Evaluation of the pressurization conditions on the aircraft C-130

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Abstract

This study focus on 2 problems related to pressurization of airplanes, pressure leaks and pressurization affect on the fuselage's structure, specifically for Lockheed Martin C-130. For the first it was identified standard procedures for detection and repair and sealing of leaks It was made a practical follow up of the procedure, not just detection of leaks but also sealing and leak's removal. The second study was relative to the impact of the pressure differential on the aircraft's structure and the quantification of the maximum pressure loads. Given the C-130 has a non-circular pressure vessel, where there is the Main Landing Gear, it was made a Finite Element Analysis to be able to study the loads on the connection areas and transferable loads. It was also made a FEA analysis on one of the MLG beams, using CAD, making it possible to compare analysis as well as the results' validation.
Keywords: Aircraft, Fuselage, Leaks, Pressure Differential, Pressurization

1. Introduction

This study is focused on an internship made at OGMA on the subject of pressurization problems on aircraft Lookheed Martin C-130 H. The problems with the pressurization are divided into two types, pressure leaks on the aircraft and structural impact of the pressure differential. The main objective is to study and evaluate the conditions of pressurization on aircraft C- 130. With this it is intended to better understand pressure leaks on the aircraft, how to anticipate them and how to better seal them. The second goal is to characterize the impact of the pressure on the structure, more specifically on non-circular structure cross sections, where failures due to pressurization have appeared.

1.1. Lockheed Martin C-130

The Lockheed Martin C-130 is a four engine military aircraft that has been in continuous production for over 50 years. The plane was designed to transport troops, cargo and medical aid having the capability to use unsuitable runways. The success of the aircraft led it to expand its use, nowadays there have been reported missions of search and rescue, scientific research, assault, fire-fighting, among others. There are more than 40 models and variants of the C-130 which serve over 60 nations worldwide.[2]

1.2. Problem Statement

As the years add up, it is common that some pressurization leaks start to appear in an aircraft. These leaks can be associated with extensive flight hours, rough landings, tough missions or simply with the stresses felt in the plane during normal use as well as the adverse effects of the weather and the environment. They can also appear due to some intervention on the plane in order to repair some other problem. Leaks in the cabin will certainly appear sooner or later.

In a maintenance environment, specially on a plane like C-130, pressurization is always a problem. Its not because its hard to repair, usually it just needs more sealant, the problem is how to detect the leaks and when you detect them. It is very common for leaks to be detected on final testing after maintenance which puts the plane back into repairing.

2. Background

2.1. Fundamentals

Throughout it's life an aircraft is subjected to various external loads whether the plane is flying or on the ground. These loads are transferred to internal loads applied on the structure of the aircraft. There are three categories of structural loads which are:

- Operating Loads: Loads experienced during normal service.
- Limit Loads: Maximum loads expected during service.
- Ultimate Loads: Limit loads multiplied by a safety factor to account for unexpected static or dynamic loads.

An aircraft's structure must be able to carry the limit loads without exceeding the yield stress of the materials and must be able to sustain the ultimate loads without failure. The ultimate loads are also referred as design loads given that these loads are the reference for the structural design of the plane and the material selection. [3]

2.1.1 Fatigue

A structure subjected to frequent and repeated stresses can suffer from fatigue failure even if they're lower than the material's yield stress. Fatigue failure usually originates cracks which due to lack of deformation are mostly detected when substantial growth has occurred. Fatigue is structural damage that the material takes when subjected to cyclic loading meaning that fatigue life of a material is the number of cycles it can sustain of a certain load before cracking. [6]

2.1.2 Joints

There are several failure modes which can affect a joint and all of them have associated an allowable load. By determining the allowable load for each mode there can be established which is the critical failure mode for a certain joint. [5]

The failure modes are commonly divided into the five categories:

- Net Tension
- Tear Out
- Bearing
- Fastener Shear
- Transitional Failure

2.1.3 Finite Element Method

The Finite Element Method (FEM) seeks an approximate solution based on the principal that it is easier to represent a complicated function as several simple polynomials (Figure 1). Therefore FEM sees a given domain as a collection of sub-domains governed by any of the traditional variational methods. Each of these sub-domains has to fit it's surroundings, given that, the functions and the derivatives up to an appointed order are continuous in the points of connection. [8]

2.2. Pressurization on aircraft C-130
When the aircraft is pressurized it means it has more pressure inside than outside. As altitude increases the Atmospheric pressure decreases and, if the interior pressure is kept constant, the differential in pressure between the inside of the aircraft

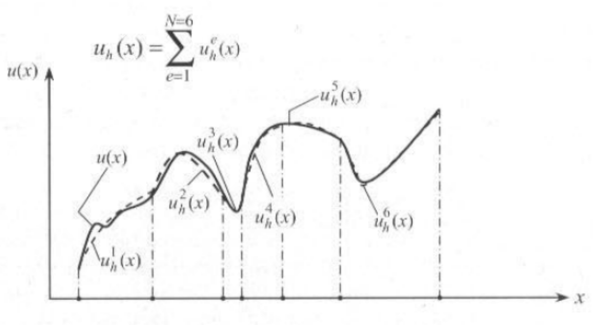

Figure 1: Approximation of a complicated function by a collection of simpler polynomial functions. [8]

and the outside will increase. Therefore there are two pressures involved, the outside pressure, referred as Atmospheric pressure, and the inside pressure, known as cabin pressure. The cabin pressure is the pressure felt by the crew and it can be maintained given that it respects the maximum differential of pressure the airplane's structure can withstand.

2.2.1 Pressurization system

The ideal pressure is the sea level pressure of 1 bar or 29.92 inches of mercury (29.92" Hg). The structure of the C-130 can withstand a maximum differential (MAX DIFF) of 15.0" Hg, which is equivalent to 5.18 tonnes/m^2. Pressurizing the aircraft uses the air from both the air conditioning and the under floor heating systems controlling it's outflow to the atmosphere. The pressure in the aircraft as well as the pressurization process is controlled by the opening and closing of the outflow valve. This control can be either automatic or manual. The pressure controller on the aircraft performs four tasks. It can keep the aircraft unpressurised when needed and can maintain a selected cabin altitude between -1000 ft and +10000 ft. It also controls the rate at which the cabin pressurizes or de-pressurizes from 20 FPM (feet per minute) to 2900 FPM. The pressure controller also limits the maximum pressure differential to 15" Hg.[2] The outflow valve is a butterfly type valve. The vent to cabin regulates the pressure in the lower chamber, setting it to the cabin pressure, which is separated from the upper chamber by a diaphragm. This diaphragm controls the opening and closing of the valve and it's held down by strings. If the pressure on the upper chamber lowers the diaphragm will be sucked upwards opening the valve. The valve is closed when both pressures on the chamber are equal. The pressure controller will control the pneumatic relay that opens and closes the outflow valve. This control is based on the settings for cabin altitude and rate of climb. It will also assure that the pressure differential doesn't go higher than 15" Hg. Figure 2 shows the complete diagram of the outflow and pressure controller interaction. [2]

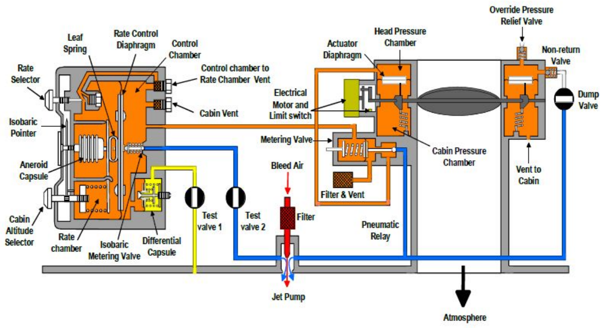

Figure 2: Pressurization control complete diagram. [2]

The airplane also possesses a safety valve to act when any malfunction occurs to the pressure control systems aforementioned. The safety valve will open when the limit of 15" Hg is exceeded by 1 inch, when the pressure outside is higher than the pressure inside by 0.76" Hg or when emergency depressurization switch is turned on. There is also an emergency de-pressurization door in an escape hatch in the middle of the plane that can be opened manually.

3. Pressurization Leaks

When an aircraft goes to maintenance the first step into solving pressurization problems is finding out if there are any. The plane is pressurized according to the pressure decay method, a Lookheed procedure in which the plane is pressurized and analysed the time it takes for the pressure to decrease from 8" to 6" Hg. If the time is below the limit set for the aircraft there are excessive leaks.

3.1. Where to find leaks

In this procedure certain areas defined as the most common places for leaks will be checked thoroughly. These areas include all the emergency exit, paratroop and crew entrance doors as well as both swinging windows, the ramp and the cargo door. Pressure panels and inspection windows are also usual places for leaks. There are several more places which are defined as crucial when searching for leaks. Any area which suffered structural reparations could also present pressurization leaks if not properly sealed.

3.2. Inspection of cabin for pressurization leaks

Once established that the aircraft has pressurization leaks the essential is to find out where they are. In order to do it there is a procedure to follow where the plane, while on the ground, is pressurized to a minimum of 2.0" Hg differential. Cabin leakage can be found through feel and in some cases identified by hearing a whistle but the best method is by using a detection fluid or a soapy solution applied on certain areas. Figures 3 and 4 show some leak tests being made on an aircraft by increasing the inside pressure to a differential between 2 and 3"Hg and applying the soapy solution on the joints and most common places.

Figure 3: figure
Soapy solution being applied

Figure 4: figure
Solution's reaction when there is a leak

3.3. Sealing procedures

The products used for sealing consist in a mix of two components, a base component and an accelerator. These products have various packages and can be obtain with the components separately for future mix or frozen but already mixed. The use of adhesion promoters can help to chemically enhance the sealant adhesion and, in some cases, it is highly recommended. For the sealant adhesion as well as the seal it self to succeed it is imperative that the surface is prepared accordingly. [7] Figures 5 and 6 shows sealant after application to eliminate leaks on the ramp door of C-130.

4. Pressurization's effect on structure

The effect of the pressurization on the structure of the fuselage is felt through the difference between the inside and outside pressures, as stated before. As the environment pressure will decrease with altitude the pressure felt on the structure will have the direction from the inside to the outside, forcing the structure to expand, as shown in Figure 7.

The pressure p is equal to the differential of pressure, Δp, between the cabin pressure and the atmospheric pressure. For example, a plane flying at 5000 feet (approximately 1500 meters), pressurized to have sea level inside pressure ($14.69 PSI = 101.284 KPa$), will have a pressure differential of $\Delta p = 2.46 PSI = 16.96 KPa$ which will be the pres-

Figure 5: figure
Sealant application 1

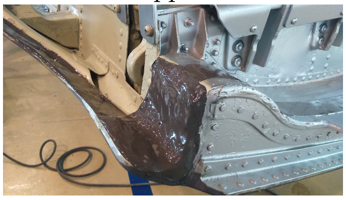

Figure 6: figure
Sealant application 2

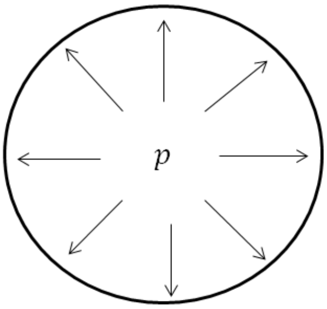

Figure 7: Pressure felt in the structure of a pressurized plane at high altitude

sure felt by the structure.

4.1. Pressure Vessels

When there is internal pressure applied to a cylindrical pressure vessel there are three stresses to be considered, the radial stress σ_r, the axial stress σ_z and the hoop stress σ_θ. The thickness of the skin is very small compared to the radius of the fuselage, $r >> t$, meaning that the radial stresses, which are equal to the internal pressure, can be neglected in comparison with the circumferential or hoop stresses, which are proportional to the ratio r/t. The axial stress and the hoop stress, shown in Figures 8 and 9,can be calculated using equations 1 and 2, respectively. [9]

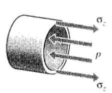

Figure 8: figure
Axial stresses. [9]

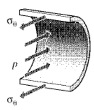

Figure 9: figure
Hoop stresses. [9]

$$\sigma_z = \frac{pr}{2t} \tag{1}$$

$$\sigma_\theta = \frac{pr}{t} \tag{2}$$

The hoop stresses are twice the axial stresses which means that the structure has to withstand greater loads in the circumferential direction.

Not all pressure vessels assume circular cross-sections. Considering a vessel with rectangular cross-section, at the same internal pressure the structure would bend towards a circular cross shape presenting critical points in the edges, as represented in Figure 10. [10]

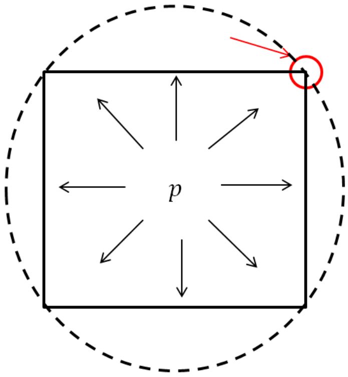

Figure 10: Rectangular pressure vessel

To quantify the loads applied in a rectangular pressure vessel, there will be studied the influence of pressure applied to a beam constrained of translations and rotations on both edges as shown in Figure 11.

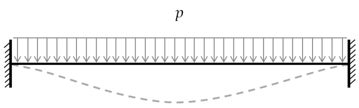

Figure 11: Loading system and geometry with boundary conditions

For this Figure 12 represents the shear force which is symmetric in relation to the point $(L/2, 0)$ having the maximum absolute values in both clamped edges.

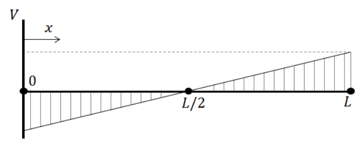

Figure 12: Diagram of the shear force

In similarity with the shear force, the bending moment will also present the maximum absolute value in both edges. Figure 13 represents the bending moment diagram with the respective maximum and minimum values.

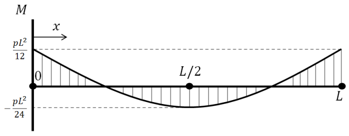

Figure 13: Diagram of the bending moment

On the contrary to what happens in a circular cross-sectional vessel, where the stress is uniform throughout the circular length of the structure, in a rectangular vessel both the shear force and bending moment present their highest values in the edges. Hence when studying a non circular vessel those should be the critical points to study.

4.2. Main Landing Gear support structure

The structure which supports the Main Landing Gear (MLG) of the Lockheed Martin C-130 is particularly different than most planes due to the fact that the C-130 is a high wing aircraft, and the landing gear has to transfer loads from the wheels to the wing. The structure of the wheel well presents two major beams on each side that connects the landing gear to the centre wing and several other beams that strengthen the structure. This particular section of the fuselage of the plane doesn't present a circular cross-section shape like the rest, instead it is straight on the sides from the bottom all the way to the centre wing, as shown in Figure 14.

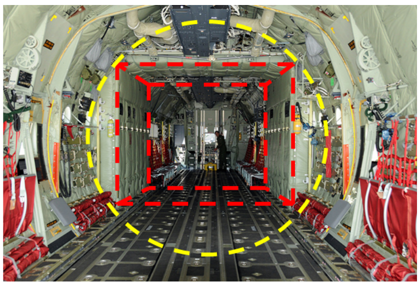

Figure 14: figure
Skin delimitation

Therefore the section of the fuselage which supports the MLG (wheel well structure) works as a non-circular pressure vessel when the plane is pressurized, on the contrary to usual fuselages which work has a cylindrical vessel. Figure 15 shows the C-130's fuselage.

The main wheel well structure is an all-metal structure composed of skin, beam assemblies, frames and tracks. The beam assemblies, frames and tracks can all be treated as beams with very different cross section which give them different purposes and characteristics. These beams are made of aluminium alloy 7075-T6 and the skin is aluminium alloy 2024-T3.

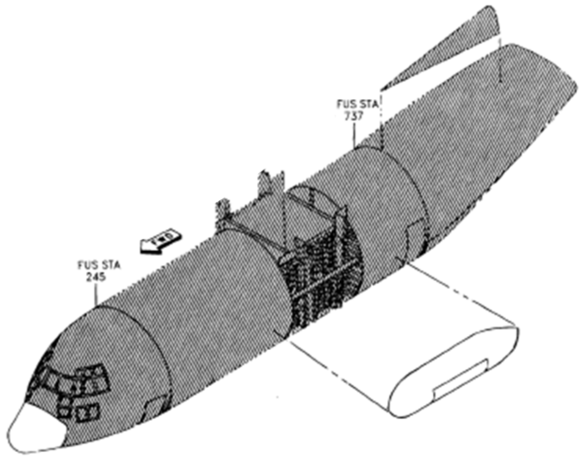

Figure 15: Fuselage of the Lockheed Martin C-130. [2]

The MLG structure connects to the centre wing through a series of bolts on each beam. There are frequent inspections to these bolts because from time to time fractures are found. Figure 16 represents the inside of the MLG structure showing in detail the bolts that connect the MLG beams to the spar of the centre wing. Figure 17 shows a fractured bolt that was removed from an inspection on this connection.

Figure 16: figure
MLG view from inside

Figure 17: Fractured bolt

4.3. Structural design

The structure of the wheel well which supports the MLG is presented in Figure 18. It is a structure with 3.2 meters in height and 3.5 meters in length.

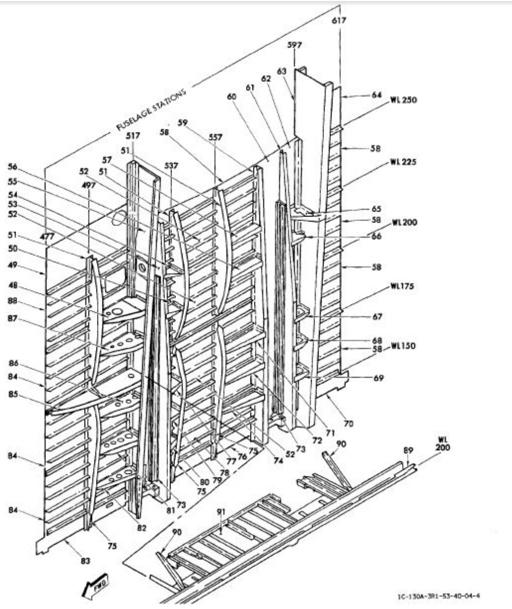

Figure 18: Wheel well structure. [2]

Using technical drawings of all the beams and reinforcement parts as well as assembly drawings for the structure itself it was designed a model of the wheel well structure using the interface of ANSYS Mechanical APDL. The interface was chosen for the development of a Finite Element Analysis of the structure and in order to facilitate de meshing and analysis the modelling was also made using this interface.

4.3.1 Modelling

The structure was modelled using three types of elements, Beam elements, Shell elements and Link elements. Given the complexity of the structure Solid elements were not used due to the number of nodes and elements it would be necessary to make the Finite Element Analysis with an acceptable mesh. [1]

Element BEAM188

This element can support different cross-sections, therefore it were developed cross-sections for all the different beams in the structure, some were also tapered according to design specifications. It were used the standard type beams I and CHAN, but for some beams it was created and imported specific sections as you can see in Figure 19.

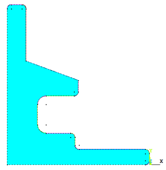

Figure 19: figure
Example of a created section for the structure

4.3.2 Meshing

One of the most important steps of the FEM analysis is the mesh of the structure. The ideal mesh will present the smallest error possible while demanding reasonable computer capabilities. The mesh built around the MLG structure was mapped and created using 2 reference values, one on the beams and one on the outer lines of the skin. This made it possible to test several mapped meshes including meshes more refined around the beams and less refined on the skin away from the loads. Using this it was possible to reduce the number of elements without affecting the results. Figure 20 presents and isometric view of the mesh.

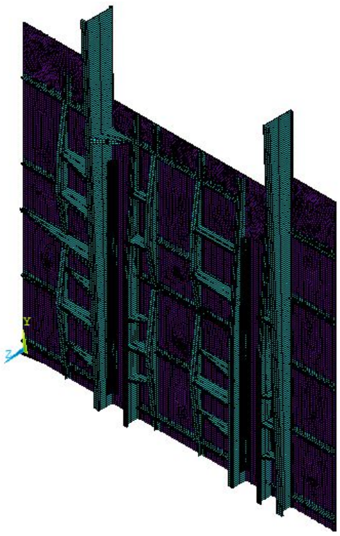

Figure 20: Isometric view of MESH 2

4.3.3 Loads and Boundary Conditions

For the boundary conditions of the Main Landing Gear structure it was assumed that the top angle wouldn't have displacement on direction z (see figure 21 for axis directions) due to the fact that both right and left angles are connected to the centre wing meaning they couldn't have displacements in opposite directions. For the left, right and down sides it was assumed that the structure wouldn't have displacement in all three directions x, y and z because firstly the geometry of the structure indicates the displacements any minimal if they exist, secondly it is very difficult to predict the behaviour of the structure with detail on this connections and thirdly the study objects are mainly on the top connection and so this assumption should have a almost insignificant affect on the results. See figure 21 to check the boundary conditions on the MLG structure.

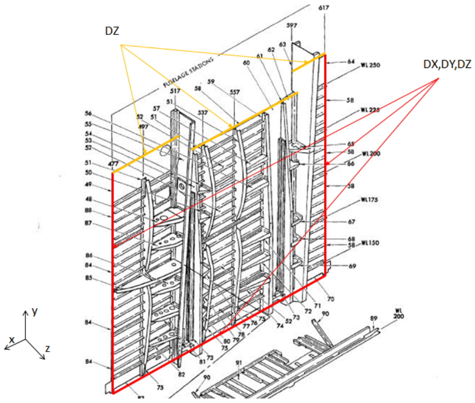

Figure 21: Boundary Conditions on the MLG strcture

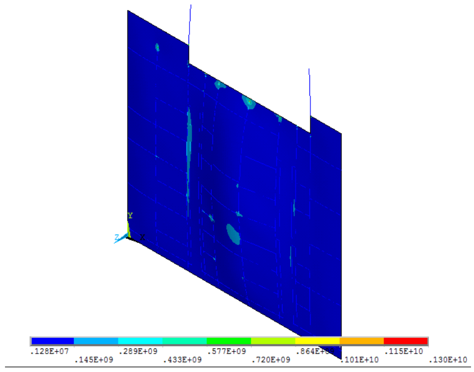

Figure 23: figure
Stress intensity results

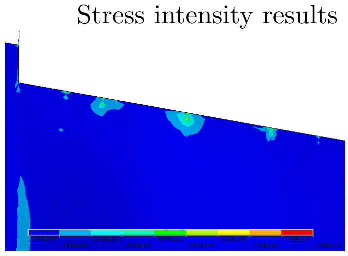

Figure 24: figure
Stress intensity detailed

4.3.4 Analysis

After modelling the geometry, defining the boundary conditions and applying the loads due to pressurization it was made a static FE analysis.

The results start with the displacement vector sum in Figure 22 and stress intensity in Figures 23 and 24. This first results will give us a primary indication if the simulation was successful.

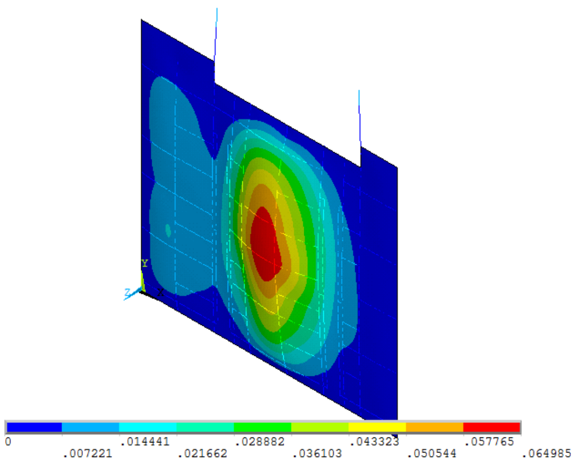

Figure 22: Displacement results

To understand and take conclusions from the results it is necessary to define the connecting elements applied in the structure. The C130-H is an airplane that was in production for many years and had a lot of changes throughout all those years. The bolts used to connect the MLG structure and the centre wing are one example of those changes. As per drawings, Bolt NAS1104 was applied up to Serial Number (S/N) 4109 but was replaced by NAS1105 starting from S/N 4110. The difference between the two is the diameter, NAS1104 has a diameter of 1/4in whereas NAS1105 has 5/16in. The material is the same in both cases, Alloy Steel 4140.

Using the Fundamentals for Shear Failure we can calculate the maximum load that meets the ultimate criteria for both NAS1104 and NAS1105 bolts (Figure 25).

BOLTS	S/N	DIAMETER	σsu (N/m^2)	Pfs (N)
NAS1104	up to 4109	1/4 in	8,274E+08	**26202,2**
NAS1105	4110 & up	5/16 in	8,274E+08	**40940,9**

Figure 25: Maximum load that meets the ultimate criteria for the connecting bolts

To compare the maximum load of the bolt to the result of the FE analysis it is necessary to detail the loads given by the analysis for each bolt and isolate the maximum shear load in a bolt for each connection. If we place the connections by its Fuselage Station (FS), as previous shown in figure **??** and compare the values to the maximum loads for NAS1104 and NAS1105 previously calculated we get the table from figure 26.

See figure 27 to associate the fuselage station to

Connection	Max Shear Load	NAS1104	NAS1105
FS 497	22898,59	OK	OK
FS 517	98356,56	NOT OK	NOT OK
FS 528	28858,18	NOT OK	OK
FS 537	22168,95	OK	OK
FS 557	3003,68	OK	OK
FS 577	34967,66	NOT OK	OK
FS 588	39521,81	NOT OK	OK
FS 597	70569,39	NOT OK	NOT OK

Figure 26: Maximum shear load in a bolt for each connection

the structure modelled in ansys.

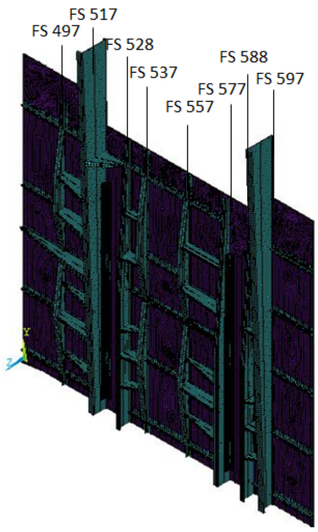

Figure 27: Fuselage stations in ansys structure

4.3.5 Results conclusions

There are several conclusions to take from the FEA presented: 1 - Both beams from FS 517 and FS 597 have bolts with shear loads highly above the maximum load for bolt NAS1105. This was expected because the beams extend past the area being analysed and functions as a rib for the spar of the centre wing. These beams are essential to the structure of the MLG but we cannot take any conclusion from its bolts without simulating the entire spar of the wing. For this both beams will not by analysed and both results are irrelevant; 2 - Having in consideration conclusion number 1 it is fair to assume that the shear load on the connections is one of the reasons, if not the main reason, for the change in bolt diameters in S/N 4110; 3 - The structure was simulated with all the stiffeners, angles and beams in the structure but it wasn't taken in account the reinforcements in the skin itself which would offer additional resistance to the pressurization of the cabin; 4 - All the beams were simulated using beam elements which simplified the analysis but doesn't guarantee reliable results for practical applications. To modulate all the structure with solid elements was too heavy to simulate.

From the four conclusions of the first FEA it was decided to make a second analysis but considering only a beam from FS 577 (figure 28), similar to FS 528 and FS 588, modelled using solid elements and subjected to the same pressure as the structure. This simulation will give us an idea of the role these beams represent in the structure and could give us a better understanding of the impact of the pressurization on the structure.

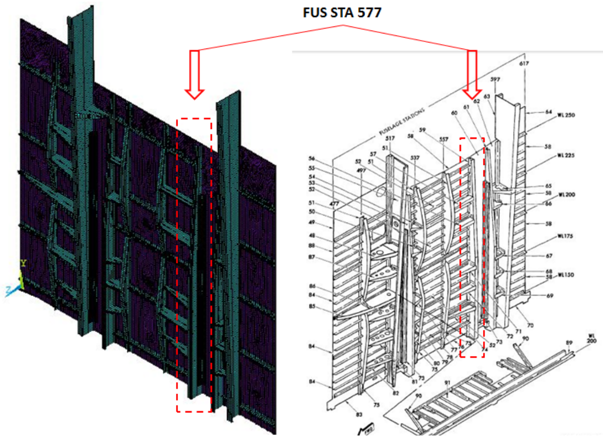

Figure 28: Beam from FS 577

4.4. Beam analysis

4.4.1 Modelling

Geometry development

The Beam was developed in the Solidworks ® environment which made it much easier to model the beam from the respective manufacturing drawing. In the structure of the Main Landing Gear the Beam as a reinforcement riveted throughout its length. This reinforcement was modelled as well to join the Beam in the Finite Element Analysis. The assembly of the Beam with the reinforcement modelled in Solidworks ® is shown in figure 29.

Bolts

The bolts were simulated with Rigid Body Elements (RBE) where the stud was simulated using Beam188 and the RBE are used for the head of the bolt. This elements transfer all the loads and well as bending effects using lesser elements than a solid simulation. That was the main reason to choose this type of simulation because there are a lot of solid elements on the beam assembly which require great computational capability and the

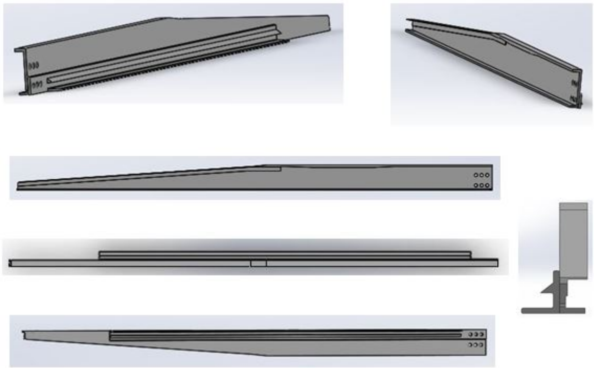

Figure 29: Beam assembly

RBE bolts can lighten the analysis and guarantee good results. [4]

Meshing

Given the complexity of the structure to develop the mesh it was used free meshing. This originated some processing problems and due to the high number of elements the refinement of the mesh was very limited. It was then manually resized the length of the elements on the lines, on the bolts side of the beam, which reduced the number of elements without affecting the simulation and eliminated the processing problems.

Loads and Boundary Conditions

The boundary conditions are follow the same principal as the first analysis, constrains in every direction on both bolts on one edge of the beam and constrains in every direction on the opposite edge, following the MLG structure. The loads applied are the same as for the first FEA, pressure on y direction equivalent to the MAX DIFF allowed by the safety valve which is 53843.57 Pa.

4.4.2 Analysis

Similarly to the first Finite Element Analysis we start analysing the displacement and the stress intensity on the beam due to the pressurization. Figure 30 is the displacement sum and figure 31 the stress intensity around the bolts.

For the second FEA it was only considered NAS1105 bolts and for this bolts, that have a diameter of 5/16in, the maximum load that meets the ultimate criteria is 40940.92N. The table in figure 32 shows the maximum shear loads in each bolt.

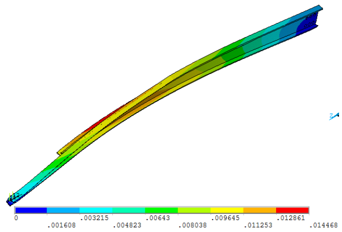

Figure 30: figure
Displacement sum vector

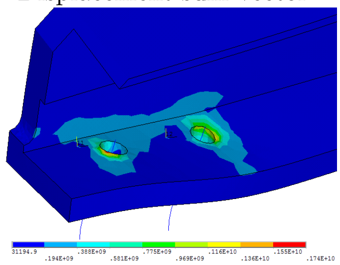

Figure 31: figure
Stress intensity

Connection	Max Shear Load	NAS1105
Upper Bolt	4770,53	OK
Lower Bolt	4930,31	OK

Figure 32: Maximum shear loads

4.4.3 Results conclusions

In conclusion we can observe several points: 1 - In this second FEA that the beam itself can sustain the loads from the pressurization without affecting the safety of the bolts; 2 - Conclusion 1 proves that the beams reinforce the MLG structure in a way it can sustain the differential in pressure due to cabin pressurization; 3 - The RBE elements used for the Bolts behaved according to predictions as the loads and stresses were transferred throughout the stud and head of the bolt and the solid beam. It proved to be a reliable solution to reduce the number of elements and facilitate the results outputs.

5. Conclusions

The focus of this study was the pressurization of aircraft Lockheed Martin C-130 H, how it works and how it affects the structure of the air plane. The pressurization system of the C-130 has the impressing characteristic of being all mechanical working with valves and pressure differentials forming a simple and intuitive system that has a very complex and important function, to regulate the cabin pressure. In order for the plane to be operational the pressurization system has to guarantee the ideal cabin conditions which depends on the system itself as well as on the ability of the structure to maintain the air inside the aircraft.

Pressure leaks are hard to detect and seal during maintenance, especially on an aircraft with more than 30 years of activity. It were made several changes in order to improve this process. In order to be able to seal pressure leaks during maintenance and repair it started to be made an inspection for pressure leaks on the arrival of the air plane. The leaks were documented to cross check with the maintenance job cards. It was also made possible to test the pressurization system of the cabin inside the hangars with a very reduced error by using an energy ground unit instead of the plane's APU (Auxiliary Power Unit). This allowed for the plane to stay inside when testing pressurization instead of having to move the plane outside, test it and bring it back to the hanger saving many man hours.

The main focus was to understand the pressurization's effect on the structure, especially around the centre of the fuselage where it worked as a non-circular pressure vessel. The structure has the critical areas around the joints where there are several job cards to inspect the connecting bolts, to verify if their torque is correct and if there are any cracks. The first FEA proved just that and came to validate the change in the bolt's diameters from NAS1104 to NAS1105 in S/N 4110. The simulations showed the structure can handle cabin's pressure but it lacks the loads from the wing and from the main landing gear.

The second FEA was based on one of the beams from the MLG structure. The first analysis used beam elements to simulate the beams and shell elements to simulate the skin whereas the second one used solid elements for the beam, which was made using a CAD environment, and RBE elements for the bolts. The beams give the structure greater resistance against the pressure and the analysis proved it.

The results on both simulations showed that the pressurization effect by itself doesn't exceed the ultimate criteria for the joints but might have a considerable impact if the added operation loads from the wings and from the landing gear.

5.1. Future Work

For future work it is proposed to study and analyse the flight loads of C-130 and their impact on the Main Landing Gear structure. To be able to join those loads to the pressure analysis would complement the work.

To be able to simulate the MLG structure with solid elements would also be a very interesting case study but would require great computational capabilities to do it using Ansys ®.

A fatigue, fracture and crack growth analysis on the bolts and on the connection is also a proposal for future work.

For aircraft sealing and pressurization tests it is proposed to make simulations using coloured Helium to be able to detect and quantify the leaks in the structure.

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