Failure analysis of a nose landing gear fork

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***Abstract*—** This paper presents a detailed analysis of a nose landing gear failure. The developed work comes following an accident occurred in which the nose of the landing gear's fork of a light aircraft bent during landing. Nose gear failures are a high concern in the aviation industry. According to Federal Aviation Administration, in average 55% of aircraft failures occur during takeoff and landing while the remaining occurs during flight

In order to determine the causes of the accident, a material analysis was performed, followed by a detailed study of the fracture's surface both visually and using optic and scanning electron microscopy. It was observed that the cracks developed in the vicinity of the bolted holes, which work as supporting connections, on the topside of the nose fork and, as such, it can be concluded that the referred area was subjected to cyclic stresses originating and propagating cracks inside the material. This cracking is characteristic of the existence of areas of stress concentration. After having identified the crack initiation zone due to the beach marks near the origin of the crack, combined with the fact that the nose wheel fork was subjected to cyclic loading, leads to the conclusion that the component failed due to fatigue. The Finite element analysis were also performed on the nose fork taking into account service conditions in order to assess the structural integrity of the referred component. During the analysis it was observed that the critical areas are located in the vicinity of the connecting holes due to the fact that they are stress concentrating features.

Keywords—aircraft; nose wheel fork; landing gear; fatigue; finite elements; fracture surface.

I. INTRODUCTION

The landing gear supports the entire weight of an aircraft during landing and ground operations. It is attached to primary structural members of the aircraft [1] and it is one of the most critical subsystems of an aircraft meaning that landing gear detail design is taken up early in the aircraft design cycle due to its long product development cycle.

The landing gear design takes into account various requirements that are stipulated by the Airworthiness Regulations to meet operational requirements of safety, strength, stability, stiffness, ground clearance, control and damping under all possible ground attitudes of the aircraft. Divakaran, Ravi and Srinivasa [2] present in their work an overview and challenges in landing gear design and development as well as how technologies help meeting each challenge.

Many manufacturers do not use Finite Element Analysis (FEA) to test the nose landing gear because the Federal Aviation Administration (FAA) does not require FEM as part of the approval process [3]. Although, some commercial available CAD/CAM/CAE/CFD and Dynamic Simulation software tools are used in the design and development of landing gears, many Knowledge Based Engineering (KBE) tools and information intelligence tools are being developed and used by landing gear designers to automate many engineering processes.

Several authors have studied landing gears, since the loads they are subjected to, design, optimization and finite element analysis. Horack [4] proposed an analysis of the landing gear structure. Yangchen [5] developed work on the light weight structural design and optimization of landing gears. The analysis of the landing gear using finite element method was proposed by Briscoe [6], Krason and Malachowski [7] proposed the finite element modeling of the landing gear and drop test simulation. An investigation of a nose landing gear failure was performed by Lal et al. [8] on fatigue fracture of a nose landing gear in military transport aircraft. A study developed by Al-Bahkali [9] with two different landing gear configurations for a light aircraft have been analyzed and modeled under different landing conditions

The aircraft under study has performed more than 17,000 landings, and being an instruction aircraft it has been subjected to high mechanical stresses and high vertical loads. The objective of this paper is to make an assessment of the component to determine the possible causes of failure. The adopted methodology involves a visual analysis, as well as an optical microscopy with low magnification of the fractured surface in order to characterize the type of fracture and identify areas of interest to perform a more detailed analysis through electronic scanning microscopy. Another step was to perform the analysis and numerical simulation using the finite element method in order to determine the stresses that the component is subject to and to understand the causes that may have led to the failure of the landing gear.

This paper will help landing gear manufacturers answer some questions related to the nose landing gear during landing, and the stress to which it is subject, so these answers can be used in the early stage of future the designs and in maintenance operations.

II. ANALYSIS OF FRACTURE SURFACES

The fractured component, Figure 1, was cut in order to allow for a more detailed analysis through optical and scanning electron microscopes. During microscopy analysis there was evidence of the existence of beach marks on the fracture surface, consistent with the occurrence of a process of material fatigue. These lines, commonly known in the scientific literature as "beach marks", result of plastic deformation of the material due to the effect of successive load cycles.

Figure 2 represents the mapping for observation under SEM, with different zones, each with its own morphological characteristics. The beach marks were observed in both surfaces covering approximately two thirds of the extension. The remaining portion, however, presents a distinct morphological pattern, characterized by a clear upper surface roughness caused by fragile fracture process, which occurs suddenly and precedes the full separation of the component. This fracture occurs due to resistance failure of the section not affected by the evolution of the crack front due to fatigue, since this causes a decrease in advancing the cross-sectional area that supports the mechanical loads acting there.

Figure 3 is an amplification of detail "A1" of Figure 2 which corresponds to the initiation zone of one of the fatigue cracks in which the shape of the fatigue surface indicates a propagation of fatigue crack with a curve front, which can be attributed to the existence, in the central zone of the specimen of an approximate state of plane strain, causing the existence of stress triaxiality and further advance breach in the referred area. Figure 3 indicates that the crack initiation does not occur due to any metallurgical defects or mechanical defects (e.g., machining, coating).

Another characteristic that can be pointed out, through the observation of the propagation of the fatigue crack region is the presence of beach marks (Figure 4). These lines display a pattern of uniform progression, without significant evidence of change in the direction of the crack front as a result of torsional effects. This evidence suggests that the fatigue process is mainly due to the cyclic bending stresses caused by the aircraft landings

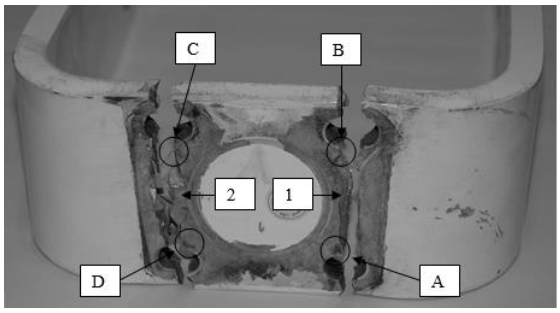

Figure 1 - Fractured component

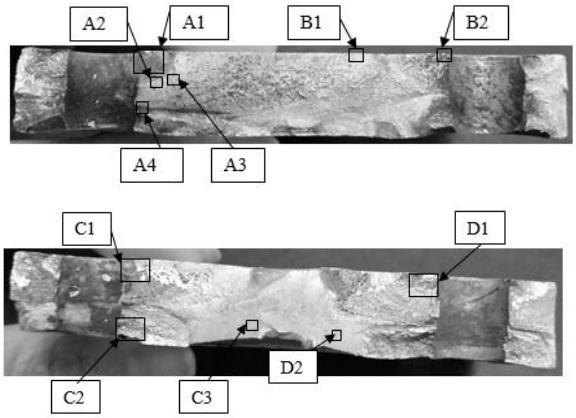

Figure 2 - Mapping of different areas along the fracture surfaces subject to SEM

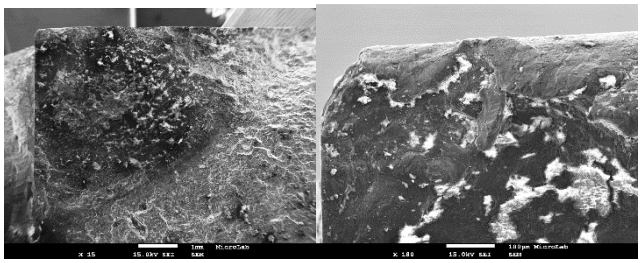

Figure 3 - Initial zone of fracture surface (detail "A1") and enlargement on right

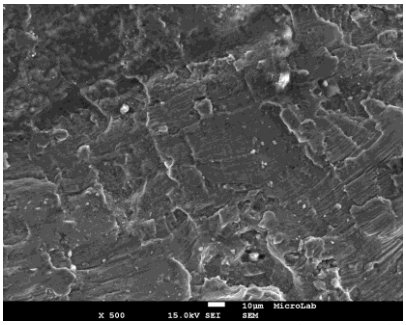

Figure 4 - Zone of crack propagation (detail "A2")

Figure 5 (magnification of detail "A3") confirms the existence of streaks on the fatigue fracture surface of the component. The transition between the stable crack propagation (fatigue) and the unstable propagation area (giving rise to total failure of the material) is visible in Figure 6 (detail "A4" of Figure 2).

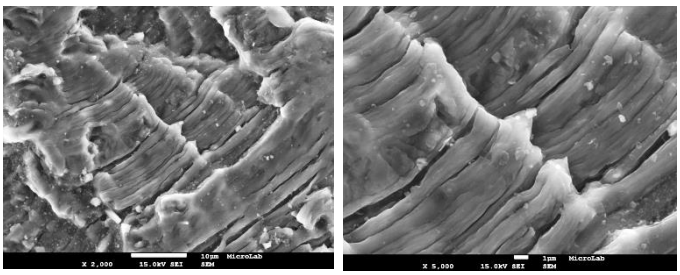

Figure 5 - Fatigue stretch marks in detail "A3" and enlargement on right

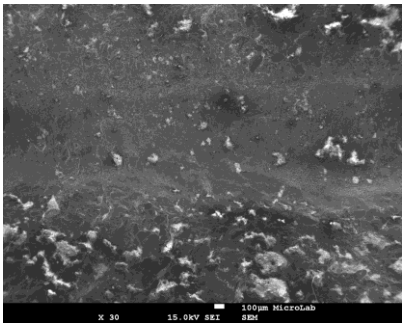

Figure 6 - Transition between the propagation zone of crack front and final unstable rupture region (detail "A4")

Figure 7 shows "ratcheting marks" located in the crack propagation area, which are the result of the merger of two micro crack propagation planes originating in the maximum stress region, resulting from the high stress state of the referred region.

Figure 8, Figure 9 and Figure 10 respectively of details B2, C1 and C2 reveal that there is no evidence of any defect responsible for the fatigue crack initiation.

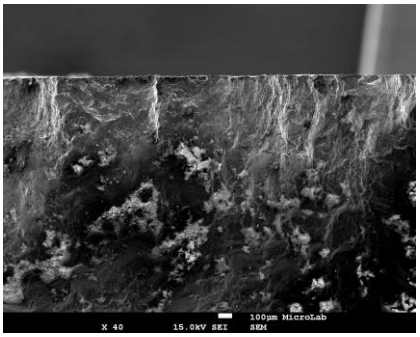

Figure 7 - Ratcheting mark in the nucleation zone of fatigue cracks (detail "B1")

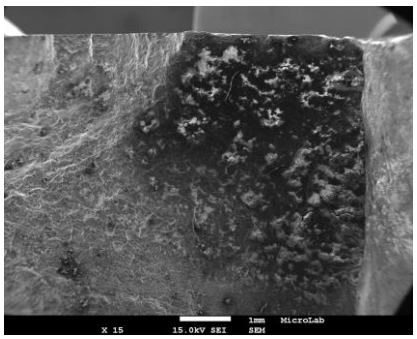

Figure 8 - Fracture surface (detail "B2)

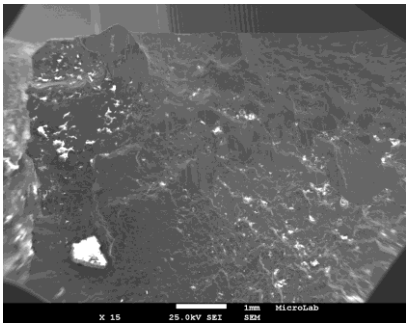

Figure 9 - Fracture surface (detail "C1")

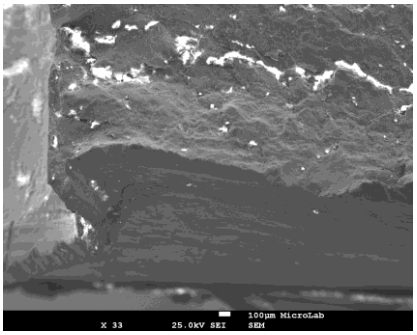

Figure 10 - Edge between fracture surface and component surface (detail "C2")

Figure 11 exhibits in detail the surface roughness increase in the final rupture area seen in details C3 and D2.

A photograph of the observation made on the fatigue initiation zone is presented in Figure 12. The facies presented on the enlargement of detail "D1" display fatigue cracking with low cracking rates and some crack propagation plans become more visible.

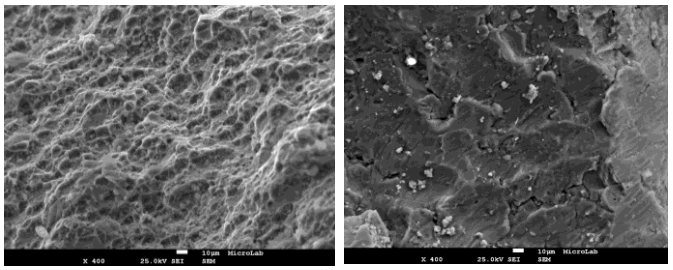

Figure 11 - Final unstable rupture region (detail "C3" on the left and detail "D2" on the right)

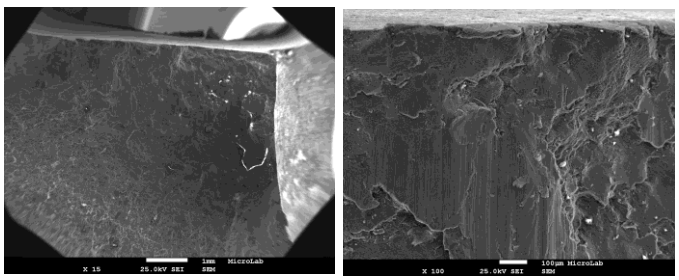

Figure 12 - Initial zone of fracture surface in detail "D1" and enlargement on the right

III. FINITE ELEMENT ANALYSIS

Before a structural integrity assessment could be performed, the nose wheel fork, as well as some of the adjacent components, needed to be modeled. To do so, the *Solidworks* software was used. The loads taken into account to this analysis were the vertical and drag forces, obtained with information based in airplane and FAA database (Part 23 of the FARs – Federal Aviation Regulations), which were applied into the bead seat region of the rim (see Figure 13). The material used in this case study was aluminum alloy 5182.

After finite element analysis the stress fields were obtained, as is depicted in Figure 14. The maximum Von Mises stress occurs on the tip of the bolts with a value of, approximately, 1GPa. The high stress values are explained due to the fact that there is a fixed geometry boundary condition in a surface with

a singularity (the chamfer between the threaded surface and the bolt's tip), therefore the results on the bolts are going to be ignored.

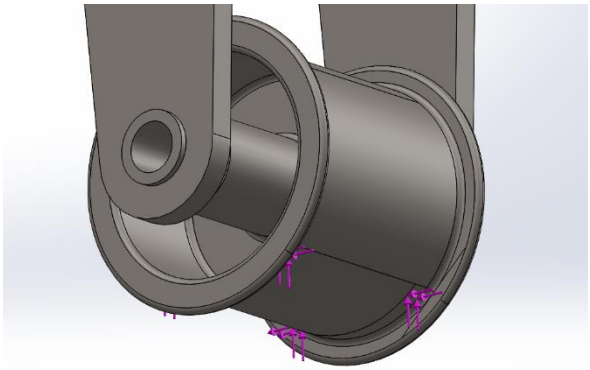

Figure 13 - Vertical and Drag forces applied in bead seat region

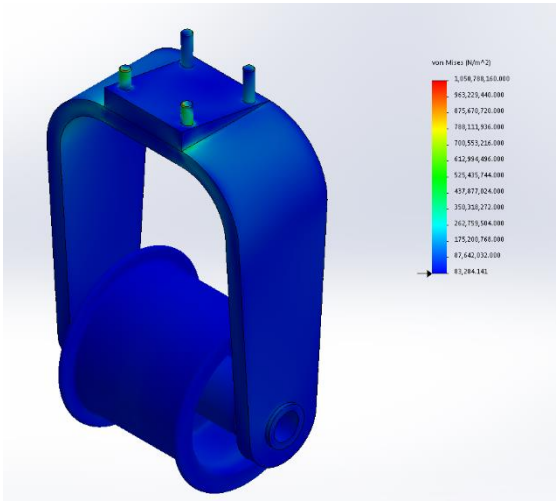

Figure 14 - Von Mises stresses distribution in nose wheel assembly

The maximum stress occurs in the rear bolts (see Figure 15) of the nose wheel fork. This occurs due to the fact that the rear bolts are under compressive normal stresses due to axial forces, caused by the impact load, and bending moments, caused by the drag force. The frontal bolts, on the other hand, are subjected to compression due to axial loads and tension due to bending moments.

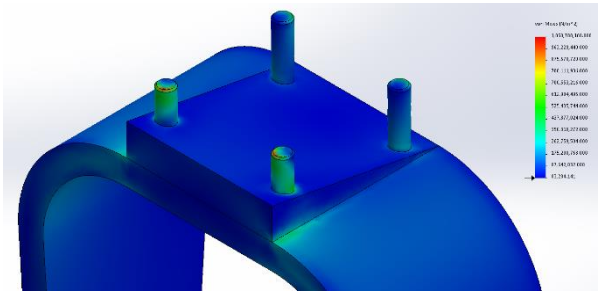

Figure 15 - Maximum stress observed in bolt tip

The main component to analyze in this paper is the fork. Figure 16 depicts the nose wheel fork isolated from the remaining parts. It can be observed that the higher stresses occur near the attachment holes. In the upper surface higher stresses appear on the line that defines the border of the contact surface between the fork and the connector. The lower surface is also under high stress values in the region around the holes. This is a zone of stress concentration, and therefore more susceptible to failure.

Figure 17 shows the progression of Von Mises stresses inside the material.

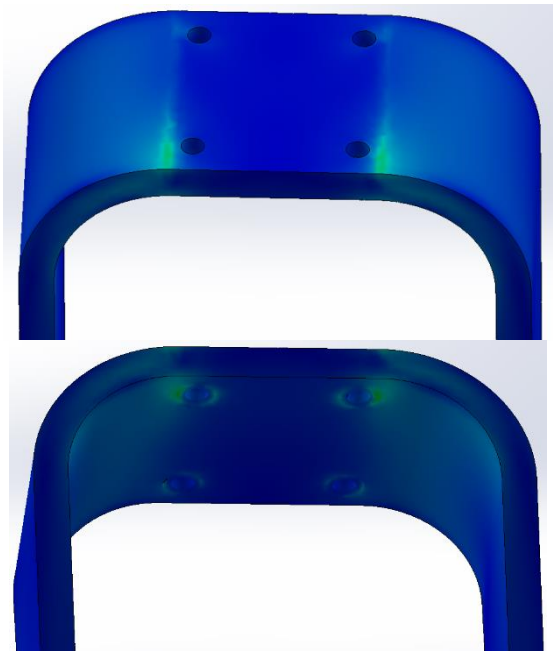

Figure 16 - Stress distribution in upper and lower part of the fork

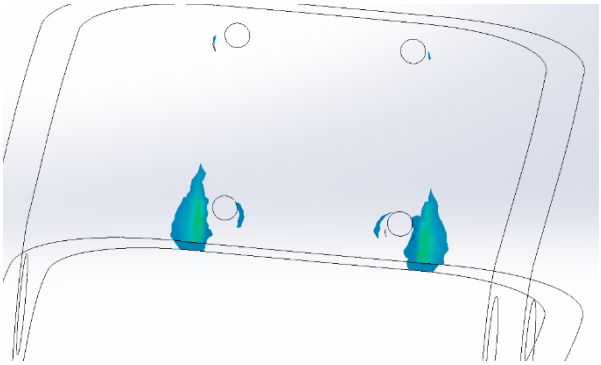

Figure 17 - Stress field progress

In order to identify the regions under plastic deformation, it was necessary to plot Von Mises stresses above the allowable stress only. The aluminum alloy used has a yield strength of 395 MPa. The allowable stress depends of the safety factor which, for aircrafts, varies between 1.2 and 3, depending on the application and material. For main landing gear structures it is often 1.25 [10].

The allowable stress was computed using equation below and then used to plot the material under plasticity in Figure 18 and Figure 19.

$$\sigma_{adm} = \frac{\sigma_y}{1.25} = \frac{395}{1.25} = 316\ MPa$$

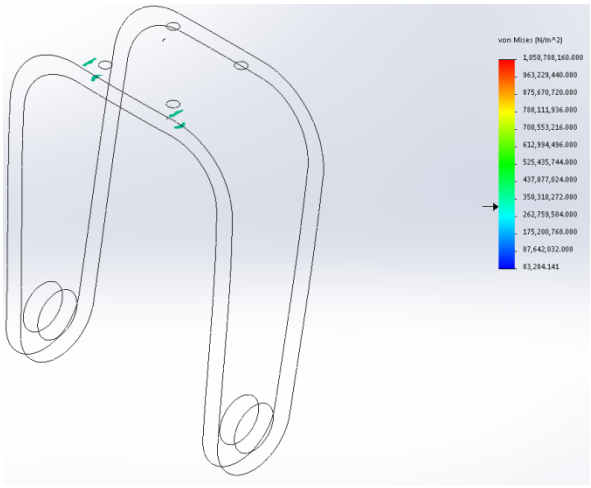

Figure 18 - Plasticity zones in the fork

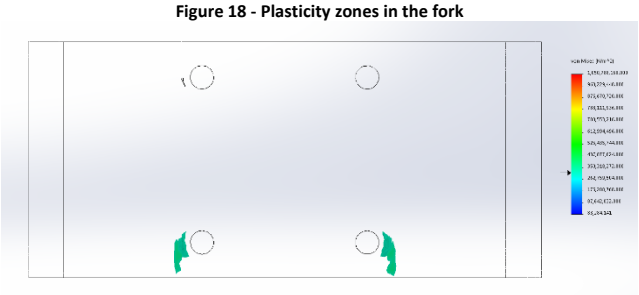

Figure 19 -Plasticity zones in the fork (top view)

IV. Discussion

Striations are the result of a plastic deformation occurring in the crack front when the latter moves due to the influence of each loading cycle, which is why striation are parallel between themselves and perpendicular to the crack propagation direction. The spacing between two successive marks allows to account for the velocity of propagation of the crack front and is therefore a determining analysis parameter for the correct characterization of a fatigue process.

Through Finite Elements Analysis, Figure 17 depicts the progression of Von Mises stresses inside the material. This type of plot helps locate areas under higher stress values and, from its analysis, it can be concluded that the critical areas are near the bolted connections. Also, it is noteworthy that higher stress zones are in the vicinity of the actual fracture surfaces meaning that it is likely that this stress state promotes crack propagation in that direction leading to component failure

The zones presented in Figure 19 are the areas under the highest stresses in the studied landing conditions. During flights, the stresses in the nose landing fork are practically inexistent, reaching their maximum when the contact between the tyre and the ground occurs. So the areas represented as being under plasticity are the ones in which the stress amplitude is higher and therefore these zones of stress concentration are more likely to create cracks that propagate through fatigue.

V. Conclusions

In this paper, a study of a nose landing gear fork is presented, with the goal of finding the causes that lead to the failure of this component.

The visual observation of the fractured surface immediately indicates that this failures occurred by a fatigue process. The main area of the fracture surfaces present high stress failure facies as concluded by the presence of a great area of overload fracture.

Evidences of a fracture surface are visible in the component. Through optical microscopy, with low magnification, it is possible to identify a crack initiation zone with beach marks near the origin of the crack which, combined with the fact that the nose wheel fork is subject to cyclic loading, leads to the conclusion that the component failed due to fatigue

Using SolidWorks, the fork was analyzed through the finite element method. The stress field on the fork has been determined and it was concluded that the region around the attachment holes is a zone of stress concentration which is critical for crack propagation.

In the present case study, cracks developed near the fixing holes, which are stress concentration zones, and propagated from the upper surface of the fork. As such, it can be concluded that this area has been subject to cyclic tensile loads, which rise to fatigue cracks. The fracture was initiated by cracking in holes of the fork structure. This cracking is characteristic of the existence of areas of stress concentration.

Any type of initial defect was not observed in the fracture surfaces, consequently it can be concluded that failure occurred by fatigue but in the presence of higher loads in the components than those that were expected.

References

[1] Currey, N.S., Aircraft Landing Gear Design: Principles and Practices. Aiaa Education Series. 1988: Amer Inst of Aeronautics & (October 1988).

[2] N., D.V., R.K.G.V. V., and S. Rao, Aircraft Landing Gear Design & Development - How Advance Technologies are helping to meet the challenges? White Paper, 2015.

[3] Nguyen, T.D., Finite Element Analysis of a Nose Gear During Landing, in Engineering. 2010, University of North Florida.

[4] Horak, I.V. Advanced Landing Gear Fatigue Test Method. in LMS Conference Europe. 2006. Munich.

[5] Deng, Y., Application Of Shape Optimization In Landing-Gear Structural Design Of Small Aircraft. Mechanics in Engineering, 2008. 30(1): p. 47-51.

[6] Briscoe, D., ME 548 Aerostructures Final Project ANSYS Analysis Landing Gear.

[7] Malachowski, J. and W. Krasoń, Effort analysis of the landing gear with possible flow during touchdown. International Journal of Mechanics, 2008. 2(1): p. 16-23.

[8] Franco, L.A.L., N.J. Lourenço, M.L.A. Graça, O.M.M. Silva, P.P. de Campos, and C.F.A. von Dollinger, Fatigue fracture of a nose landing gear in a military transport aircraft. Engineering Failure Analysis, 2006. 13(3): p. 474-479.

[9] Al-Bahkali, E.A., Analysis of Different Designed Landing Gears for a Light Aircraft. International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 2013. 79: p. 406 - 409.

[10] Burr, A.H. and J.B. Cheatham, Mechanical Analysis and Design. 2 ed. 1995: Prentice Hall.