

**FAILURE ANALYSIS OF NIGERIAN
AIR FORCE AIR BEETLE (ABT-18)
NOSE WHEEL STRUT**

BY

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B.ENG (METALLURGICAL AND MATERIALS ENGINEERING)

(MME/99/2299)

**A THESIS IN THE DEPARTMENT OF METALLURGICAL AND MATERIALS
ENGINEERING SUBMITTED TO THE SCHOOL OF POSTGRADUATE
STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR
THE AWARD OF M.ENG IN METALLURGICAL AND MATERIALS
ENGINEERING OF THE FEDERAL UNIVERSITY OF
TECHNOLOGY, AKURE, ONDO STATE IN NIGERIA.**



DECEMBER, 2009

CERTIFICATION

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This work has not been presented elsewhere for the award of a degree or any other purpose

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ACKNOWLEDGEMENT

My sincere gratitude goes to my supervisor, Professor John Ade Ajayi whose values for integrity, professionalism and excellence have been contagious. These have contributed immensely to the successful completion of this project. Others I cannot forget to include are: Air Vice Marshal Awarun, Air Commodore Smith, Air commodore Soladoye, Wg Cdr Jemitola, Rtd Sgt Abdulraheem, all of the Nigerian Air Force Base, Kaduna for their assistance in collecting the material samples and taking of photographs for this project.

My profound gratitude goes to Engr. O.A. Adeleke and Mr. Francis Irete Alo, both of Department of Materials Science and Engineering, Obafemi Awolowo University (OAU), Ile-Ife with whose assistance I was able to carry out my tests. I cannot but mention Dr Oluwole of the Department of Materials Science and Engineering, OAU; I also thank my head of department, Dr B. A. Adewuyi and Dr. S.B. Hassan of Metallurgical Engineering Department, Ahmadu Bello University, Zaria, for their scholarly advice and contribution; my colleague Awe Olaniyi, for his encouragement and contribution. . Furthermore, I appreciate my husband Mr. Olaleye Joseph, my parents Mr. and Mrs. Olorunleke, my mother-in-law, Mrs. Adenike Joseph, my elder brother Mr. Olubunmi, my elder sister, Biodun Bamidele and my siblings, Feyi, Toyin, Titi, Tola and Faith for their love, guidance and financial support throughout the duration of the programme. My apology goes to those whose names are not mentioned, due to their large number and limited available space. Thank you all.



DEDICATION

This project report is dedicated to God Almighty, my Source and Inspiration.

ABSTRACT

This research centres on failure analysis of the nose wheel strut of the Nigerian Air Force trainer aircraft, ABT-18, which collapsed especially during hard landings. Visual examination with the unaided eye and fractography revealed beach marks on the fracture surface which indicates fatigue failure characteristic of brittle fracture. The fractograph of the fracture surface shows high energy fracture. Chemical analysis of the as-received failed nose wheel strut was carried out. The results showed that the material is medium carbon steel of the tough grade and not the required spring steel. The experimental procedure consists in the characterization of fracture aspects of the standard and failed nose wheel struts using mechanical tests and metallographic methods of analysis. The results of the mechanical tests revealed that there is loss of strength and ductility in the failed sample as a result of fatigue. Micro structural examination revealed fatigue cracks in the failed sample, which led to failure. These cracks propagated from the dark inclusions present in the microstructure. Re-selection of spring steel material is a suggested appropriate solution.



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CHAPTER ONE



1.0 INTRODUCTION

Public acceptability of aviation injuries is extremely low, and since aviation is inherently sensitive to failures, there is great reliance on design and manufacturing approaches that minimize the risk of losing an aircraft. Several approaches to aircraft design and construction have evolved since the beginning of aviation and these include fail safe, safe life and crash resistance. However, things still go wrong and forensic engineering- finding out why an event occurred-is a key part of maintaining aviation safety (Graham, 2005). The failure of engineering materials occurs when materials can no longer operate or operate but no longer be able to perform satisfactorily the function it was designed for. Types of failure include: fatigue failure, creep failure, fracture failure, wear failure, yielding of components, stress corrosion failure and buckling.

Aircraft represents the quickest and most efficient means of transport, but people are still afraid of flying. The reason probably lies in the near impossibility of surviving an aircraft crash. Aircraft crashes may be due to several factors such as materials failure (impact damage, low fatigue strength, hidden defects, corrosion and quick crack propagation), adverse atmospheric conditions, and human errors.

In the philosophy of a safe flight an important role is played by the materials performance (Carosena *et al.*, 2006). Military aircraft can operate under conditions that are more severe than their civil counterparts; examples include dust-laden environments, heavy and repeated exposure to salt water, and operation from rough airstrips. It is therefore; hardly surprising that forensic engineering is a critically important part of operating and maintaining military fleets (Graham, 2005).

Failure analysis is based on investigating failure that occurs in machine component to pinpoint product reliability so that pre-matured fracture are prevented. Frequently, failure analysis requires the effort of team of experts. It is applicable in material behaviour, stress analysis, vibration and sophisticated structural analysis. Military helicopters provide ideal conditions for the nucleation and propagation of failure damage. Very few modern machines are expected to perform under such diverse loading and environmental conditions. It is often assumed that failures are a direct consequence of these extreme operating conditions. The failure of a component on a military helicopter can have wide reaching implications involving flight safety, fleet status and operational requirements (Pitt *et al.*, 2006). The necessity of ensuring the required durability of particular construction elements, engine, separate installations and even minor equipment details is a key factor. Especially important is the construction elements that are most important concerning safety in each phase of the flight. One of such elements is the landing gear, which has direct influence on

safety of the aircraft during the most neuralgic phases of the flight (take-off and landing).

For the Nigerian Air Force, the Air Beetle (ABT-18) introduced in 1994 has had its fair share of problems. One of these has to do with the aircraft nose wheel landing gear. It is the main point of contact between the aircraft and the ground as well as supports the weight of the aircraft and its crew members. The landing gear comprises of the nose wheel and two main landing gear assemblies.

The nose wheel of the ABT-18 aircraft is equipped with spring steel shock absorbers underlain with wood and wrapped with fiber glass fairing while the former trainer aircraft such as Piaggio and Bulldog makes use of oleo-pneumatic shock absorbers. The nose wheel is the only component of the landing gear system that has exhibited shortcomings due to frequent failures, hence the need for its failure analysis with respect to proper material selection.

1.1 JUSTIFICATION OF THE STUDY

Failure analysis of the Nigerian Air Force Air Beetle nose wheel strut is important for the following reasons:

- i. Hard landings of the Air Beetle cannot be ruled out since it is a trainer aircraft.
- ii. The failure of the aircraft poses a great danger to the life of its crew members and results in severe damage of the propeller, engine and

airframe.

iii. Disruption of pilot training.

The thrust of this work is aimed at providing appropriate solution through suitable material selection.

1.2 OBJECTIVES OF THE STUDY

The specific objectives of the study are to:

- i. Ascertain the mode of failure by visual observation.
- ii. Determine the possible cause of failure through mechanical properties testing (hardness, tensile, compression, impact and fatigue tests).
- iii. Study the mechanism of failure through metallography.
- iv. Prescribe an appropriate solution by way of suitable material selection.

1.3 EXPECTED CONTRIBUTION TO KNOWLEDGE

This research is expected to provide lessons and precautions to be taken in order to avoid future failures and improvement in design, manufacture and operation of aircrafts.

1.4 THE SCOPE OF STUDY

The assessment of the material integrity of the NAF Air Beetle nose wheel strut is the preoccupation of this study. It is expected that the cause of failure, would be ascertained so that suitable material can be selected to enable the trainer aircraft operate safely in service.

The study will encompass the following:

- i. Site investigation of the Nigerian Air Force Air Beetle (ABT-18) failed nose wheel strut and taking of photographs of several failures.
- ii. Collection of standard and failed nose wheel strut samples.
- iii. Visual observation.
- iv. Chemical analysis of standard and failed samples.
- v. Carrying out mechanical testing on both the standard and failed samples:
 - * Hardness test
 - * Tensile test
 - * Compression test
 - * Impact test
 - * Fatigue test
- vi. Metallographic investigation of the standard and failed samples.
- vii. Appropriate material selection.

This investigation is restricted to material selection option.

CHAPTER TWO

2.0 REVIEW OF LITERATURE

2.1 AIRCRAFT DESIGN



Design is an iterative process. The starting point is a market need or a new idea; the end point is the full specifications of a product that fills the need or embodies the idea. It is essential to define the need precisely, that is, to formulate a need statement, often in the form, "a device is required to perform task X". Between the need statement and the product specification lie the set of stages shown in Figure 1: the stages of conceptual design, embodiment design and detailed design (Michael, 1999).

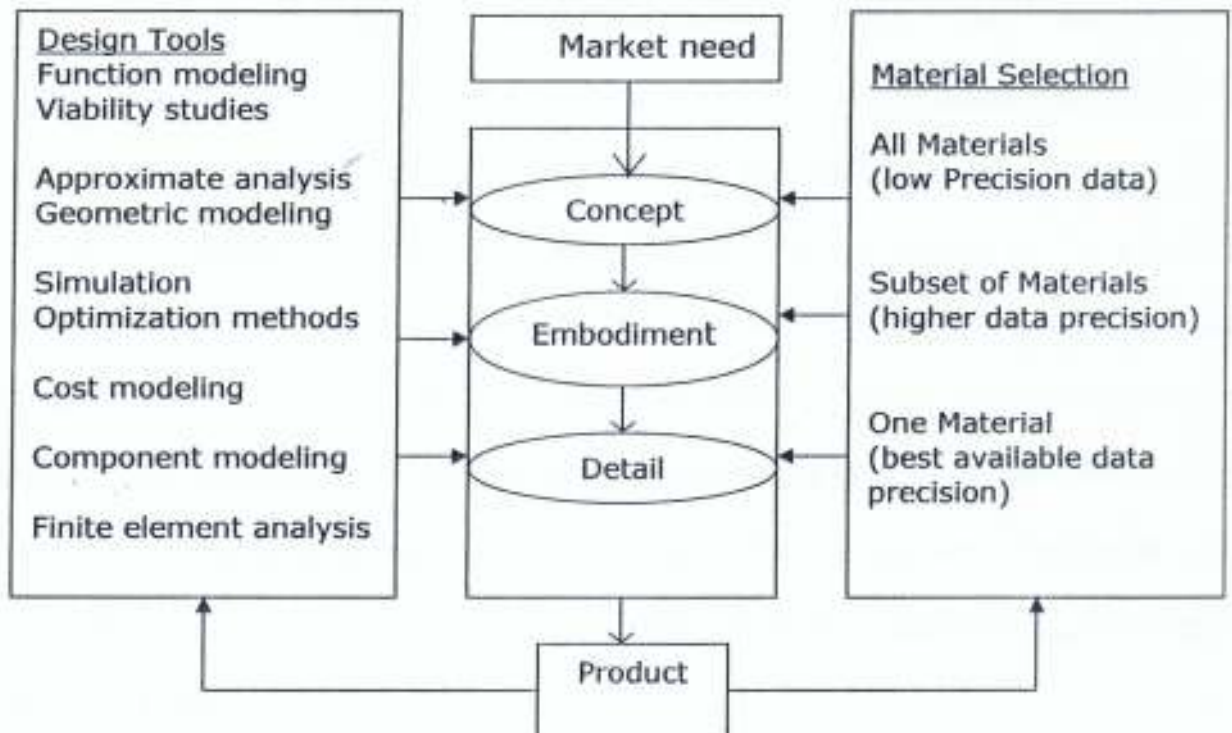
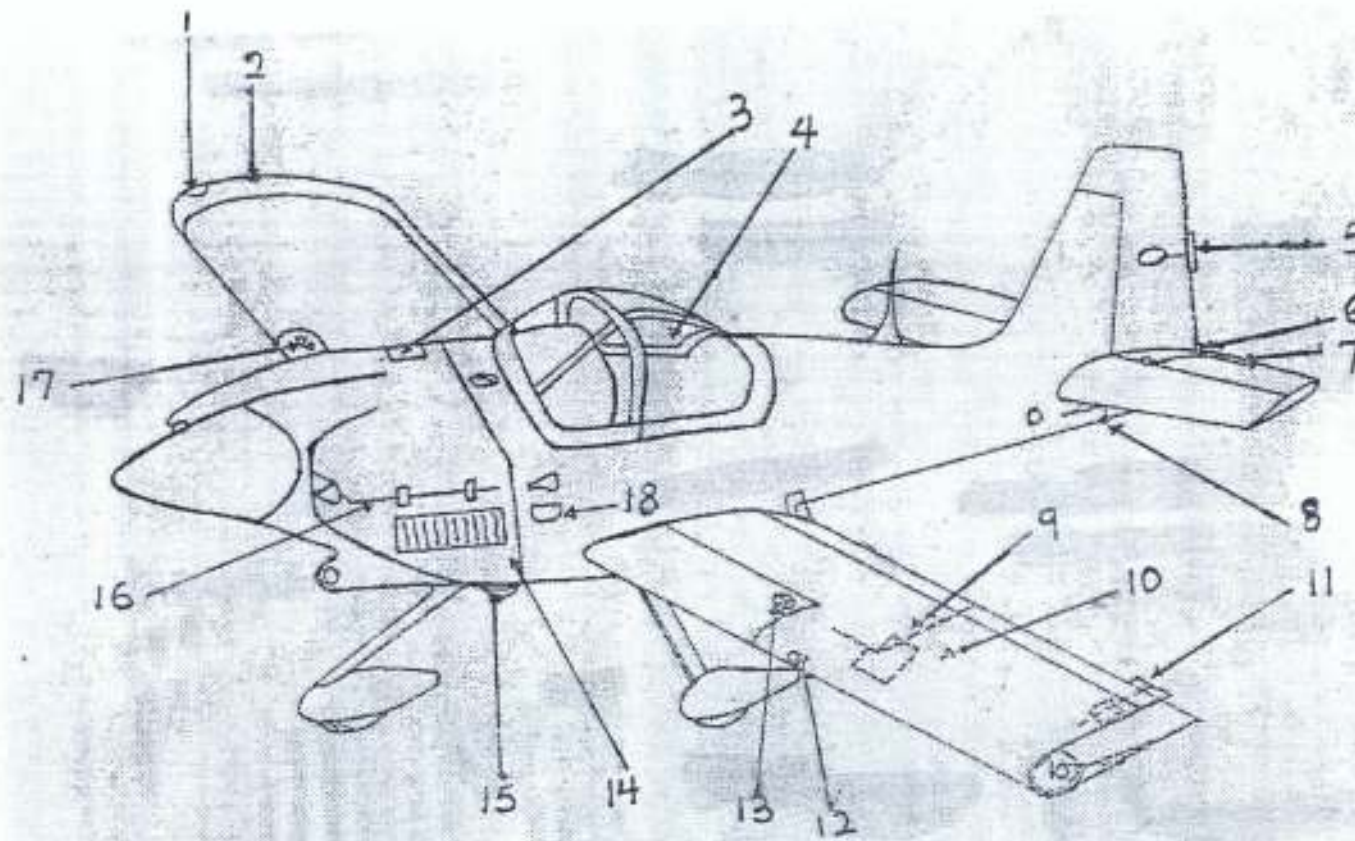


Fig. 1. The Design Flow Chart

Aircraft represent the quickest and most efficient means of transport (Carosena *et al.*, 2006). It is made of a mixture of metals, plastics and composites, with limited redundancy and a service requirement to fly in a diverse range of environments (Pitt *et al.*, 2006). The aircraft is a technical system which consists of assemblies, sub-assemblies and components, as shown in Figure 2, put together in a way that performs the required task. A high standard of quality at every stage of production is paramount; when errors introduced at any stage in the process can eventually, under the right circumstances, lead to catastrophic failure (Pitt *et al.*, 2006)

The design proceeds by developing concepts to fill each of the sub-functions in the function structure. The next stage, embodiment, takes each promising concept and seeks to analyse its operation at an approximate level, sizing the components and selecting materials which will perform properly in the ranges of stress, temperature and environment required by the specification, examining the implications for performance and cost. The embodiment stage ends with a feasible layout which is passed to the detailed design stage. Here, specifications for each component are drawn up; critical components may be subjected to precise mechanical and/or thermal analyses; optimization methods are applied to components to maximize performance; a final choice of geometry and material is made; the production is analysed, and the design is costed. This stage ends with detailed production specifications (Michael, 1999).



COMPONENTS

1	Landing Light
2	Strobe Light
3	Oil Dipstick and Filler
4	Cover, Cockpit
5	Rudder Trim
6	Tail Light
7	Elevator Trim
8	Tail Tie Down
9	Aileron Bell crank
10	Cover, Pilot Tube
11	Aileron Trim
12	Stall Warning Lift Vane
13	Fuel Filler Cap
14	Gills
15	Cowl Flap
16	Cowl Latches
17	Fuel Filler Cap
18	External Power Plug

Fig. 2: Schematic Diagram of the Aircraft Showing its Components and Assemblies.

Materials selection enters each stage of the design. At the concept stage, the designer requires approximate property values, but for the widest possible range of materials. The problem at this stage is not precision, it is breadth and access: how can the vast range of data be presented to give the designer the greatest freedom in considering alternatives? Embodiment design needs data for a subset of materials at a higher level of precision and detail, but for only one or a very few materials. The materials input into design do not end with the establishment of production. Products fail in service, and failures contain information. It is an imprudent manufacturer who does not collect and analyse data on failures. Often this points to the misuse of a material, one which re-designs or re-selection can eliminate.

The selection of a material and process cannot be separated from the choice of shape. To achieve the shape, the material is subjected to processes which collectively is called manufacture: they include primary forming processes (like casting and forging), material removal processes (such as machining and drilling), finishing processes (such as galvanizing and polishing) and joining processes (welding, soldering and brazing). It is important to state that function, material, shape and process do interact. Specification of shape restricts the choice of material and processes but equally the specification of process limits the materials you can use and the shapes they can take. The interaction between function, material, shape and process lies at the heart of the material selection process (Michael, 1999).

Aircraft crashes may be due to several factors, such as materials failure (impact damage, low fatigue strength, hidden defects, corrosion and quick crack propagation), icing adverse atmospheric conditions and human errors. In the philosophy of a safe flight an important role is played by the materials performance. The material should have superior mechanical, chemical and physical characteristics such as fatigue, impact and damage tolerance, burn-through resistance and corrosion resistance. But the material should also be light and compromise "lowest weight, highest strength" (Carosena *et al.*, 2006).

Two categories of aircraft are in use namely: the civil aircraft and the military aircraft. For many years, fail-safe design, in which load path redundancy allows the aircraft structure to survive one failure long enough for it to be detected, has been the mainstay of civil aircraft design, and in view of low rate of aircraft loss due to structural failure, this approach has been largely successful. In contrast, high-performance military aircraft rely for their performance on minimal weight design in which redundancy is more limited, and accept a somewhat higher risk of failure. Furthermore, military aircraft can operate under conditions which are more severe than their civil counterparts: dust laden environments, heavy and repeated exposure to salt water, and operation from rough airstrips. Hence, failure analysis (forensic engineering) is a critically important part of operating and maintaining military fleets (Graham, 2005). The Nigerian Air Force Military fleets include the military transport aircraft and the trainer aircraft. The aircraft under study is the trainer aircraft.

2.2 FAILURES IN MILITARY AIRCRAFTS

The severe operating conditions for components in military aircraft are related to a wide range of failure modes and introduce many factors which influence those failures. Complicating factors are the increasing age of military fleets, as a result of the rising cost of fleet replacement, increasing reluctance or inability of OEM (Original Equipment Manufacturers) to provide impartial technical support, and the widespread use of materials and processes near their stress and environmental limits, in an effort to achieve that last little bit of operational performance (Graham, 2005).

The Nigerian Air Force Air Beetle (ABT-18) aircrafts were produced by Dornier Aviation Nigeria AIEP Limited (DANA), the Original Equipment Manufacturers (OEMs) in a mass production. Not all the aircrafts have experienced failure of the nose wheel landing gear since they were adopted for training. Hence, it is likely that there were discrepancies in the material property for some of the aircrafts, most especially those that have failed in service. Forensic engineering (Failure analysis) for aircraft components relies on a wide range of "traditional" metallurgical methods, including metallography, fractography, microscopy (light or electron-optical), micro-analysis, metrology, strength measurements and non-destructive examination (Graham, 2005).

Landing gears are usually subjected to severe environmental conditions, such as temperatures, climates and operational situations such as runway conditions among others. Franco *et al.*, (2006) analysed the rupture

of the nose landing gear of a military transport aircraft, EMB 121 – Xingu, which collapsed during take-off procedure. Since this component is considered to be critical to aircraft safety, the Brazilian Air Force requested a failure analysis investigation.

2.3 NIGERIAN AIR FORCE AIR BEETLE (ABT-18) AIRCRAFT AND ITS FAILURE

On its silver anniversary April 22, 1989, the Nigerian Air Force unveiled and conducted a test flight of a prototype of Nigeria's first domestically assembled aircraft, the Air Beetle shown in Plate 1. It was jointly built over two years by the NAF and Dornier Aviation Nigeria AIEP Limited (DANA), a West German Kaduna-based firm, from the design of the United States Van RV-6 sport aircraft shown in Plate 2. The Air Beetle had the unique feature of being able to fly on standard automobile fuel. This two-seater, single airplane was intended to be the primary trainer for the NAF, replacing the aging British Bulldog trainers (www.photius.com, 1991).





Plate 1: The Air Beetle (ABT-18) Aircraft

The Air Beetle aircraft is a trainer aircraft used for ab-initio training at the 301 Flying Training School of the Nigerian Air Force Base, Kaduna. Its basic design is a cantilever low wing monoplane with a single tractor engine, low mounted tail plane and elevator. The fuselage is a conventional stressed skin all-metal monocoque aluminium alloy airframe construction except for steel components comprising of the engine mount, landing gear struts, main landing gear mounts, elevator bell cranks and other miscellaneous items. Fiberglass moulds are used for the tips of wings and tail surface as well as for cowls, wheel spats and empennage fairings. It has a stainless steel firewall and engine mount (Abdullahi *et al.*, 2006). Its general characteristics are as follows:

- Crew : one pilot
- Capacity : one passenger
- Length : 6.21m
- Wingspan : 7.10m
- Height : 1.62m
- Wing area : 10.2m
- Empty weight : 437kg
- Loaded weight : 724kg
- Maximum take off weight : 724kg
- Power plant : (112-134KW) (Van's Aircraft, 2008)



Plate 2: The United States Van Rv-6 Sport Aircraft

Training and maintenance deficiencies in the Air Force, however, resulted in high loss of aircraft and pilots (www.photius.com, 1991). The Air Beetle (ABT-18) has had its fair share of problems, one of which has to do with the aircraft nose wheel landing gear. The landing gear of the Air Beetle comprises of the nose wheel and two main landing gear assemblies. The nose wheel of the ABT-18 aircraft is equipped with spring steel shock absorbers underlain with wood and wrapped with fiberglass fairing while the former trainer aircrafts: Piaggio and Bulldog, makes use of Oleo-Pneumatic shock absorbers (Abdullahi *et al.*, 2006).

It has been observed that during the years of conducting flying training, the NAF has recorded several incidents whereby the nose wheel strut collapses particularly during hard landings. This had resulted in severe damage to the propeller, engine, airframe and sometimes injury to Pilots. This situation has contributed to delays and disruption of Pilot training. The nose wheel assembly of the ABT-18 aircraft is located far forward to maintain the centre of gravity and stability characteristics of the aircraft. However, a proper balance in terms of load distribution between the nose and main assembly must be maintained. When the load on the nose wheel is less than about 8% of the maximum take off weight (MTOW), controllability on the ground will become marginal, particularly in crosswind conditions. On the other hand, when the static load on the nose wheel exceeds about 15% of the MTOW, braking quality will suffer, the dynamic braking load on the nose assembly may become excessive and thus lead to failure (Abdullahi *et al.*, 2006).

Failure occurred essentially by the student pilots. The failure modes include: buckling of the strut as shown in Plates 3-5 and complete fracture of the strut from the firewall where it was mounted as shown in Plate 6. Fracture could have occurred as a result of stress concentration on the upper part of the strut, which may have been prevented if the stress could be transmitted through the entire length of the strut.



Plate 3: A Buckled Nose Wheel of the Air Beetle



Plate 4: A Buckled Nose Wheel of the Air Beetle



Plate 5: A Buckled Nose Wheel of the Air Beetle



Plate 6: Fracture of the Air Beetle Nose Wheel

Since the adoption of the ABT-18 aircraft as the ab-initio trainer aircraft for the Nigerian Air Force, a number of modifications to improve on the nose wheel structure have been made. The first modification was the removal of the fairings covering the strut. The second modification was the change of the nose wheel tyre size from 4:00-4 to 5:00-5. This was to augment the absorption of both vertical and horizontal shocks, which invariably led to improved stability and balance of the aircraft. The third modification was the increase in the angle of inclination between the aluminium fork which houses the nose wheel to the horizontal. This increases the propeller-ground clearance. However, the result of the increase in propeller-ground clearance could obstruct a short pilot's view. Appropriate

seating cushion was provided to eliminate the problem (Abdullahi *et al.*, 2006).

The modifications had some consequences in that when a pilot weighing over 80kg initiates entrance into the aircraft, the tail had the tendency to hit the ground. Thus the center of gravity variation of the airplane ought to be determined and it may require the need to re-establish a new baggage load limit for the aircraft. The fourth proposed modification, which is yet to be applied, is the integration of an oleo-pneumatic shock absorber with a spring steel structure of the nose wheel. This is to increase the touch down force on landing from 1634.44N to 4903.33N before failure can occur. Owing to the additional parts of the oleo-pneumatic shock absorber, trunnion, bolts and nuts, the weight of the nose wheel assembly would increase from 15.87kg to 19.95kg. This would bring about an overall increase in the Total Empty Weight of the aircraft from 437.51kg to 441.59kg. To compensate for this, the baggage weight will be reduced from 30kg to 25kg. This would also impose a change in the center of gravity position on the aircraft (Abdullahi *et al.*, 2006).

Having carried out a thorough review of the ABT-18 aircraft and its in-service failures, it is worth noting that the performance of a component or structure, particularly under dynamic loading is strongly influenced by the interaction between design, manufacture and materials. Poor management of this interplay in the design process can lead to premature and unexpected in-service failures (James, 2005). It is of fundamental importance to understand

the concept of aircraft landing gears; their requirements and materials selection.

2.4 AIRCRAFT LANDING GEARS: REQUIREMENTS AND MATERIAL SELECTION

The landing gear of an airplane acts as the connecting link between the fuselage and the ground. Its weight constitutes some 3 to 5 percent of the maximum take off weight, which is equivalent to about one third to one half the structural weight of the wing. The main costs associated with the landing gear, such as inspection and replacement of tyres and brakes, represent major contributing factors which increase the final maintenance bill. This is particularly hard to accept because the landing gear contributes virtually nothing to the flying and economic capabilities of the airplane, so it is not surprising that many unsuccessful attempts have been made to eliminate it. The landing gear serves the purposes of pre-or post flight taxiing, take off run and landing roll, towing forward and backward and braking of the aircraft to a stop.

During a landing, for example, the landing gear must be capable of absorbing the total kinetic energy of the aircraft, which is:

- The energy resulting from the descent velocity, which is absorbed by the landing gear shock absorber units, given by

$$E = \frac{1}{2}mw^2 \dots\dots\dots (2.1)$$

where

E is Kinetic energy,

m is maximum mass of the airplane for landing,

w is vertical component of velocity = descent velocity

- The energy resulting from the horizontal component of the velocity, which is absorbed by the brakes, given by

$$E = \frac{1}{2}mv^2 \dots\dots\dots (2.2)$$

where

v is the horizontal component of velocity

For the particular layout of landing gear, the energy absorption requirements should comply with a vertical velocity of descent of $3.048 \frac{m}{s}$ (sink rate). The requirements for special or carrier-based airplanes are higher (Ref: Dornier Training). The following functional requirements influence the landing gear layout:

- i. During the phases of take off rotation and lift off and landing flare-out and touch down, only the wheels should be in contact with the ground. There should be adequate clearance between the runway and all other parts of the airplane.
- ii. The inflation pressure of the tyre and the configuration of the landing gear should be chosen in accordance with the bearing capacity of the airfields from which the airplane is designed to operate.
- iii. The landing gear should be able to absorb the normal landing impact loads and possess good damping characteristics.
- iv. Braking should be efficient, the maximum braking force allowed by the condition of the runway being the limiting factor.

Various configurations for landing gears have been adopted in the past, but many of them were designed for special purposes (Ref: Dornier Training).

Tail wheel landing gear: this type of landing gear was the conventional landing gear during the first three decades of aviation; it is now regarded as obsolete for most designs.

Four-wheel landing gear: consists of two wheels mounted on each side of the airplane centerline in tandem fashion. This type of wheel arrangement is frequently used with amphibious floats, in which the small wheel forward is mounted in the bow of the float.

Tandem landing gear: here, the main wheels are arranged practically in the plane of symmetry of the airplane and the front and rear wheel absorb landing impact forces of the same magnitude.

Single-wheel landing gear: found most in sailplanes where in the single-wheel gear is usually mounted just forward or after the center of gravity with a landing skid to protect the fuselage.

Skid landing gear: was used by the Wright brothers for their early designs and then again through World War I. Skid gears are used on modern helicopters and have been proposed for recoverable space vehicles.

Nose wheel landing gear: Glenn Curtis developed the first nose wheel landing gear in 1908. The nose wheel is a safeguard against turning over and so protects the propeller(s) when used. Also the pilot's view is good. The nose unit must take 20 to 30 percent of the airplane weight in a steady braked

condition; it is therefore comparatively heavy (this is the landing gear under study).

2.4.1 MATERIAL SELECTION FOR LANDING GEARS

Numerous studies, including the ones by leading worldwide aviation companies (Kaplan *et al.*, 2001) and national scientific centres (Jachimowicz *et al.*, 1998) have been carried out on the most effective methods of aircrafts landing gear design as well as the evaluation of the gear's condition during utilization period and possibilities of extending its durability.

Landing gears are usually subjected to severe environmental conditions, such as temperatures, climates and operational situations such as runway conditions among others. Complicating factors are the increasing age of military fleets as a result of the rising cost of fleet replacement and the widespread use of materials and processes near their stress and environmental limits, in an effort to achieve that last little bit of operational performance (Graham, 2005). The material selection for the nose wheel design puts into consideration so many factors ranging from the aircraft operational performance to the environmental factors that may from time to time affect the part. In aviation industries, the parameter that is of paramount importance is the lightweight construction. Other factors are:

- 1) Ease of fabrication-described by its machinability
- 2) High strength to weight ratio

- 3) Resistance to stress corrosion and cracking
- 4) Good weldability, needing no preheating and restoring its properties after welding by ageing
- 5) Impact and creep properties
- 6) Fatigue strength

The aircraft landing gear must be equipped with a strut capable of absorbing the taxiing, takeoff and landing shocks that would otherwise be sustained by the aircraft fuselage. The material should have superior mechanical, chemical and physical characteristics such as fatigue, impact and damage tolerance, burn-through resistance and corrosion resistance. It should also be light and so compromise "lowest weight, highest strength," (Carosena *et al.*, 2006). Early landing gear systems used flexible material for landing gear struts. Various methods have also been used to absorb the shocks of the airplane when landing. Examples include the shock cord, rubber discs, air and oil (air-oleo strut), liquid spring, trailing beam strut and springs (Ref: Dornier Training).

Whereas the former trainer aircrafts, Piaggio and Bulldog uses the oleo-strut, the ABT-18 aircraft is fitted with the spring steel type of strut. The coils of compression springs tend to set with time, so progress favored the development of the leaf spring gear, made of fiberglass, aluminium and steel (Abdullahi *et al.*, 2006)

2.4.2 MATERIAL SELECTION OF SPRINGS FOR LANDING GEARS

High tensile steel makes good springs. The primary function of a spring is that of storing elastic energy and—when required—releasing it again (Table 2.1). Springs come in many shapes and have many purposes: axial springs (a rubber band, for example), leaf springs, helical springs, and torsion bars, as shown in Figures 3-6. Regardless of their shape or use, the best material for a spring of minimum volume is that with the greatest value of and

$\sigma^2 f/E$ for minimum weight it is that with the greatest value of $\sigma^2 f/E\rho$ where

σ = Yield strength

ρ = Density

E = Elastic Moduli (Michael, 1999)

Table 2.1: Design Requirements for Springs (Michael, 1999)

Function	Elastic Spring
Objectives	(a) Maximum stored elastic energy per unit volume (b) Maximum stored elastic energy per unit mass
Constraints	(a) No failure by yield, fracture or fatigue, meaning $\sigma < \sigma_f$ everywhere in the spring (b) Adequate toughness: $Gc > 1 \text{ KJ/m}^2$



Fig. 3: Axial Spring

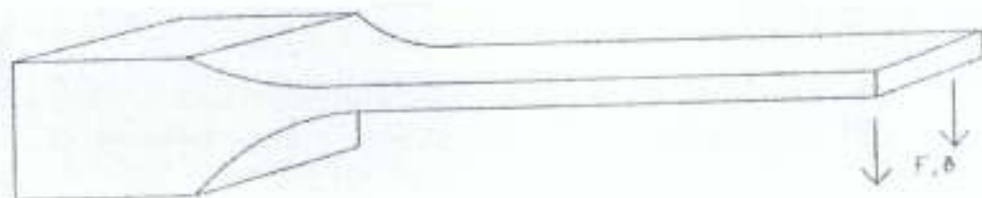
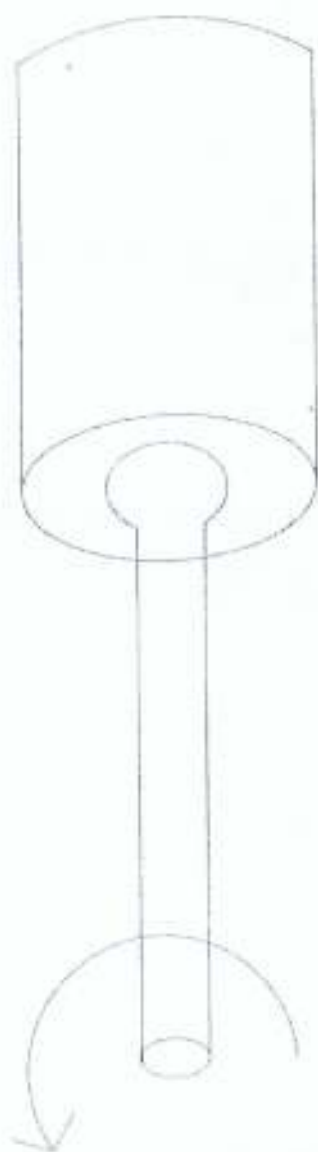


Fig. 4: Leaf Spring



Fig. 5: Helical Spring



T, θ

Fig. 6: Torsion bar

The elastic energy stored per unit volume in a block of material stressed uniformly to a stress σ is

$$w_v = \frac{1}{2} \frac{\sigma^2}{E} \dots\dots\dots (2.3)$$

where E is Young's modulus.

It is this w_v that we wish to maximize. The spring will be damaged if the stress σ exceeds the yield stress or failure stress σ_f ; the constraint is $\sigma \leq \sigma_f$.

So the maximum energy density is

$$w_v = \frac{1}{2} \frac{\sigma_f^2}{E} \dots\dots\dots (2.4)$$

For torsion bars,

$$w_v = \frac{1}{3} \frac{\sigma_f^2}{E} \dots\dots\dots (2.5)$$

And for leaf springs

$$w_v = \frac{1}{4} \frac{\sigma_f^2}{E} \dots\dots\dots (2.6)$$

But as these results show-this has no influence on the choice of material. The best material for springs is that with the biggest value of

$$M_1 = \frac{\sigma_f^2}{E} \dots\dots\dots (2.7)$$

If weight, rather than volume matters, we must divide this by ρ (giving energy stored per unit weight), and seek materials with high values of

$$M_2 = \frac{\sigma^2 f}{\rho E} \dots\dots\dots (2.8)$$

The choice of materials for springs of minimum value is shown in Figure 7. A family lines of slope $\frac{1}{2}$ link materials with equal values of

$$M_1 = \frac{\sigma^2 f}{E} \dots\dots\dots (2.9)$$

Those with the highest value of M_1 lie towards the bottom right. The heavy line is one of the family; it is positioned so that a subset of materials is left exposed. The best choices are a high-strength steel (spring steel, in fact) lying near the top of the line, and at the other end, rubber. Certain other materials are suggested too: Glass Fibre Reinforced Plastic (GFRP) (now used for truck springs), titanium alloys (good but expensive), glass (used in galvanometers) and nylon (children’s toys often have nylon springs).

Table 2.2 and Figure 7 give the materials for efficient small springs (Michael, 1999).

Table 2.2: Materials for Efficient Small Springs

Material	$M_1 = \frac{\sigma^2 f}{E} (MJ/m^3)$	Comment
Ceramics	(10-100)	Brittle in tension, good only in compression
Spring Steel	15-25	The traditional choice: easily formed and heat treated
Ti Alloys	15-20	Expensive, corrosion-resistant
Carbon Fibre Reinforced Polymer (CFRP)	5-20	Comparable in performance with steel, expensive
Glass Fibre Reinforced Polymer (GFRP)	10-12	Almost as good as CFRP and much cheaper against damage; very low loss factor
Glass (fibres)	30-60	Brittle in torsion, but excellent if protected

From the Table; it can be seen that the traditional choice for small springs is spring steel. High strength (spring) steel is good. Glass, CFRP, and GFRP, all make good springs. Elastomers are excellent. Ceramics are eliminated by their low tensile strength.

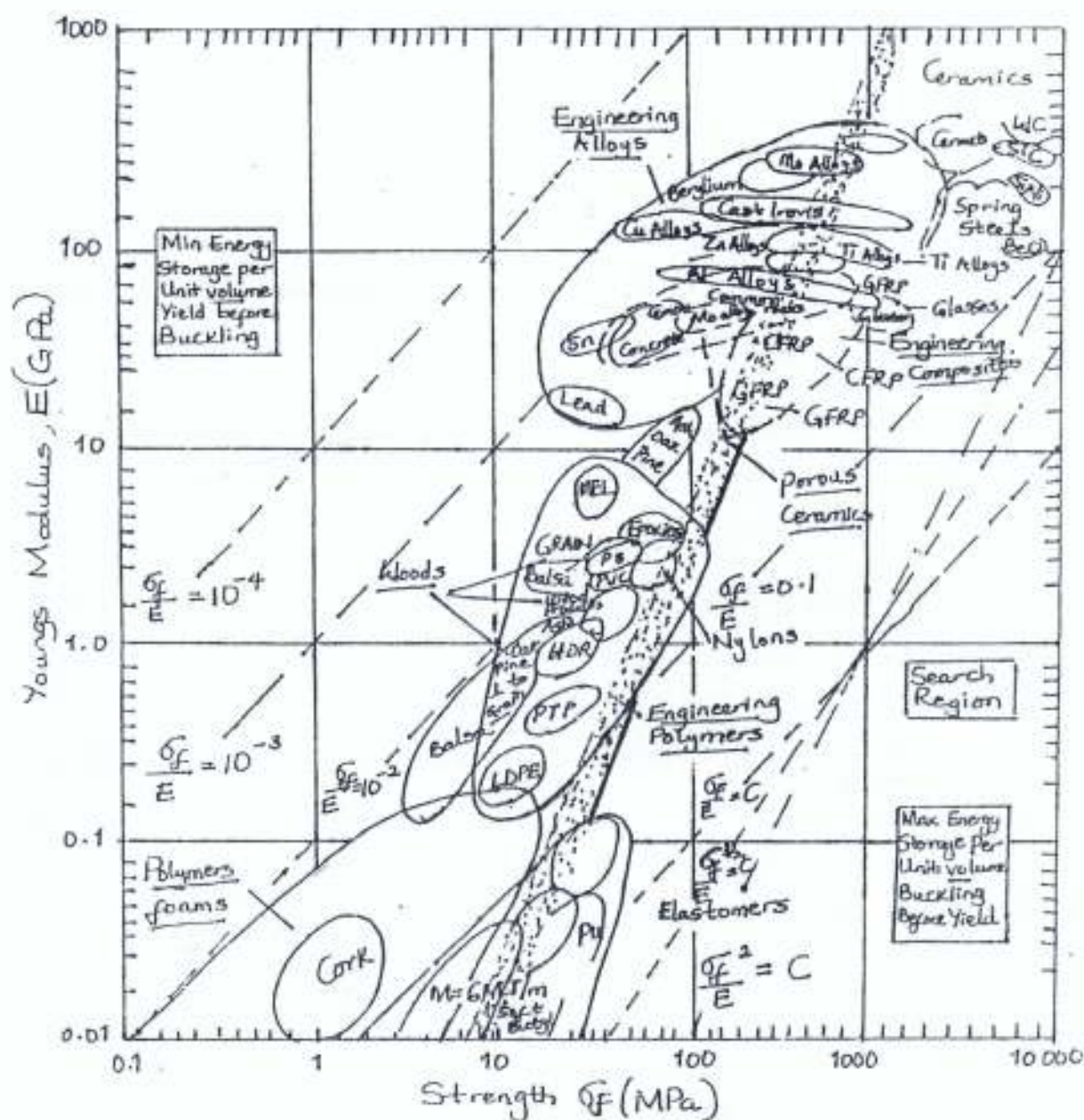


Fig. 7: Materials for Small Springs.

Material selection for light springs is shown in Figure 8. Here,

materials with high values of $M_z = \frac{\sigma^2 f}{\rho E}$ are sought for. Metals, because

of their high density are less good than composites, and much less good than elastomers (you can store roughly eight times more elastic energy, per unit weight in a rubber band than in the best spring steel), (Michael, 1999). Candidate materials are listed in Table 2.3.

Table 2.3: Materials for Efficient Light Springs

Material	$M_z = \frac{\sigma^2 f}{\rho E}$ (KJ/Kg)	Comment
Ceramics	5-40	Brittle in tension; good only in compression
Spring steel	2-3	Poor, because of high density
Ti alloys	2-3	Better than steel; corrosion resistant; expensive
Carbon Fibre Reinforced Polymer (CFRP)	4-8	Better than steel; expensive
Glass Fiber Reinforced Polymer (GFRP)	3-5	Better than steel; less expensive than CFRP
Glass (fibres)	10-30	Brittle in torsion, but excellent if protected
Wood	1-2	On a weight basis, wood makes good springs
Nylon	1.5-2	As good as steel, but with a high loss factor
Rubber	20-50	Outstanding; 10 times better than steel, but with high loss factor

In the absence of a shock absorbing mechanism, the material for the nose wheel strut of an aircraft could be a high strength spring steel useful in aircraft with the following composition:

Carbon	0.65 - 0.85%
Silicon	1.90 - 2.40%
Manganese	0.50 - 1.50%
Nickel	0.50 - 2.50%
Chromium	0.70 - 1.30%
Molybdenum	more than 0.60 - 1.50%
Vanadium	0.20 - 0.50%
Niobium	0.01 - 0.04%
Aluminium	0.005 - 0.100%

The balance being Iron and unavoidable impurities (www.freepatentsonline.com, 2009). The components of the steel are specified as above for the following reasons:

- Carbon is an effective element to increase the strength of the steel. When its content is less than 0.65%, strength adequate for springs cannot be obtained. On the other hand, when in excess of 0.85%, the springs become too brittle.
- When the Silicon content is less than 1.90% strength sufficient for the preparation of springs cannot be ensured. An excessive content of more than 2.40% tends to cause a decarburization problem on the steel surface during

the hot forming of the steel into a spring and hence affect the durability of the springs.

- Manganese is effective to improve the hardenability of the steel and for this effect, more than 0.50% is needed. When in excess of 1.50%, the toughness is adversely affected.
- Nickel also has an effect in improving the hardenability of the steel. At least 0.50% is needed. An excess of 2.50% results in a deterioration in the fatigue strength of the springs.
- Chromium is effective to strengthen the steel. When its content is less than 0.70%, strength adequate for springs cannot be obtained. An amount above 1.30% results in a deterioration in toughness.
- Molybdenum is required to increase the strength and toughness of the steel. Less than 0.60% cannot sufficiently provide this effect, while an amount above 1.50% causes precipitation of coarse carbides, which impair the spring properties.
- Vanadium also strengthens the steel. When its content is less than 0.20%, a sufficient strengthening effect cannot be obtained. On the other hand, when it exceeds 0.50%, a substantial amount of carbides may not dissolve into the austenite; hence the spring characteristics are impaired.
- Niobium increases the strength and toughness of the steel due to its grain refinement function and precipitation effect of fine carbides. When the content is less than 0.01%, the effect is not sufficiently obtained. But, when in excess of 0.40%, the spring characteristics are impaired.

- Aluminium is needed for deoxidation and control of the austenite grain size. When it is present in amounts less than 0.005%, grain refinement cannot be expected. While an excessive amount of above 0.100% tends to reduce the alloys castability (www.freepatentsonline.com, 2009).

The thrust of this research is to analyze the buckling and fracture of the Nigerian Air Force Air Beetle (ABT-18) nose landing gear.

CHAPTER THREE



3.0 MATERIALS AND METHODS

3.1 MATERIALS

3.1.1 Materials Procurement

Standard and failed nose wheel strut samples (Plates 7 and 8) designated as S and F respectively were obtained from the 333 Logistics Group of the Nigerian Air Force Base, Kaduna.

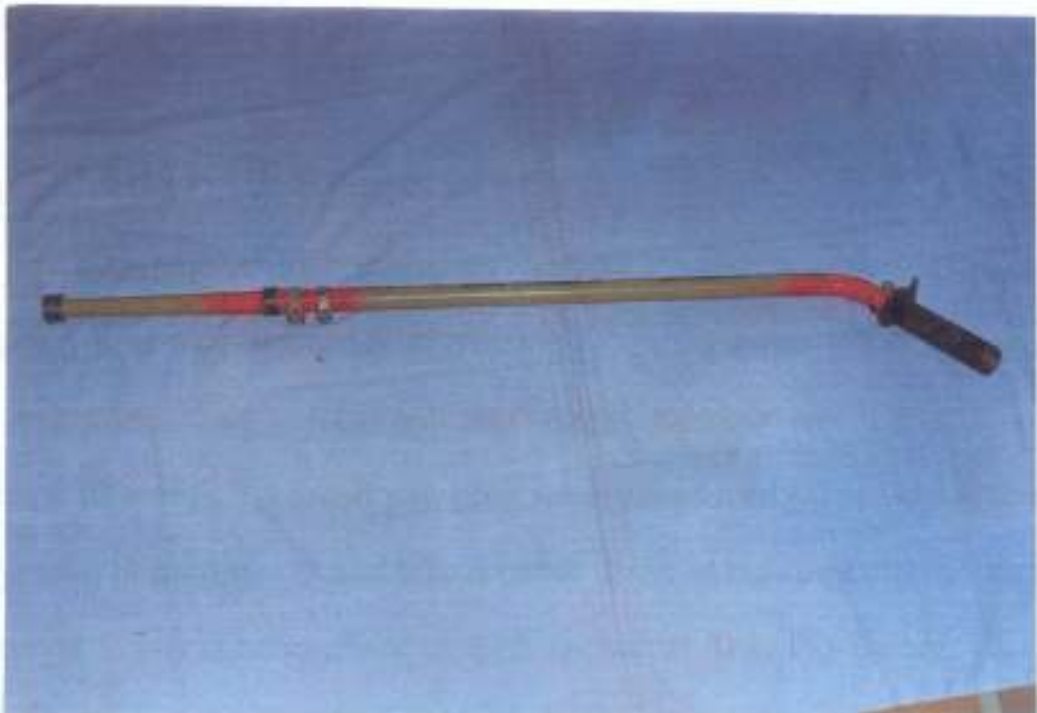


Plate 7: As- Received Standard Sample (S)



Plate 8: As- Received Failed Sample (F)

3.1.2 Materials Preparation

Removal of the fairing on sample F using a grinding machine at the Metallurgical and Materials Technology Development (MMTD) Laboratory of 320 Technical Training Group, NAF Base, Kaduna was carried out. The dimensions of the as-received samples were measured. This was followed by the reduction of samples S and F to smaller sizes using the cutting machine at the Material Science Laboratory of 320 Technical Training Group, NAF Base, Kaduna. Samples S and F were further machined into standard sizes for mechanical tests and metallography with the Centre Lathe Machine (Harrison M300) at the Material Laboratory of the Department of Materials Science and Engineering, OAU, Ile-Ife, Nigeria. The dimensions are as follows:

As-received standard sample (S):	1060mm x 25.5mm
Chemical analysis samples (2):	25mm x 25mm
Hardness test samples (4):	25mm x 25mm
Tensile test samples (2):	46mm square of height 9mm
Compression test samples (4):	20mm x 20mm
Impact test samples (4):	46mm square of height 9mm
Fatigue test samples (7):	46mm square of height 9mm

3.2 METHODS

3.2.1 Visual Examination of the Failed Sample

Visual examination was carried out first by means of the unaided eye followed by fractography with a Leica M400 microscope. The fractograph was taken at Empa, Swiss Federal Laboratories for Materials Testing and Research, Switzerland. The result is shown in Plate 11.

3.2.2 Chemical Analysis of the Standard and Failed Samples.

Chemical analysis was carried out on 25mm square of height 25mm of samples S and F respectively using a spectrometer analyzer at the Nigerian Foundries Limited, Ilupeju, Lagos, Nigeria.

The specimens were grounded on the Herzog grinding machine in the quality control laboratory to ensure a flat and smooth surface for sparking. The grounded specimens were taken to the spectrometer room and placed on

the petry table inside the counter electrode box of the spectrometer. It was clamped down and sparking commenced using the computer system connected to the spectrometer. The results obtained are shown in Table 4.1.

3.2.3 Mechanical Testing

In this analysis, five mechanical tests were carried out on both samples S and F at the Material Laboratory of the Department of Materials Science and Engineering, OAU, Ile-Ife. The tests are:

- i. Hardness test
- ii. Tensile test
- iii. Compression test
- iv. Impact test
- v. Fatigue test

i. Hardness Test

Two test pieces 25mm square of height 25mm each were cut from samples S and F for the hardness test. The universal tensile/compression testing machine was used to determine the hardness values of sample S and Sample F. A flat and polished surface was made on the specimens using the grinding machine. A Brinell ball bolster and a compression die were inserted in the tensometer. The mercury level was adjusted up to zero. Holding the polished surface of each specimen against the Brinell ball, load was applied with the quick-acting handle until the mercury reached 750kg graduation.

The mercury was kept up to this mark for 15 seconds to obtain the desired impression. Thereafter, the specimen was removed from the machine and the diameter of the impression was measured with the Brinell reading microscope. The corresponding Brinell hardness number was obtained from the appropriate table. Results are presented in Table 4.2.

ii. Tensile Test

This was carried out on two test pieces, 46mm square of height 9mm each from sample S and F using the universal tensile/compression machine to determine the tensile strengths of the samples.

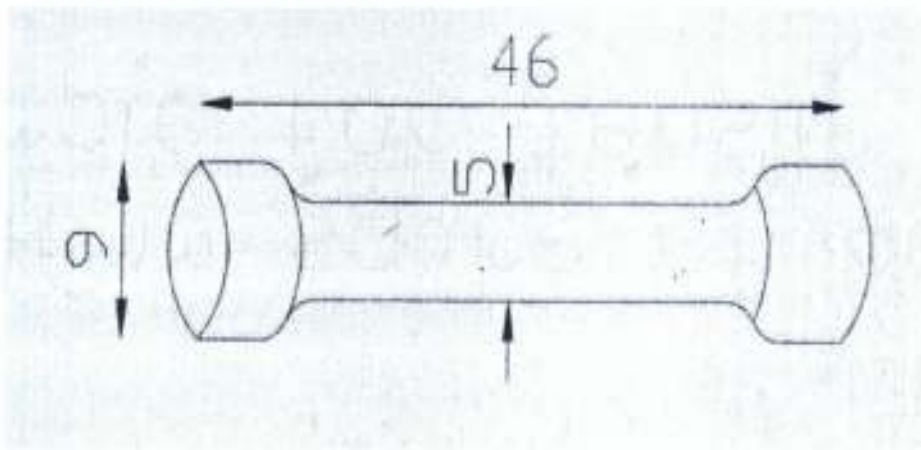


Fig. 9: Tensile test sample (all dimensions in mm).

Having made the test pieces using the lathe machine, two half chucks were selected and assembled on the machine. Rings were slipped over the chucks to keep them together. A test piece was assembled in the chucks with the rings in position. The graph paper was folded round the drum so that

the left-hand edge of the paper was outside, taking care to see that the base line was continuous at the over-lap. The mercury adjusting screw was turned anticlockwise until the mercury was drawn out of the glass tube, and then adjusted up to zero.

With the left hand on the chucks, the handle was turned slowly until the chucks tightened and became rigid. Then, the drum was rotated till the needle came to a convenient starting place to the right of the spring and with the pointer opposite the end of the mercury column, punctured the paper. This was the first point of the curve, which was not on the zero line because there was a slight tension in the test-piece. The load was increased and the paper punctured alternately. Punctures were more frequent in the neighborhood of the yield point. After the yield point the punctures were more widely spaced until fracture took place. The graph produced was removed from the drum by placing the flanged end flat on the table and removing the spring. The procedure was followed for the second test-piece. Results are as shown in Table 4.3 and Figures 12 and 13.

iii. **Compression Test**

Two test-pieces, 20mm square of height 20mm were cut each from samples S and F for the test. The universal tensile/compression machine was used to determine the compressive strengths of samples S and F. Having made the test pieces using the lathe machine, two compressive dies were selected and assembled on the machine. Rings were slipped over the dies to keep them together. A test piece was assembled in the dies with the rings in

position. The graph paper was folded round the drum so that the left-hand edge of the paper was outside, taking care to see that the base line was continuous at the over-lap. The mercury adjusting screw was turned anticlockwise until the mercury was drawn out of the glass tube, and then adjusted up to zero. With the left hand on the dies, the handle was turned slowly until the dies tightened and became rigid. Then, the drum was rotated till the needle came to a convenient starting place to the right of the spring and with the pointer opposite the end of the mercury column, punctured the paper. This was the first point of the curve, which was not on the zero line because there was a slight tension in the test-piece. The load was increased and the paper punctured alternately. The graph produced was removed from the drum by placing the flanged end flat on the table and removing the spring. The procedure was followed for three other test-pieces. The result obtained is presented in Table 4.4.

iv. **Impact Test**

Izod impact test was carried out on four test-pieces, 46mm square of height 9mm. Two pieces were cut from sample S and the other two from sample F.

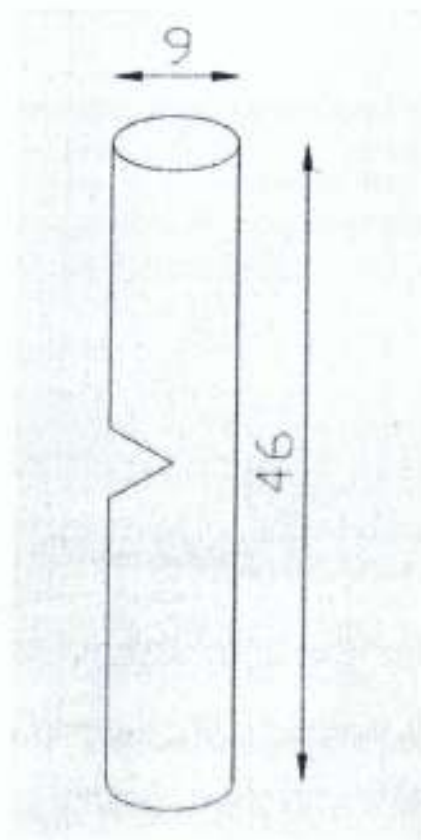


Fig. 10: Impact test sample (all dimensions in mm).

The test-pieces were notched on the notching machine by gripping each in the test-piece clamp and the handle was turned clockwise till the point of the depth screw dropped down the steep side of the depth feed cam. Thus the notch was cut. After cutting the notch, a test-piece was mounted on the impact testing machine with the notch facing the hammer. The hammer was released from a fixed height and it struck the test-piece until failure took place. The reading was taken and the procedure repeated for three other test-pieces. The results are tabulated in Table 4.5.

v. Fatigue Test

This was carried out on seven test-pieces; 46mm square of height 9mm from samples S and F each using the Avery Denison 7305 fatigue testing machine.

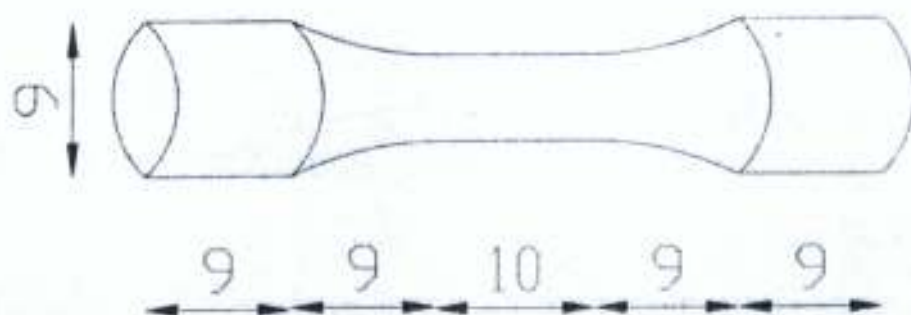


Fig. 11: Fatigue test sample (all dimensions in mm).

The machine is designed to apply reversed loads with or without an initial static load. The load was imposed at one end of the test-piece by an oscillating spindle driven by means of a connecting rod, crank and double eccentric. The load was measured at the opposite end of the test-piece by means of a Torsion Dynamometer, the angle of twist of which was registered on dial gauges. The revolution counter fitted to the motor recorded the number of stress cycles to failure. When the test-piece failed, the machine was stopped automatically by cut-out switches. The procedure was repeated

for six other test-pieces. Results are as presented in Tables 4.6 and 4.7, Figure 14.

3.2.4 Metallography

(a) Cutting of the specimen

Two small samples, 10mm square of height 10mm were cut from samples S and F. The cutting was done by the use of the lathe machine.

(b) Grinding

The surface of each specimen was grinded to remove the rough scale and gross imperfection on their surfaces. Grinding was accomplished by a grinder having four different grits (240, 320, 400 and 600). The 320, 400 and 600 grits were used consecutively. Each specimen was taken to 320 grit to clean the scratches but it also created finer scratches in its own direction. Each specimen was then turned through 90^0 for 400 and 600 grit. At this point, all the scratches were removed and the surfaces reflected light slightly. The grinding was performed in a stream of water which acted as coolant and dirt or scrap removal.

(c) Polishing by Universal polisher

The polishing was accomplished by first putting the polish on the rotary polisher, thereafter the machine was switched on and each specimen

pressed against the polish as the machine rotated until a mirror-like surface was produced.

(d) Microscopic scratch examination

To ascertain the complete removal of the scratches, each specimen was examined under a microscope of X100 magnification. Scratches were still present and the specimens were taken back for repolish.

(e) Etching of the specimen

Each scratch free specimen was etched with 2% nital for 10 seconds to eat away some metallic structures which appear as dark shadows under microscope. Before etching, the polished surface of each specimen was rinsed in a stream of water and allowed to dry. After etching, the rinsing and drying process was repeated.

(f) Microscopy

With the camera put in place, the two specimens were placed on the metallurgical microscope one after the other for the examination of the microstructure and snapping. The magnification used was X200. Results obtained are as shown in plates 10 and 11.

CHAPTER FOUR



4.0 RESULTS AND DISCUSSION

4.1 RESULTS

In this chapter, the results obtained from the chemical analysis, mechanical tests and metallography of samples S and F are expressed in terms of Tables, Graphs and Plates.

4.1.1 Chemical Analysis

Table 4.1 gives the result of the analysis of the Nigerian Air Force Air Beetle nose wheel strut showing elemental composition by using Atomic Absorption Spectrometer.

Table 4.1: Percentage Chemical Composition of the Standard and Failed Nose Wheel Strut Samples

Element	Composition of Standard Sample, S (%)	Composition of Failed Sample, F (%)
Fe	96.800	96.820
C	0.400	0.426
Si	0.319	0.074
Mn	0.750	0.931
P	0.005	0.015
S	0.035	0.021
Cr	0.887	0.917
Mo	0.010	0.026
Ni	0.055	0.208
Al	0.013	0.007
Co	0.013	0.007
Cu	0.299	0.129
Ti	0.007	0.004
V	0.191	0.177
B	-	0.002
Nb	-	0.015
Sn	-	0.001
Mg	-	0.008

4.1.2 Hardness Test

Table 4.2 gives the result of hardness test on standard and failed Air Beetle nose wheel struts.

Table 4.2: Hardness values (HBr) of Standard and Failed Nose Wheel Strut Samples

Test Result	Standard Sample (S1)	Standard Sample (S2)	Failed Sample (F1)	Failed Sample (F2)	% Discrepancy (%D)
Hardness Value (HBr)	524	524	432	432	
Average Hardness Value (HBr)	524		432		17.6

4.1.3 Tensile Test

Table 4.3 gives the result of tensile test on standard and failed Air Beetle nose wheel struts.

Table 4.3: Tensile Strength (N/mm²) of Standard and Failed Nose Wheel Strut Samples

Test Result	Standard Sample (S)	Failed Sample (F)	% Discrepancy (%D)
Tensile Strength (N/mm ²)	15,400	13,650	11.4

4.1.4 Compression Test

Table 4.4 gives the result of compression test on standard and failed Air Beetle nose wheel struts.

Table 4.4: Compressive Strength (N/mm^2) of Standard and Failed Nose Wheel Strut Samples

Test Result	Standard Sample (S1)	Standard Sample (S2)	Failed Sample (F1)	Failed Sample (F2)	% Discrepancy (%D)
Compressive Strength (N/mm^2)	17,250	15,800	15,800	14,200	
Average Compressive Strength (N/mm^2)	16,525		15,000		9.2

4.1.5 Impact Test

Table 4.5 gives the result of impact test on standard and failed Air Beetle nose wheel struts.



Table 4.5: Impact Energy (J) of Standard and Failed Nose Wheel Strut Samples

Test Result	Standard Sample (S1)	Standard Sample (S2)	Failed Sample (F1)	Failed Sample (F2)	% Discrepancy (%D)
Impact Strength (J)	60.1	59.6	54.5	53.3	
Average Impact Strength (J)	59.8		53.3		10.8

4.1.6 Fatigue Test

The fatigue test results are presented in Tables 4.6 and 4.7.

Table 4.6: Result of Fatigue test on standard Air Beetle nose wheel strut samples.

Moment	Gauge length (mm)	Final length (mm)	Initial revolution	Final revolution	Diameter (mm)	Stress (N/mm ²)	No of cycles (N)	Log N
30	28	51.3	4459.99	4460	5.5	4750	0.002	0.3
50	28	51.3	4464.99	4465	5.5	3970	0.004	0.6
60	28	51.3	4472.99	4473	5.5	3263	0.006	0.8
70	28	51.3	4479.98	4480	5.5	2740	0.016	1.2
80	28	51.3	4484.94	4485	5.5	2360	0.065	1.8
87	28	51.3	4490.20	4490.6	5.5	1978	0.400	2.6
98	28	51.3	4491.00	4495	5.5	1543	4.000	3.6

Table 4.7: Result of Fatigue test on failed Air Beetle nose wheel strut samples

Moment	Gauge length (mm)	Final length (mm)	Initial revolution	Final revolution	Diameter (mm)	Stress (N/mm²)	No of cycles (N)	Log N
30	28	51.3	4480.20	4481.5	5.5	5124	1.30	2.1
50	28	51.3	4479.84	4480.0	5.5	4250	0.16	2.2
60	28	51.3	4479.65	4480.9	5.5	3067	0.25	2.4
70	28	51.3	4478.10	4478.9	5.5	2580	0.80	2.9
80	28	51.3	4478.70	4480.7	5.5	2478	2.00	3.2
87	28	51.3	4480.00	4484.0	5.5	2243	4.00	3.6
98	28	51.3	4490.00	4499.9	5.5	2000	9.90	4.0

Table 4.8: Combined Mechanical Test Results

Mechanical Test Results	Standard Sample (S)	Failed Sample (F)	Percentage Discrepancy (%D)
Hardness	524HBr	432HBr	17.6
Tensile strength	15,400 N/mm ²	13,650 N/mm ²	11.4
Compressive strength	16,525 N/mm ²	15,000 N/mm ²	9.2
Impact energy	59.8J	53.3J	10.8
Fatigue limit	2,750N/mm ²	2,500N/mm ²	9.1

%D = Percentage discrepancy from standard

$$\%D = \frac{\text{Standard} - \text{failed}}{\text{Standard}} \times 100 \quad \dots\dots\dots (4.1)$$

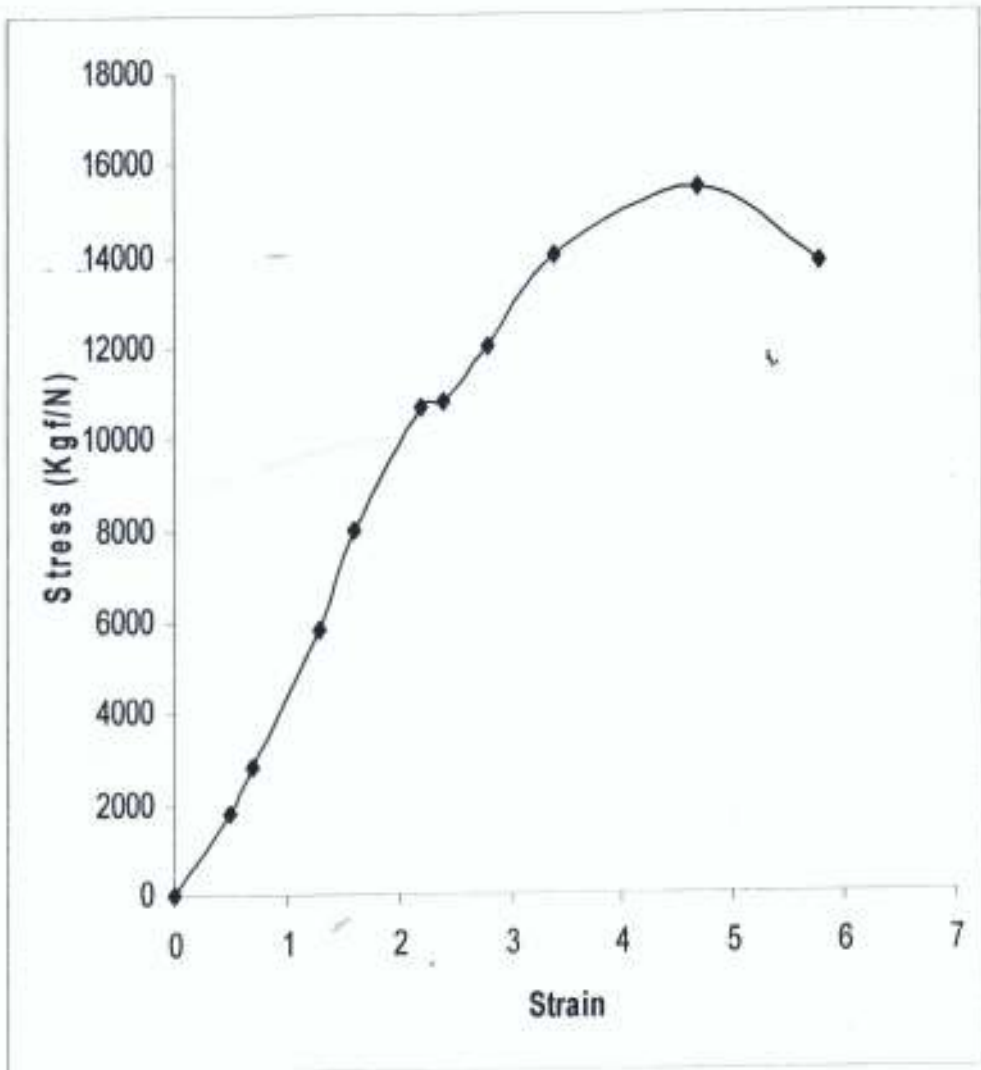


Fig. 12: Stress strain curve on standard sample S

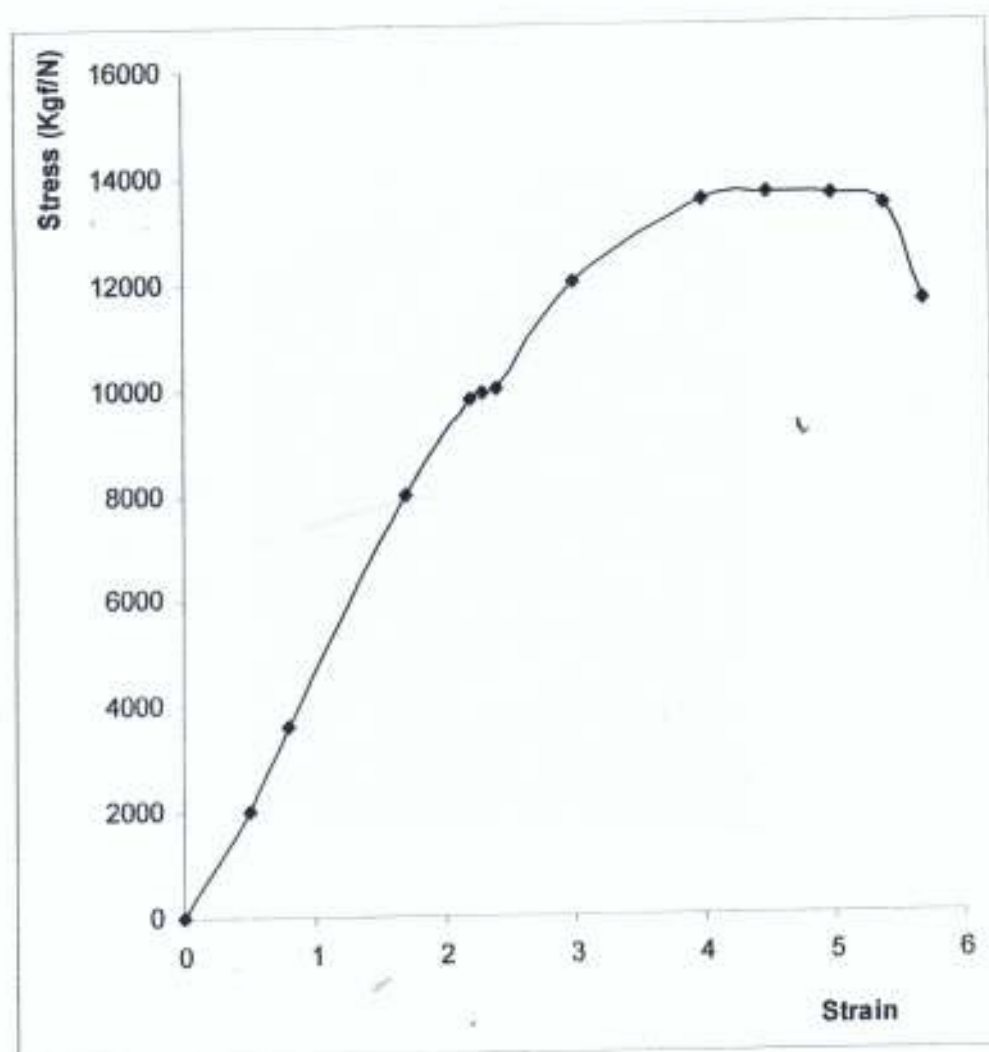


Fig. 13: Stress strain curve on failed sample F

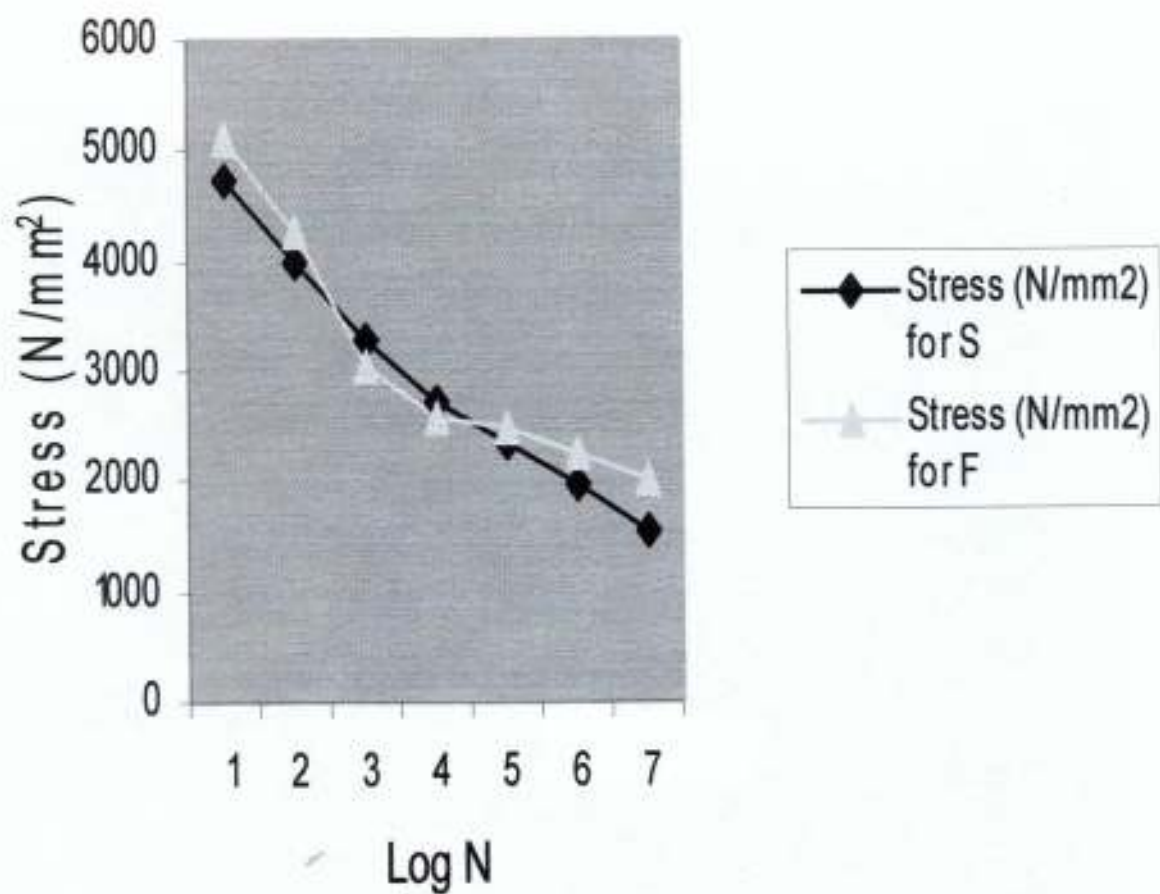


Fig. 14: Endurance Curves for Standard and failed Nose Wheel Strut Samples

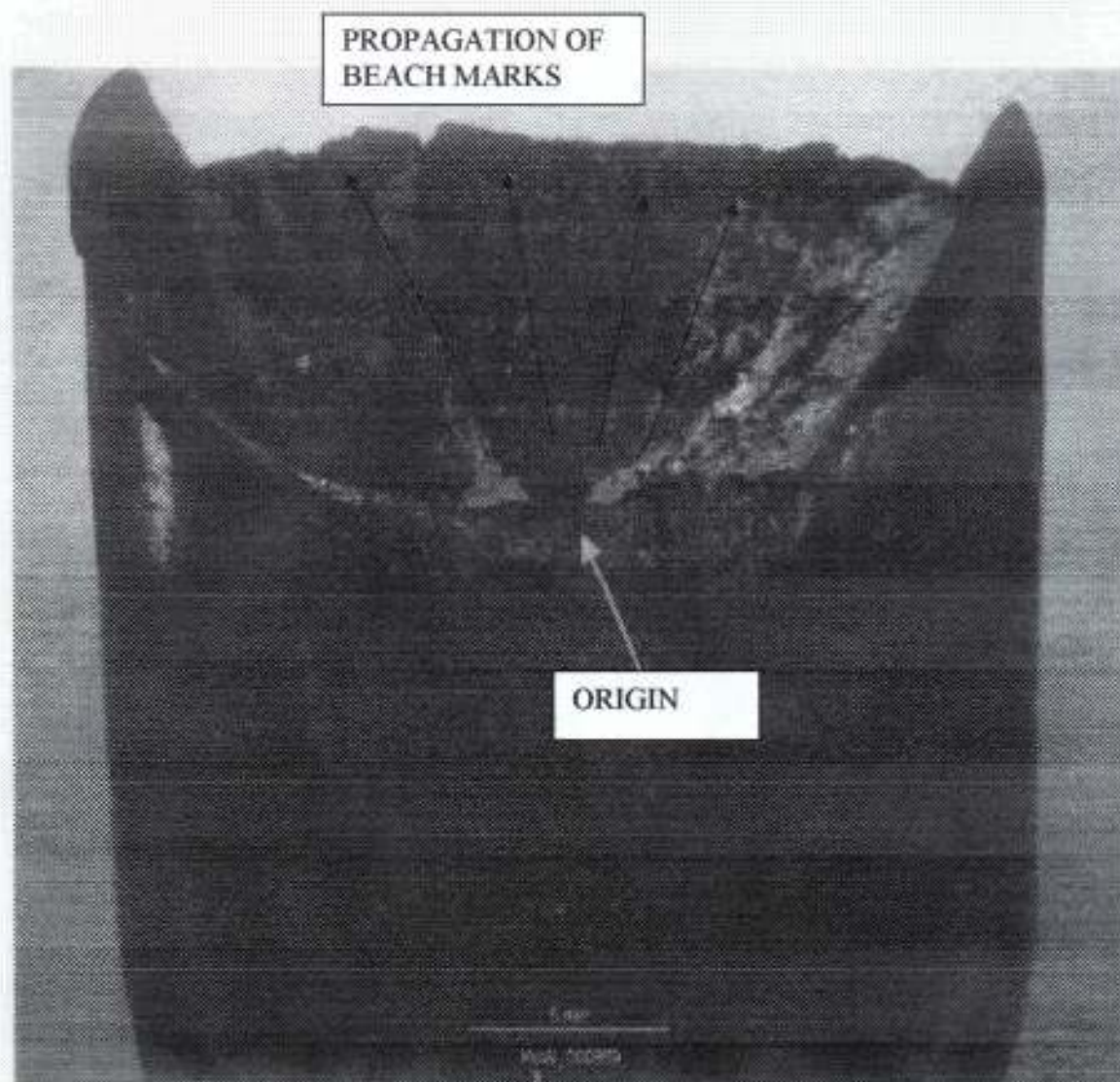


Plate 9: Fatigue Fracture Surface of the Nose Wheel Strut



Plate 10: Photomicrograph of Standard Sample showing few large inclusions with pearlite (dark) in ferrite matrix (white); Longitudinal section



Plate 11: Photomicrograph of Failed Sample showing fatigue cracks propagating from dark inclusions; longitudinal section.

4.2 DISCUSSION

4.2.1 VISUAL EXAMINATION



According to Griffith, there are submicroscopic micro cracks in metal that causes local concentration of stress to values high enough to propagate the crack and eventually to fracture the metal. He demonstrated that the critical stress σ_c required for crack propagation on a brittle material

$$\text{is } \sigma_c = \sqrt{\frac{2E\gamma_s}{\pi a}} \quad \dots\dots\dots (4.2)$$

where

E = modulus of elasticity

γ_s = specific surface energy

a = one half of the length of an initial crack.

Visual examination was carried out on the failed sample (F) by means of the unaided eye and fractography. With both the unaided eye and fractography, V-shaped markings (chevrons) or beach marks were seen on the fracture surface converging to a point which is the origin of the fracture as shown in Plate 9. These chevrons are characteristic of brittle fracture associated with fatigue in which there is no gross deformation and very little mass deformation. Such a fracture is sudden, thus produces disastrous consequences (Khana, 1995).

Investigations carried out on the failure in a low-temperature separator vessel revealed that the through-wall crack was an arrested brittle fracture, that had initiated on both sides of the nozzle penetration in the

vessel wall and had propagated outwards (Han *et al*, 2006). Likewise, in the failure analysis of a transmission axle-small engine, micro-fractographic examination revealed the action of brittle fracture by an impact mechanism originated at the sharp edge of the keyway bottom surface (Alves *et al*, 2006).

4.2.2 CHEMICAL ANALYSIS

Chemical analysis was carried out on the as-received standard and failed samples. The purpose of analyzing the chemical composition of the steel samples was to enable its classification to be made. They were found to be 0.4% carbon steels with few alloy additions and inevitable impurities as well as slight variations in elemental compositions of the two samples due to different production periods as presented in Table 4.1. It has been shown (Lindberg, 1977) that carbon steel with carbon content between 0.3 and 0.6% is termed medium carbon steel. While those with lower and higher carbon contents are respectively classified as mild and high carbon steel. Likewise, AISI classified steel whose carbon content ranges between 0.29% to 0.54% (for example AISI 1040 steel) to be medium carbon steel (Smith and Hashemi, 2006). Based on these findings, the nose wheel strut material can be classified as medium carbon steel of the tough grade; specification number- 0050 (Society of Automotive Engineers Specification, 1957).

Franco *et al.*, (2006) carried out chemical analysis of an as-received failed landing gear component during a failure investigation. A

comparison of its composition within the range of commercial alloys available indicated that the material was a micro alloyed Vanadium steel.

4.2.3 MECHANICAL TESTS

Hardness Tests Result

The result of the hardness tests is as presented in Table 4.2. For the standard sample (S), the average hardness value was 524HBr while for the failed sample (F), it was 432HBr. There was a discrepancy of 92HBr between them amounting to a percentage discrepancy of 17.6%. In this case, the ability of the material to resist plastic deformation under indentation was used to evaluate hardness. The loss in hardness is as a result of fatigue behaviour which is marked by loss of strength and loss of ductility (Yu and Xu, 2005).

Tensile Test Results

These are as shown in Table 4.3 and Figures 12 and 13. The ultimate tensile strength of the standard sample (S) is $15,400\text{N/mm}^2$ while for the failed sample (F) is $13,650\text{N/mm}^2$. There is a percentage discrepancy of 11.4% between them. There was no plastic deformation in sample F before failure hence the absence of a sharp yield point. The absence of a sharp yield point is characteristic of brittle fracture.

During the failure analysis of a crane bolt by Graham (2005), tensile tests were carried out on the bolts to test their material properties in comparison with the standards. The results showed that the yield strength

and ultimate tensile strength of the original bolts are only two thirds that required by the standards. The failed sample of the Air Beetle nose wheel strut reflects a small area of failure in tension (noting the high tensile strength).

Compression Test Results

As presented in Table 4.4, the average compressive strength of the standard sample (S) was $16,525\text{N/mm}^2$ while for the failed sample (F), it was $15,000\text{N/mm}^2$. This revealed a discrepancy in percentage of 9.2. The failed sample (F) reflects a large surface of failure in compression (noting the lower strength in compression) which is actually a compressive failure (Graham, 2005).

Impact Test Results

The values indicated in Table 4.5 is the energy absorbed when a striking energy of 300J was initiated at the notch created on the specimen. This strength is an indication of the level of toughness of the material. It is the notch that actually led to failure. It is expected that the impact strength of the failed material would be less than that of the standard material as shown by the result in Table 4.5. Materials with impact strength of 60J can find applications in axles, gears, drop forgings, buildings, bridges, washing machine and fridge bodies (Spotts, 1988).

Fatigue Test Results

Gagg and Lewis (2008) stated that, as a failure mechanism, fatigue involves initiation and gradual growth of cracks until the remaining section of material can no longer support the applied service load. The results of the fatigue tests carried out are as presented in Tables 4.6 and 4.7 and shown in Figure 14. The fatigue strengths are $2,750\text{N/mm}^2$ and $2,500\text{N/mm}^2$ for the standard and failed samples respectively, which is quite lower than the maximum stress of 6000N/mm^2 . The low fatigue resistance of the samples and high stress to which the strut was subjected to are the root causes of the fracture. This was also ascertained by visual examination where chevrons were seen on the surface originating from a point which could be the initiation site.

The beach marks (chevrons) characteristic of fatigue that radiate from the initiation site and location of final fracture, being off-centre, indicated that initiation did not occur evenly around the circumference of the strut (Wilde, 1986). From the results of the analysis of a failed nose landing gear, Franco *et al.*, (2006) concluded that the initial crack growth in the landing gear was due to fatigue. A secondary initiation site was also observed and corrosion pits were identified, suggesting that corrosion was the main cause of fatigue initiation. A non-destructive test such as high-quality dye penetrant inspection was recommended to detect cracks.

4.2.4 MICRO STRUCTURAL ANALYSIS

Results are as shown in Plates 10 and 11. Microscopic examination of the standard sample at magnification of X200 revealed large inclusions with pearlite (dark) in ferrite matrix (white). This defect is a design problem since it is present in the standard sample; hence there are equal chances of failure of the standard sample under fatigue loading. Microscopic examination of the failed sample at magnification of X200 revealed these inclusions more widely spread in the core of the material; with pearlite in ferrite matrix. Some are seen as degenerated inclusions. These inclusions acted as stress raisers and thus fatigue initiation sites resulting in fatigue cracks as shown in Plate 11.

Inventors of spring steel superior in fatigue properties, US Patent 6328820 carried out extensive studies and found that fatigue properties can be effectively improved by controlling the average composition of these inclusions. It was also found that fatigue properties are greatly affected by the thickness of the inclusions in the longitudinal cross-section of steel products. Breakage starts from the inclusions if they are thick even though they are ductile. In other words, the width of the inclusions plays an important role in the improvement of fatigue properties.

Likewise, Fonte and Freitas (2008) found that microstructural defects or inclusions are intrinsic latent defects which could propagate failure. Their absence could lead to the conclusion that failure was probably originated by an external cause.

CHAPTER FIVE



5.0 CONCLUSIONS AND ENVISAGED FURTHER WORK

5.1 CONCLUSIONS

Based on experiments and comprehensive analysis, the following conclusions can be drawn:

- Visual examination with the unaided eye and fractography revealed chevrons which indicate a brittle fracture associated with fatigue failures.
- From the analysis of its chemical composition, the as-received material was found to be medium carbon steel of the tough grade which did not meet the standard requirements for high strength spring steel useful in aircrafts.
- There were discrepancies in the mechanical properties of the failed nose wheel strut from the standard.
- The failure mode was impact fatigue failure initiated at the inclusions present in the microstructure resulting in crack propagation through the matrix.

5.2

ENVISAGED FURTHER WORK

Further analyses should be carried out on the failure of the NAF Air Beetle nose wheel strut in respect of fracture mechanics, stress analysis and finite element model.

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