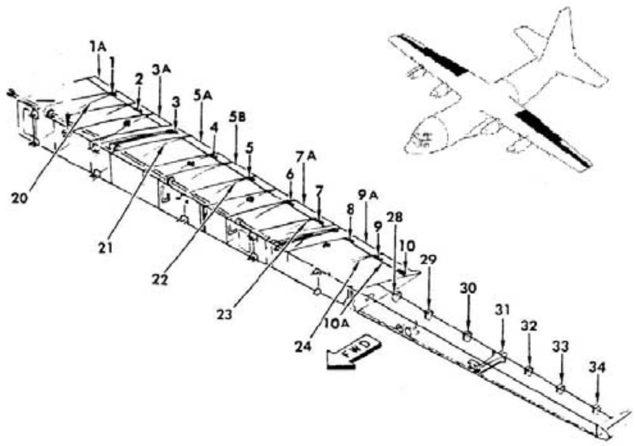

Figure 2.1: Trailing edge of C-130

Outer wing box
In the current C-130 fleet, the outer wing box has several smaller problems, related to corrosion and fatigue. The cost of replacing the outer wing box with respect to the benefit in maintenance is small, because a new outer wing box eliminates the aforementioned corrosion and fatigue problems and part count is reduced as well.

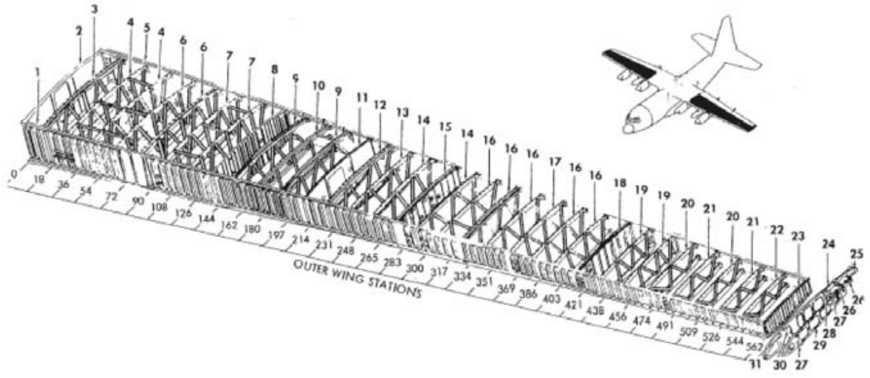

Figure 2.2: Outer wingbox of C-130

Center wing box

Research showed that the center wing box (CWB) is the largest driver in maintenance costs. A redesign of the CWB is therefore a bare essential in the life extension program.

The CWB can be split up into two main problematic areas, the rainbow fitting and the lower skin area.

The rainbow fitting is the connection of the center to the outer wing box. It is prone to cracking due to the high cyclic loadings. Since MERCER Engineering Research Center is already working on a redesign of the rainbow fitting, it was decided to only treat the lower skin area.

Due to the time constraint of ten weeks, only one item was chosen to be worked out in detail. This was further motivated by the wishes of the US Air Force. They made clear that they preferred a narrow but detailed solution instead of a broad but general solution

After a trade-off the CWB redesign was selected to work out in detail.

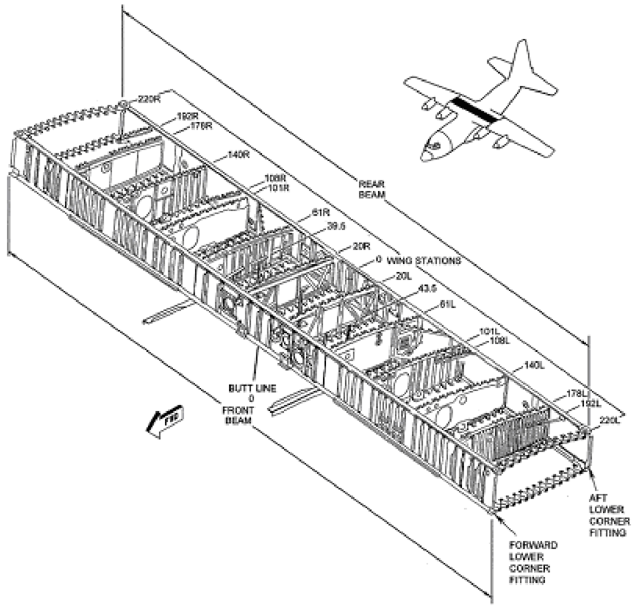

Figure 2.3 Center wing box of the C-130

5 CWB detailed design

The CWB is chosen as a showcase for the feasibility of the whole LEP. Requirements are first identified. Secondly design options are created and the design option which best matches the requirements is chosen and further developed. To check whether the chosen design meets the loading requirements, the C-130 flight envelope was modeled. This model was then used to verify whether the chosen design satisfies the loading requirements. If the requirements were not met, the design was further tweaked until all requirements were satisfied.

Fiber Metal Laminates (FML) are composite materials combining the performance benefits of both metals and composites. Glare is a FML developed at TU Delft, combining aluminum with glass fibers. Because Glare has significantly better fatigue properties, it is the material of choice for the new design.

The lower surface panel is an assembly of skin panels and stiffeners. The design options, with the material selection in mind, come down to the following list:

1. Aluminum panel and stringers
2. Glare panel with aluminum stringers
3. Glare panel and stringers
4. CentrAl panel with aluminum stringers
5. Composite panel and stringers

As can be seen above, the only difference between the different designs is the material selection.

Because pure composites are difficult to inspect when it comes to impact damage, and because the C-130 is operated in a hostile environment, option 5 can be eliminated immediately.
The use of two different materials induces complex loading patterns on the structure and it was therefore decided to eliminate options 2 and 4 as well, which reduces the design selection to option 1 and 3.
Because of the better fatigue properties of Glare, it was decided to continue with option 3.

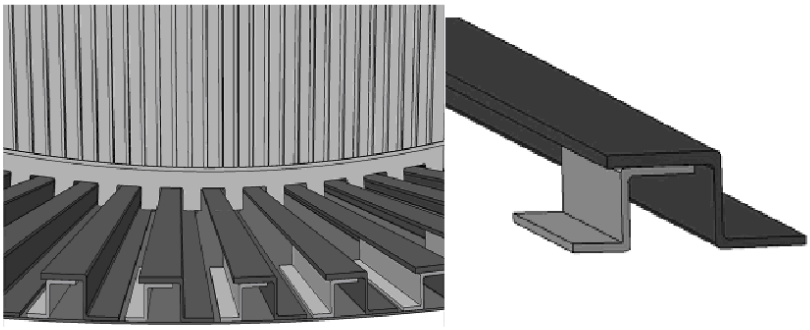

Figure 2.4: detail of the center wing box

In the original design, hat stringers were used. This made visual inspection impossible, because of the enclosed area. As can be seen in figure 2.4, the new design contains Z-stringers, which do not have an enclosed area. However, to reduce the impact on the surrounding structure the connection between the rainbow fitting and stringer was left unchanged. This connection was originally designed for a hat stringer. A transition between Z and hat stringer thus had to be created. This transition, the light gray part in the right of figure 2.4, is basically a mirrored Z-stringer attached to the end of the original stringer.
To attach the stringer to the skin, a hybrid bond is used. Hybrid bonding is a technique where rivets are applied on a bonded joint. The need for rivets flows down from the inspectability requirement. Ballistic tests show that purely bonded joints show very little visible damage after impact, although damage is definitely present. The rivets are there to assure a structurally safe joint after impact. If the Center Wing box does not have any impact damage, the bonding transfers all the loads and the rivets are there "just in case".
Bonding has superior fatigue characteristics because it has very little stress concentrations with respect to riveted joints.
The combination of bonded Glare Z-stringers on a Glare skin should dramatically increase the fatigue life of the Center Wing Box.

6 Results

The results can be split up into structural and financial improvements.
The fatigue is the main structural improvement, which is discussed below.

Fatigue

The new design is based on the same stiffness and buckling resistance as the current CWB. The fatigue resistance is improved. Due to higher stress levels in the Glare panel, the crack initiation begins at a lower number of cycles compared to the aluminum panel; This can be seen in figure 2.5. However, a Glare panel has not reached its end of life once a crack has initiated. Cracks in an aluminum panel grow exponentially and reach its critical value far sooner than a Glare panel. In Glare stresses are redirected around the crack, As can be seen in figure 2.6. This reduces the crack growth significantly. The result is a slowly increasing crack length. A fatigue life calculation, figure 2.5, shows the described behavior. The fatigue life the CWB is now assumed to be doubled.

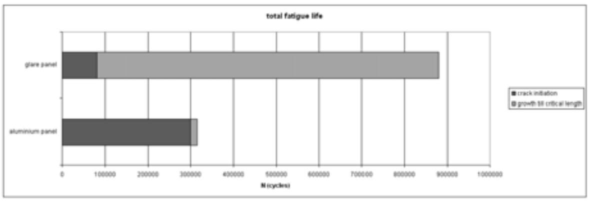

Figure 2.5: total fatigue life for the aluminum- and Glare panel

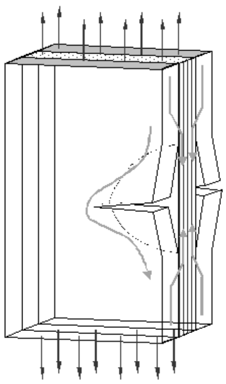

Figure 2.6 redirecting stresses around the crack in a FML

Financial

The LEP is based on cost reduction in the operational life. This reduction is achieved in two steps. First the maintenance costs per flight hour are lowered. Secondly the operational life is assumed to be doubled. This means that a very costly replacement can be left out. In figure 2.7, these two changes are made clear. The sudden jump in costs of the "New" aluminum design curve indicates the aforementioned replacement. The "Glare" Center Wing box does not have this jump because it does not need another replacement due to the doubled fatigue life.

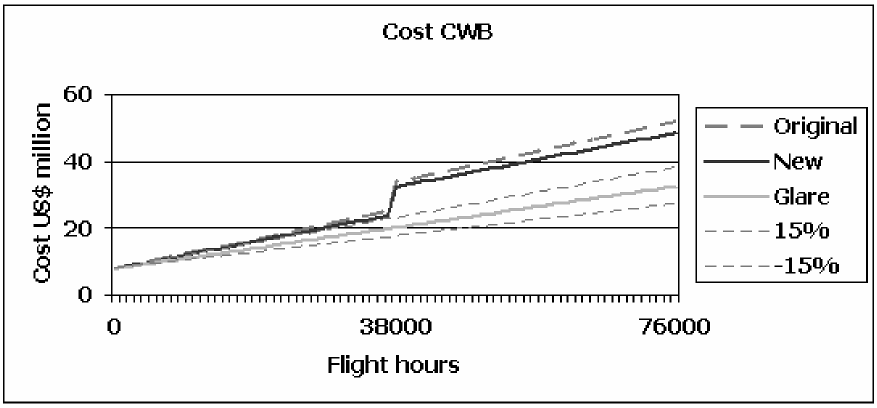

Figure 2.7: Qualitative CWB cost per life cycle

7 Conclusion and recommendations

The United States Air Force is in need of a solution for the aging problems posed by their Hercules C-130 fleet. Fatigue and corrosion are the main problems. Furthermore the complexity of the original design complicates maintenance. The fifties design offers a lot of opportunities for improvement, in material use, jointing techniques and structure design.

Four different areas should be addressed to assure a life extension up to 2040. The center wing box is the part of the airframe that contains the most serious problems. Therefore this part is selected to be redesigned.

Two major areas of improvement are the rainbow fitting and the lower surface panel.
The rainbow fitting is currently redesigned by other parties. Therefore the lower surface panel provides the most room for improvement.

Fiber metal laminates, such as Glare, are very good composite materials to deal with fatigue problems. Although cracks initiate earlier in Glare than in monolithic aluminum, the crack growth is slower, resulting in a much longer life. The proposed design of the lower skin is a Glare skin with Glare Z-stringers bonded and riveted on top, this technique is called hybrid bonding. This redesign more than doubles the fatigue life.
Ultimately this will improve the overall performance of the proposed center wing box.

The improved performance has its effect on the life cycle cost. The need for inspectability and maintenance is lowered. Depending on the strengthening of other parts these cost can be decreased by 30%. Additionally the operational life is doubled, so a replacement can be omitted. This will lower the operational cost about 15%.

Further research has to be done with multiple participants and more accurate data. This study has clearly illustrated the advantages of FML's. A more detailed design with more accurate knowledge can achieve even better performance.