Addressing Adaptive Structure Technology to Reduce the Airframe Noise

Hakan Şahin

Degree project in
Solid Mechanics
Second level, 30.0 HEC
Stockholm, Sweden 2012
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ABSTRACT

The purpose of this thesis is to design and analyze the new generation leading edge slat of a commercial jet to reduce the structural noise with the application of new conceptual design approaches. Recent scientific research show that the leading edge slats account for the structural noise during the flight operation therefore, when the leading edge slat is deployed under different flight conditions, an open gap/slot is formed between the high lift device and the wing box. However, since the leading edge slat includes flexible sections, it is assumed that defining an adaptive system inside the leading edge slat may reduce the structural noise by utilizing bending properties of these flexible sections. Hence, electromechanical actuator designing gains also great importance in the whole process.

In this study, we have used, finite element modelling of the slat structure to examine the required structural deformations and strengths; our work is based on the software ANSYS/Workbench. To be realistic in deciding the right geometry in the follow up steps, we have first studied a generic geometry having no aerodynamics or actuator forces application. The whole simulation was performed by defining dummy forces and dummy material properties. The simulation lead to having a global overview of the mechanical behaviour of the structure; further, once the influent parameters were tested, realistic aerodynamic forces and material properties were defined, and as a result of bending of the flexible sections the required gap closure was formed between the trailing edge of the slat and the wing box. Subsequently, the suitable actuator design and required strength analysis are also performed on the last section. This study has also proved that the use of adaptive systems on the leading edge slats improves flight comfort by reducing the structural noise and provides less fuel consumption; this is significant for the long run considerations of aeroplane manufacturers.
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<tr>
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<td>( m^2 )</td>
<td>Bolt cross-sectional area</td>
</tr>
<tr>
<td>( C )</td>
<td></td>
<td>Fraction of external load ( P ) carried by bolt</td>
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<tr>
<td>( C_D )</td>
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<td>( D )</td>
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<td>Bolt nominal shank diameter,</td>
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<td>( E_b )</td>
<td>( Pa )</td>
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<td>Stiffness Matrix</td>
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<td>( \Delta )</td>
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<td>Measured bolt elongation in units of length.</td>
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<td>( V_\infty )</td>
<td>( m/s )</td>
<td>Speed of the non-distributed air flow</td>
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<td>( Pa )</td>
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<td>( P )</td>
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<td>$P_m$</td>
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<td>$P_b$</td>
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<td>$p_{(+)}$</td>
<td>Slope parameter of fracture curve</td>
<td></td>
</tr>
<tr>
<td>$p_{(-)}$</td>
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<td>$R$</td>
<td>Fracture resistance</td>
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<td>$R_{(+)}$</td>
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<td>$R_{(-)}$</td>
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<tr>
<td>$R_{(-)}$</td>
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<tr>
<td>$s$</td>
<td>Surface Area</td>
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<tr>
<td>$T$</td>
<td>Bolt installation torque, Nm</td>
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<tr>
<td>$X_c$</td>
<td>UD tensile and compressive strength</td>
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<td>$X_t$</td>
<td>UD tensile (basic) strength parallel to the fiber direction</td>
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<tr>
<td>$Y_T$</td>
<td>UD tensile and tensile strength</td>
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</tr>
<tr>
<td>$Y_C$</td>
<td>UD tensile and compressive strength</td>
<td></td>
</tr>
<tr>
<td>$Z$</td>
<td>Elevation</td>
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</tr>
<tr>
<td>$\varepsilon$</td>
<td>Strain</td>
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<td>$\varepsilon_2$</td>
<td>Principle strain</td>
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</tr>
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<td>$\rho_\infty$</td>
<td>Non distributed air density</td>
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<td>$\sigma_n$</td>
<td>Stress on the arbitrary plane</td>
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<tr>
<td>$\tau_{13}$</td>
<td>Shear Stress in direction 13</td>
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</tr>
<tr>
<td>$\theta$</td>
<td>Inclination angle</td>
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</tr>
<tr>
<td>$\delta$</td>
<td>Elongation</td>
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</tr>
<tr>
<td>$\vartheta_{LT}$</td>
<td>Poisson’s ratio</td>
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<td>$\vartheta_{TT}$</td>
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<td>$\theta_{21}$</td>
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# Abbreviations

<table>
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<tr>
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<tr>
<td>ADP</td>
<td>Aerodynamic Pressure</td>
</tr>
<tr>
<td>AoA</td>
<td>Angle of Attack</td>
</tr>
<tr>
<td>APDL</td>
<td>Algorithmic Processor Description Language</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft und Raumfahrt</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>EMA</td>
<td>Electromechanical Actuator</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Agency</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FF</td>
<td>Fiber Failure</td>
</tr>
<tr>
<td>FNG</td>
<td>Flugzeug Nachster Generation (Aeroplane New Generation)</td>
</tr>
<tr>
<td>GFRC</td>
<td>Glass Fiber Reinforced Carbon</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass Fiber Reinforced Plastic</td>
</tr>
<tr>
<td>IFF</td>
<td>Inter Fiber Failure</td>
</tr>
<tr>
<td>IRF</td>
<td>Inverse reserve factor</td>
</tr>
<tr>
<td>MoS</td>
<td>Margin of Safety</td>
</tr>
<tr>
<td>POST</td>
<td>Post Processor</td>
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<tr>
<td>PRE</td>
<td>Pre Processor</td>
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<tr>
<td>RF</td>
<td>Reserve Factor</td>
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About the German Aerospace Center (DLR: Deutsches Zentrum für Luft- und Raumfahrt)

DLR, the German Aerospace Center, is Germany’s national research centre for aeronautics and space. Its research and development work in aeronautics, space, energy, transport, defence and security is integrated into national and international cooperative ventures. As Germany’s Space Agency, DLR is tasked with the planning and implementation of Germany’s space programme. In addition, two project management agencies have been established to promote DLR’s research.

DLR conducts research into Earth and the Solar System, it delivers important data for the preservation of our environment and develops environment-friendly technologies to enhance power supply, mobility, communication and security. DLR’s research portfolio ranges from basic research to the development of products for tomorrow.

DLR operates large research facilities for its own projects and also acts as a service provider for customers and partners from business and industry. It also promotes and encourages new scientific talent, provides advice to politicians and is a driving force in the regions that are home to its 16 sites.[21]

Working at DLR

DLR employs 7000 people; the Center has 32 institutes and facilities at 16 locations in Germany: Cologne (headquarters), Augsburg, Berlin, Bonn, Braunschweig, Bremen, Göttingen, Hamburg, Jülich, Lampoldshausen, Neustrelitz, Oberpfaffenhofen, Stade, Stuttgart, Trauen and Weilheim. DLR also has offices in Brussels, Paris, Singapore and Washington DC.

In the financial year 2011, DLR’s budget for research and operations amounted to roughly 796 million Euro, of which about 55 percent came from competitively allocated third-party funds. The Center also administers the space budget for the German government, which totalled some 1147 million Euro. Of this total, 65 percent covered the German contribution towards the European Space Agency, ESA, 21 percent went towards the German space programme and 14 percent was used to fund DLR’s aerospace research. The funding from the DLR Project Management Agency amounted to 1060 million Euro, while that of the Project Management Agency for Aeronautics totalled 164 million Euro.

DLR’s productivity is made possible by its highly trained and motivated employees, who are able to continuously develop themselves professionally at DLR. Equal opportunity is a key mantra at DLR. With flexitime, part-time employment and specific support measures, a good balance between career and family is ensured.[21]
INTRODUCTION

International air passenger traffic has grown rapidly in recent years and this has led to new demands from manufacturers of aeroplanes. Increasing number of passengers mean higher production of aeroplanes. This situation is also related to environmental issues; aeroplane manufacturers are focused on producing aeroplanes with less dependence on fossil fuel and lower weight. During several decades, reducing the weight of aeroplanes was not the only requirement for manufacturers of aeroplanes; another significant demand by aviation authorities was quieter aeroplanes. Therefore, scientists and engineers today are researching on production of quieter aeroplanes. In this thesis, we also focus on environmentally friendly solutions; our goal is finding an optimum way for reducing aeroplane noise that is structural.

![Airbus A350 Composite Aeroplane](image)

Figure 1.1 Airbus A350 Composite Aeroplane [16]

Many noise sources have already been identified, evaluated and classified under three different titles:

- Aerodynamic noise
- Engine and other mechanical noise
- Noise from systems and structures of aeroplanes.

Aerodynamic noise arises from the airflow around the fuselage during the flight and the noise level is directly related to the speed and the altitude of the aeroplane. Aeroplane’s engines and rotating parts of the engine such as turbines, gearboxes and mechanical chains cause loud noise mainly in the aeroplane. The last category of noise sources is investigated the electronic equipments, navigation systems and the airframe; from the structural perspective of the
airframe, control systems such as the slats, flaps, spoilers, and gears play a major role, and contribute highest level of noise on the aeroplane structure.

In our case we focused particularly on a high lift device and leading edge slats. (Fig.1.2). The adaptive slat concept had already been found [5]; we tried to build a model to observe whether or not the new generation adaptive system technologies are applicable in real life. To do so, we first applied generic material properties, dummy forces and dummy boundary conditions on generic geometry of the ambient FEM software; post processing results were checked in order to understand whether or not the system works properly. In this way, a global overview of follow up steps was obtained just before carrying out the geometry to real dimensions. With the use of generic studying method, we made faster and accurate decisions for the follow up steps; an effective and advantageous study was conducted throughout the whole design process. Afterwards, generic analysis and design results were carried out by implementation of realistic material properties, forces and boundary conditions. At last, closer realistic consequences were obtained by validating the results. It must be noted that validation process is of great importance for obtaining better engineering knowledge about the study.

We defined the use of high lift devices in aeroplanes and detailed their mechanisms by comparing various types of devices. Prior to pointing possible solutions to reducing the noise produced by the leading edge slats, we focused on high lift devices and explained how these devices generate noise.


2. FUNDAMENTALS

Since the invention of aeroplanes, much progress has been achieved in the aviation industry. New demands and requirements were raised as technology developed; these new demands and requirements enabled scientists to find efficient solutions for obtaining more economic and ecological profits for journeys by aeroplanes. In order to produce faster, lighter and more powerful aeroplanes, many studies were carried out especially on the structures of aeroplanes (Airframe), engines and aerodynamics.

As is well known, the wings and their parts play vital role in enabling the aeroplane fly. In this section, we review body parts of aeroplanes and their scientific backgrounds. Significance is paid in particular to the most sophisticated parts of aeroplanes: the wings and their main (Control) components such as flaps, slats, spoilers and ailerons. The last section of the chapter is dedicated to the leading edge slats; a comprehensive review of leading edge slats, their parts and working principles are provided in this chapter. Understanding these fundamentals well has great impact on chapters that follow.

2.1. Main Aeroplane Structures

Mainly, aeroplane structures are defined in five groups. (Fig. 2.1)

- Power Plant
- Landing Gears
- Fuselage
- Wings
- Empennage

![Figure 2.1 Aeroplane Main Components](image)
2.1.1. The Fuselage

The fuselage is the central body of an aeroplane and it is designed to accommodate the crew, passengers, and cargo. It also provides the structural connection for the wings and the tail assembly.

![Figure 2.2 Fuselages](image)

2.1.2. The Wing

An aeroplane’s sectional wing components are represented from inside section to outside. (Fig.1.2 & Fig.2.3) The wings are airfoils that are attached to each side of the fuselage and they provide the main lifting surfaces and support the aeroplane in the flight. Numerous wing designs, in varying sizes, and shapes were used by various manufacturers. Each one fulfills certain needs with respect to expected performance for the particular aeroplane.

![Figure 2.3 Airbus-wing structure’s Terminology](image)
The principal structural parts of the wing are defined as spars, ribs, and stringers. These parts are reinforced with the trusses, I-beams, tubing and other devices including the skin. The wing ribs determine the shape and thickness of the wing (airfoil). (Fig.2.3) In most modern aeroplanes, the fuel tanks are either an integral part of the wing’s structure or consist of flexible containers mounted inside of the wing. [23]

**2.1.3. The Empennage**

The empennage includes the entire tail group and consists of fixed components such as the vertical and horizontal stabilizers. Also, the flexible components are the rudder, elevators and trim tabs.

![Empennage components](image)

*Figure 2.4 An empennage with the components [23]*

The empennage parts control different axes of an aeroplane during a flight (Fig.2.4). Mainly, rudders create rotational motion around the vertical axis and the elevators provide another axial motion on the horizontal axis that provides descending and ascending from one flight level to another one.

**2.2. Mechanics of Flight**

Aerodynamics studies are based on three fundamentals:

1. The Bernoulli’s principle,
2. Aerodynamic forces,
3. Airfoil geometry.

In order to enable an aeroplane to fly with its heavy body, some important parameters play a major role such as fluid density, velocity and wing surface area. In this section some fundamental principles will be revisited title by title.
2.2.1. Bernoulli’s Principle

The principle states that the pressure of a fluid decreases as the speed of the fluid increases. This phenomenon allows the lifting aeroplane using the wings. In principle, “the airfoil is designed that the air moves more rapidly over its upper surface than its lower surface, thereby decreasing pressure above the airfoil. At the same time, the impact of the air on the lower surface of the airfoil increases the pressure below the airfoil. This difference between the decreased pressure above and the increased pressure below produces lift. Thus, a wing with more curvature on the top surface has greater lift than a wing with flat surfaces.” [26]

![Figure 2.5. Bernoulli’s principle on the airfoil](image)

Bernoulli’s famous formula;

\[
\frac{p_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + z_2 \tag{Eq. 2.1}
\]

Where is;

- \(p_1\) & \(p_2\) : Fluid Pressures
- \(V_1\) & \(V_2\) : Fluid Velocities
- \(\rho\) : Density of the fluid
- \(g\) : Gravity force
- \(Z\) : Elevation
2.2.2. Aerodynamic Forces

There are four different types of forces acting on an aeroplane during flight; thrust, drag, lift and weight. The sum of these forces is also acting on the plane must be zero. Therefore, opposite forces must be balanced.

The first force is the weight; the weight is the combination of loads such as crew, fuel, aeroplanes itself and cargo (Fig. 2.6), and directed downward due to the center of gravity.

The second force is the thrust; the thrust is created by the propulsion system (power plant) to overcome the drag force. (Fig. 2.6)

The third force is the drag; the air resists the motion of the aeroplane during the flight; this resistance is called the drag force. The drag force is affected by the shape of airfoil, stickiness and velocity. The following famous formulation in aerodynamics (Eqn. 2.2) defines the drag force.

\[ D = \frac{1}{2} C_D \rho S V^2 \]  

Eq. 2.2

**D**: Drag,

**C_D**: The drag coefficient,

\( \rho \): Density of the fluid,

**S**: Surface area of the wing,

**V**: Velocity of the aeroplane.

---

**Figure 2.6 Forces on the Aeroplane** [23]
The fourth force acting on the aeroplane during flight is the lift: to overcome the weight force, aeroplanes generate this opposing force, called the lift. It is generated by aeroplane motion through the air and is perpendicular to the direction of the flight. The magnitude of the lift depends on several factors including the shape, size, and velocity of the aeroplane. Each part of the aeroplane contributes to the lift force; the wings have the utmost contribution. The lift force acts through a single point called center of the pressure. The center of pressure is defined just like the center of gravity, but using the pressure distribution around the body instead of the weight distribution.[20] Hence, the lift is as follows (Eqn.2.3):

\[
L = \frac{1}{2} C_L \rho SV^2
\]

\[\text{Eq. 2.3}\]

\(D\): Drag
\(C_L\): The lift coefficient,
\(\rho\): Density of the fluid,
\(S\): Surface area of the wing,
\(V\): Velocity of the aeroplane,

### 2.2.3. The Airfoil

The wing of an aeroplane has a special shape called an airfoil; it generates the aerodynamic forces such as lift and drag. Basically, (as is briefly introduced in section 2.2.1), an airfoil produces high pressure under the wing and low pressure above the wing to maintain the aeroplane flies.
There are important geometrical parameters for the airfoil geometry such as the chord line, thickness, camber and chord. All of these parameters affect the flight characteristics and cause different responses relating to different type of airfoils. As is well known from aerodynamics, acting pressure on the airfoil creates moment and this moment in turn defines the angle of attack (AoA). The AoA is the angle between the wing and the direction of the flight. A convenient way to describe the aerodynamic characteristics of a wing is to plot the values of coefficients against the AoA.[6]

![Figure 2.8 Coefficients of lift and drag](image)

The Figure 2.8 illustrates three different types of wing profile comparisons related to the lift and the AoA. When the leading edge of the wing is configured downward, the wing creates negative AoA and reduces the lift; inversely, when the AoA is increased, the aeroplane produces higher amount of lift; it is important however to remember that there is a critical point between the angle of attack and the lift force. Extreme incensement of the AoA causes the stall during the flight operation. Higher amount of surface area (Fig 2.8/Red Line) helps us obtain higher lift under low speed conditions; this is required for deployment of the slats or flaps.

There are however some limitations for the deployment of the slats and flaps based on planes. For example, “15° is a typical angle of attack at the stall of a basic airfoil; modification of such an airfoil using leading edge slot can increase the stalling angle to 22° or even 25°. “[3]

2.3. High Lift Devices

We have so far given a review of the general structures and aerodynamics of aeroplanes. We now go into the details and focus on our main point of interest: high lift devices. The main purpose of the high lift devices is to create higher lift under low speed conditions; this is vital for an aeroplane. When a slat or flap is deployed, increased wing surface area produces higher lift because of higher pressure differences. (Section 2.2.1, section 2.2.2, Fig.2.8)

Although slats have advantages while creating high lift, they also have some drawbacks such as structural noise. In this thesis, we introduce a new generation high lift device by “OPEN AIR PROJECT”; detailed technical information is given in this chapter.
Let’s begin by introducing different kinds of high lift devices; (Fig.2.9):

- Hinged leading edge (droop nose),
- Variable-camber (VC) leading edge,
- Fixed slot,
- Simple Krueger flap,
- Folding, bull-nose Krueger flap,
- VC Krueger flap,
- Two-position slat (single slot),
- Three-position slat (double slot).

2.3.1 Slat Design

Structurally point of view slats are manufactured within three different sections:

- The nose,
- The center (flexible),
- Trailing edge.

These three sections are connected with the support of rear and front spars. (Fig.2.10)
When the slats are deployed, a gap is formed between the wing box and the slat is named as slot. (Fig.2.11). The slot is an important phenomenon from the aerodynamics perspective; it creates higher angle of attack in low speed conditions. So, higher angle of attack and reducing stall speed are advantageous during low speed flights; it does however have a disadvantage too; this is because of creating extra drag that increases the fuel consumption in the cruise flight conditions.

Further, slat deployment and retraction are under control by the help of special mechanisms so as to provide efficient flight conditions. The mechanism consists mainly of, curved slat track and track support rollers. (Fig.2.11) To provide required deployment or retraction under different conditions, the slat track is triggered by either hydraulics systems or electric motors (actuators). Hydraulics and electric motors have advantages, as well as disadvantages. For instance, hydraulic actuators can be simpler than electric motors for the slat mechanisms. The risk with the hydraulic system is the possibility of oil leakage that can cause global failure. On the other hand, the electrical motors (actuators) can be problematic from the space allocation perspective because of their complexity and weight.
When designing the slat, one other important consideration is weather conditions. All Aeroplanes fly under different weather conditions. For instance, when an aeroplane reaches 33000 ft (10000 m) altitude, the ambient temperature drops down to more or less -50 degree Celsius. Such a temperature drop induces ice formation on the aeroplane structures, especially in the wing (flexible) structures. Nowadays, anti-icing and de-icing are methods for prevention of the ice; the anti-icing and de-icing systems are located in the slat for precluding ice stacking to the slat structure. In general, two methods are used to prevent the ice formation: the electric heating system and the steam produced by the aeroplane engine. These anti icing systems cause difficulties however during the design process of the slats; examples are actuators space allocation, weight and cost.

### 2.3.2 Mechanism of Slats

As is well known from the aerodynamics and fluid mechanics, under higher AoA conditions, air flow separation occurs: When the airflow separates, fluid flow goes to turbulence; as a result of vortices and turbulence of air flow, the stalling occurs at higher AoA. In order to prevent stalling, wing surface area is increased. As is mentioned in sections 2.2.3 and 2.3.1, slot phenomenon has great importance when the leading edge slat is deployed. In this situation, the slot conducts the flow of higher air energy from lower surface of the wing to the boundary layer of the upper one. In this way, airflow separation is delayed. Also, slats deploying i.e. reducing stall speed allow good low-speed handling during take-off and landing.

![Figure 2.12 Effect of slat on airflow](image)

**Figure 2.12 Effect of slat on airflow** [1]
3. ADAPTIVE SLAT DESIGN

To begin with, we have to remember that the project’s main purpose is to reduce the airframe noise by addressing active and adaptive structural technologies on the inside of the slat structure. According to the flight mechanics overview (Chapter 1), the slot between the leading edge slat and the wing is defined as structurally essential noise source that negatively effects the flight comfort and unnecessarily increases fuel consumption. In order to achieve minimum noise generation with the sufficient lift, it is necessary to find right AoA and appropriate gap distance between the leading edge slat and the wing box. To reduce the structural noise, the flexibility of the structure of leading edge slat is utilized, and the required bending for obtaining the effective gap closure is provided. This work is performed by the cooperation of DLR “the Institute of Composite Materials and Adaptive Systems” and AIRBUS under the name of ‘OPEN AIR Project’.

Figure 3.1 Adaptive leading edge slat (slot closed) [9]

In the adaptive slat design process, series of FE modelling properties can be used on the software ANSYS Workbench. We first examined the feasibility of the geometry on different types of CAD software; we then assigned properties of the material. In addition, suitable mesh sizing and different types of element applications are studied. Finally, required deformations and reaction forces are achieved after defining aerodynamic pressure on the slat structure.
3.1 Design Process

In building advanced engineering systems, engineers and designers go through a sophisticated process of modeling, simulation, visualization, analysis, designing, prototyping, testing, and fabrication. [4] In this section, the design process of the slat structure is presented by in a flow chart.
3.2 Geometry Creation

Geometry creation is the first step for the structural analysis. CFD and structural engineers co-operated during the whole project process so that 2-D wire frame geometry is obtained on the software ambient based on wind tunnel parameters and CFD calculation results. Subsequently, all structures related to whole wing are defined such as flap, main wing geometry and different slat positions with respect to different flight conditions in the CAD step. We consider only deployed leading edge slat position (open gap) i.e. deployed slat under low speed flight conditions. (Fig 3.2)

![Figure 3.2 2-D wire frame geometry with different positions (CATIA V5)](image)

In the geometry creation process, we have used two different types of CAD software, the CATIA V5 and ANSYS/Workbench design module. CFD calculation results are visualized on the CATIA V5. Subsequently, deployed slat geometry and main wing profile are picked up from the 2-D wire frame profile. In the second step, selected geometry sections (Slat + Main Wing) are transferred to the ANSYS/Workbench using “import geometry” property. After transferring the geometry to the Workbench, the first step is scaling the geometry. Since CFD and wind tunnel engineers work with scale models, it is needed to scale the geometry by a scale factor of 0.0033 to reach realistic dimensions. After obtaining the realistic dimensions on the wire frame geometry, we have crated 3-D geometry using of “extrude” property. However, before going to real extrusion dimensions, the geometry is created as 10 mm thick profile. In this way, possible geometry manipulations are performed without losing time and also possible design faults are minimized. (Fig 3.3)

Leading edge slat structure consists of different types of materials such as flexible sections on top and rigid section on the trailing edge of the geometry. Flexible region is divided by eight different composite sections. In order to define these eight different composite sections, the geometry’s top surface is divided by the “Split Surface” property of Workbench which also required dimensional information related to composite sections shown on Fig 3.4.
Composite sections’ thicknesses are defined on the flexible part of the leading edge (Fig 3.4)
Another geometric manipulation is performed for the rigid trailing edge section of the slat that plays vital role because high speed flow can cause the flutter (Bending + Twisting) of slender structures which is an unwanted situation during the flight operation since flutter occurrence mainly demolishes the flight stability. In order to prevent the flutter’s occurrence on the leading edge slat trailing edge, the solid section is defined with different stiffness and different material properties($E, \theta$). Detailed information about the material will be given in this section. In addition, the workbench provides “thick surface” property in order to obtain solid body on the trailing edge of the slat. At the same time, contact surface between surfaces and solid material come into question when defining rigid trailing edge section. Fortunately, surface to surface contact is done by ANSYS’ itself automatically, but after all, the contact region is checked manually in order to decide whether or not the contacts are defined correctly. Finally, after testing the compatibility of the geometry on the generic case, the design process is carried out on a wider 3-D case where the geometry is extruded 2 meters and realistic slat structure is formed with its real dimensions.

![Figure 3.5 Slat back and front](image)

**3.3 Material Properties**

In this chapter, glass fiber reinforced plastic (GFRP) and its material properties will be defined by the giving summary information about the composite materials. Usage of the linear elastic isotropic materials on the slat structure and definition of the material properties and failure criterions of the composite materials will be assessed. These information give the reader a comprehensive point of view about the application of the materials on the slat structure.
3.3.1 Composite Materials and GFRP

In the aviation industry, it is very important to design lighter and stronger aeroplanes with low cost. With the developments of material technologies, new materials like composites are invented. The composite materials are widely used in the aviation industry because of their advantageous mechanical properties. Due to increasing demands, many different types of composite materials are produced and used in the industry. We are going to focus on some widely used composite materials that play important role in the aviation industry; these are carbon fiber reinforced composites (CFRC), glass fiber reinforced plastics (GFRP), and some linear elastic isotropic materials. GFRP are widely used on the wing and mainly in slat structures. There are three different types of GFRP used in the industry based on glass, aramid and carbon. Glass is by far the most widely used reinforcement fiber and the one with the lowest in cost. Aramid and carbon also have great strength properties and light weight but their costlier than the glass fibers.

![Glass Fiber](image)

Figure 3.6 Glass Fiber [25]

In addition, series of tests like tensile and compression were applied carried out to determine the properties of the GFRP. Mechanical properties of GFRP are presented in Appendices A and B, and compared with the carbon fiber reinforced composite. Below given table (Table 3.1) presents some physical properties of GFRP fibers; these properties guide us when deciding the most suitable material for the slat structure.
### Table 3.1 Physical properties of GFRP[12]

<table>
<thead>
<tr>
<th>Material Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of fiber</td>
<td>6 – 17</td>
</tr>
<tr>
<td>Tex (g/km)</td>
<td>17 – 480</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2540 – 2600</td>
</tr>
<tr>
<td>Elasticity modulus (kg/mm²)</td>
<td>7200</td>
</tr>
</tbody>
</table>

#### 3.3.2 Material Definition of Rigid Trailing Edge

It is important to note that the material property of the slat trailing edge is different than the flexible part. As mentioned before, the slat trailing edge is a slender structure, so that the slender structures causes the flutter (bending + twisting) under high speed air flow conditions; high speed air flow conditions affect the flight stability negatively. In order to prevent the flutter at the trailing edge, the linear isotropic material property is defined as solid body. In this way, a rigid material behavior is obtained and the flutter problem is delayed. (Table 3.2)

### Table 3.2 Physical properties of isotropic Material[9]

<table>
<thead>
<tr>
<th>Material Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity</td>
<td>7.310x10^{13}</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>3.30x10^{-1}</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>2.760 x10^{13}</td>
</tr>
<tr>
<td>Density</td>
<td>2.80 x10^{3}</td>
</tr>
</tbody>
</table>
3.3.3 Material Definition on ANSYS / Workbench

There are different types of methods for applying material properties while assigning them on the FEM software ANSYS/Workbench. One of the methods is to use an auxiliary FEM module called “composite pre-post” in which composite layers and their properties are defined by a special and easy way. Composite layers and their mechanical properties can also be defined with the help of writing APDL commands in ANSYS classic. In addition, there are some new facilities in the new version of ANSYS software for assigning the material properties. In this project, APDL commands are written on the workbench ambient. Using classical methods, we took advantage in defining the layers and their failure criterions. Hereby, the time is gained and wide range corrections obtained during the study.

3.4 Aerodynamic Pressure

Aerodynamic pressure application on the slat structure is another important step in order to simulate the structure on the FE ambient. Aerodynamic pressure parameters file from the CFD simulation is provided by the AIRBUS and DLR engineers for different positions of the slat structure, such as cruise, take-off or landing. We only considered “Step33_alpha_18.235” aerodynamic input file related to angle of 27.834 degree deployed slat from the cruise position. Obtained aerodynamic pressure file consists of three coordinates x, y, z and coefficient of pressure ($C_p$). Parametric pressure file application on the FEM software requires converting pressure coefficient into pressure difference using of special equation (Eq.3.1). Compatibility of parameters from the file is verified with MATLAB software. (Fig 3.7)

![Figure 3.7 Aerodynamic pressures plotting on MATLAB](image)
The pressure coefficient $C_p$ is given by:

$$C_p = \frac{\rho - \rho_\infty}{\frac{1}{2} \rho_\infty v_\infty^2}$$  \hspace{1cm} \text{Eq 3.1}$$

$C_p$: The pressure Coefficient

$\rho - \rho_\infty$: The difference of pressure compared to the atmospheric pressure

$\rho_\infty$: Non distributed air density

$v_\infty$: The speed of the non-distributed air flow

Another parameter that must be considered when calculating the aerodynamic pressure is the swept angle of the wing profile. The importance of the swept angle is reflected in the fact that wing profile is staying constant while slat is deployed; the angle difference created affects the pressure direction during the flight operation directly. In order to simulate the structure under real conditions, FE ambient “The clean 2D section is taken from the mid-board region of the FNG (Flugzeug nächster Generation, new generation) wing; this is equivalent to DLR’s F15LS”; and its dimension corresponds to 8301 mm and the swept angle is 30° with reference to fixed coordinate system. (Fig 3.8)
3.4.1 Implementing Aerodynamic Pressure on the ANSYS

On the FEM software ambient, different kinds of aerodynamic pressure application procedures are available. One of them is to use the APDL commands on the ANSYS Workbench to apply the aerodynamic pressure on the slat structure in order to do required series of scripts.

In the application process, each pressure point from the input file must correspond to the nodes of the structure. In order to define proper and more realistic calculation, the pressure distribution is performed on the elements of the structure in a way that each pressure point corresponds to the center of each element, instead of the nodes after APDL command manipulation. Technology development on the ANSYS’s new versions provides easier pressure and temperature application so that the external file reading property with the definition of coordinates and pressure is a relatively easier method while applying the aerodynamic pressure on the slat structure. The biggest advantage of this method is to reduce the time and provide simple modification facility on the geometry. (Fig 3.9)

As is shown in Figure 3.9, the pressure distribution is considered on the back side and on the flexible top region of the slat structure, with the help of external file reading properties of the ANSYS/Workbench. Pressure distribution on the leading edge of the slat is negligible because of its rigidity; hence, it is not taken into account during pressure distribution. 2437 Pa and -12687 Pa are the maximum and minimum, in order, pressure values that have been found on the slat structure.
3.5 FEM Modeling (Meshing & BC’s)

Boundary conditions, meshing and element type studying are performed to evaluate the feasibility of the slat structure. First, we created 3-D surfaces in the modeling process. Then, the shell element is assigned to the back and flexible section of the slat structure. At the same time, since the geometry includes rigid section (solid body) at the trailing edge of the slat, a solid element is assigned, too. We then defined the contact region between solid and surface elements of the structure. After we defined elements on the FEM software, contact region definition property is automatically performed. Acceptability of the contact region is examined manually to see whether or not it is done correctly by the system itself. After assigning suitable element types, decision making process for the suitable mesh sizing is performed. In addition, since the computation time plays vital role during the calculation process, we used 10 mm thick geometry and examined required deviations with coarse and fine meshes. Once the converged values between coarse and fine meshed structures were obtained, the suitable mesh sizing were found to be 0.025 m on the surface section and 0.1 m for the solid case. (Fig 3.10)
As seen in Figure 3.10, the flexible region is defined by fine mesh (mapped) and the leading edge of the slat is defined by coarse mesh. The leading edge of the slat is not taken into account due to its rigid material behavior. Definition of boundary conditions should be considered in order to solve the system properly. During the geometry creation process, two different kinds of boundary condition’s application are tested. At the first step, each sides of the slat were locked and it was observed that the structure deforms abruptly. This means, we are not able to obtain flexible regions’ deflection and we have to try to find another boundary condition. In the second boundary condition application, the connection between leading edge section and flexible section is locked on the top surface. The edges which are on the back and bottom side of the geometry are also locked too in x, y, z directions (3-DOF) and rotationally.

**3.6 Deformation Analysis (Post Processing)**

Post processing is the last step on the FEM software that gives to results relating to FE model created. The scope of results on structural analysis module of ANSYS is extensive and includes stress, strain, deformation, and reaction force. In this section of the project, the main consideration is evaluation of total deformations with or without actuator force. In addition, reaction force that is caused by the actuator and ADP is also considered. Position of the actuator is also assigned by the FE displacement properties of the ANSYS/Workbench.

At first, the generic studying is performed before extruding the 2m width geometry for reviewing the compatibility of the assigned properties. Only ADP and calculations are calculated before post processing step. Obtained deformation under ADP, the gap (slot) distance was registered between the leading edge slat and the wing box. Table 3.3 and figure 3.11 present results achieved under only ADP with generic geometry study.

![Figure 3.11 Deformation under ADP (without actuator force)](image)

<table>
<thead>
<tr>
<th>Maximum Total Deformation (m)</th>
<th>7.3987x10^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Table 3.3 Total deformation (ADP)</strong></td>
<td></td>
</tr>
</tbody>
</table>
In the second step, eventual actuator locations and required displacements are examined by the mathematical interpolation of the right points from data provided by DLR. It is necessary to execute a series of system solving processes for finding the right position of the actuator; these processes are which a computationally expensive and time consuming way is. Generic geometry study is advantageous as it reduces computation time while finding the right location of the electromechanical actuator. Also, the application of “pattern” property is a helpful method on the ANSYS / Workbench while positioning the EMA. After finding the right location of the EMA, the system is resolved and the reaction force on the slat is obtained. Finding reaction force provides numerous tracks for designing suitable electromechanical actuators that will be considered in Chapter 4 in detail.

![Figure 3.12 Deformation under ADP (without actuator force)](image)

<table>
<thead>
<tr>
<th>Maximum Total Deformation (m)</th>
<th>0.108</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Force Z - Direction (N)</td>
<td>-2.048</td>
</tr>
</tbody>
</table>

Table 3.4 Total deformation & Reaction Force (ADP + Actuator Displacement)
Once the results are obtained from the generic study case, we can access to build 2m extruded structure to reach more realistic geometry. It was noticed that creating structure with 2m width was not difficult after generic geometry studying. Since the volume of the extruded body includes much more nodes and elements than before, the computation time is dramatically increased. ADP and results obtained differed.

In the 2m extruded geometry case, total deformations are calculated only under aerodynamic pressure effect in which the slat structure is examined without having electromechanical actuator force. As is seen in Figure 3.14, the aerodynamic pressure pushes the slat through the direction of the flight up to 0.01m. Defining the actuator force on the structure, we try to compensate the aerodynamic pressure effect by closing the gap between the wing box and leading edge slat. (Fig 3.14)
<table>
<thead>
<tr>
<th></th>
<th>Total Deformation (m)</th>
<th>Reaction Force Z-Axis (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation with ADP</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Deformation with ADP+EMA</td>
<td>0.092</td>
<td>-58841</td>
</tr>
</tbody>
</table>

Table 3.5 Displacement and reaction force

Finally, table 3.5 presents results achieved under different force application conditions. It is observed that the possible actuator must compensate minimum 58.841 kN force for the whole slat structure deformation to fulfil its duty. Therefore, the reaction force gives us a track about the type and amount of actuators to compensate the required gap closure between the leading edge slat and wing box. However, more comprehensive information will be defined in the actuator design section.

3.7 Linear vs. Non-Linear Analysis

In this section, linear and non-linear analysis comparison will be explained and some specific brief information will be given from the deformation analysis. Basically “linear static analysis deals with static problems in which the response is linear in the sense of cause-and-effect.” For example: if the applied forces are doubled, the displacements and internal stresses also double. Problems outside this domain are classified as nonlinear. [7]

Linear analysis is generally used due to,

- Relatively easy computation,
- Advantageous computational time, and
- Solutions that can be superposed on each other.

However, non-linear analysis is necessary for,

- Designing high performance components,
- Large deformation analysis, and
- Material behavior.

Since ADP causes relatively large deformations on the slat structure, linear static FE analysis does not give right results about the real deformation of the slat. Additionally, in the properties of non-linear FEM, sub-step definition has also great importance. Our experience in this project is that 33 iterative sub-steps are to be defined to reach realistic results.
4. ELECTROMECHANICAL ACTUATOR DESIGN

In the recent years, the use of electromechanical actuators has been expanding in various areas of civil aviation industry; their applications had been observed in military aeroplanes previously. Aeroplane manufacturers generally prefer to use the hydraulic based actuators in their aeroplanes, this is because the hydraulic based mechanical actuators bring some drawbacks such as high weight, oil leakage and high volume space allocation. Developments in technology have brought great advantages to the invention of electromechanical actuators; the most important one being the weight impact. For instance, EMAs provide lower weights unlike the hydraulic based actuators; since the aeroplane systems are sophisticated, space allocation plays important role, too.

When we look at the actuators use in aeroplanes, we observed that hydraulic or electromechanical actuators are generally used for control of surfaces of aeroplanes; i.e., required maneuver capability has to be provided with controlling electromechanical devices on the control structures such as slats, flaps, ailerons, rudders and elevators.

In this section, we address the most feasible electromechanical actuators for the adaptive slat. Particularly, the weight impact, minimum space allocation, and required force are our will be main concern while deciding the most efficient one. Comparisons will be performed between current EMAs in the market and the peculiar designed EMA.

Usage of the new systems also brings one other concerning for structural engineers; namely, the installation process of the electromechanical actuators to the slat. During this process any kind of structural damage must be prevented by finding the optimum installation method. That is why feasible structural methods are studied to find out right location of the actuators by providing structural safety.
4.1 Linear and Rotational Electromechanical Actuators

In this section, we give general information about the various types of actuators and their advantages and drawbacks, and present comparisons in Table 4.1. We mainly focus on two types of electromechanical actuators: such as linear and rotational.

4.1.1 Mechanical Actuators’ Working Principle and Linear Actuators

“An actuator is an actuator that creates motion in a straight line, as contrasted with circular motion of a conventional electric motor. Linear actuators are used in machine tools and in many other places where linear motion is required.” [27] (This is probably the simplest definition of linear actuators). Once the working principle and general properties of mechanical actuators are understood, the electromechanical actuators’ working principles can also be understood, easily because of similarities.

“In the majority of linear actuator designs, the basic principle of operation is that of an inclined plane. The threads of a lead screw act as a continuous ramp that allows a small rotational force to be used over a long distance to accomplish movement of a large load over a short distance.” [27] the only difference between the electromechanical actuators and the mechanical actuators is “control knob or handle that is replaced with an electric motor.” [27]

Various components are used to build mechanical actuators:

- **Screw**: lead screw, screw jack, ball screw and roller screw,
- **Wheel and axle**: Hoist, winch, rack and pinion, chain drive, belt drive, rigid chain and rigid belt act,
- **Cam**: Cam actuators.

![Figure 4.2 Linear Mechanical and Electromechanical actuators](19)
Figure 4.2 and table 4.1 show different kinds of actuators’ advantages and disadvantages of actuators. As mentioned before, the most suitable actuator is electromechanical actuator for the slat structure because of its several superior advantages. The use of piezoelectric actuators is also possible; but they required further technology development because they do not produce sufficient force to provide required gap closure for the current slat structures.

<table>
<thead>
<tr>
<th>Actuator Types</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-mechanical</td>
<td>Cheap. Repeatable. Operation can be automated. Self-contained. Identical behavior extending or retracting. DC or stepping motors. Position feedback possible.</td>
<td>Many moving parts prone to wear</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Very small motions possible.</td>
<td>Requires position feedback to be repeatable. Short travel. Low speed. High voltages required. Expensive. Good in compression only, not in tension.</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>Very high forces possible.</td>
<td>Can leak. Requires position feedback for repeatability. External hydraulic pump required. Some designs good in compression only.</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>Strong, light, simple, fast.</td>
<td>Precise position control impossible except at full stops</td>
</tr>
</tbody>
</table>

Table 4.1 Advantages and disadvantages of different types of actuators [27]

4.1.2 Rotational Actuators

“A rotary actuator is an actuator that produces a rotary motion or torque.” [27] Like Linear actuators, Rotary actuators too can also be applicable instead of linear actuators in the slat structure. As is intrinsic in their titles, the rotary electromechanical actuators provide rotational motions while linear actuators provide linear motions. Advantageous and drawbacks of Rotary and Linear actuators are also the same (Table 4.1).
4.2 De/Anti-Icing and Space Allocation

De-icing and anti-icing systems must be considered while deciding the right actuator for the slat. The purpose of both systems is to provide heat. In this way, ice forming is prevented on the aeroplane structures in the various weather conditions. Various de-icing and anti-icing systems are used in the aviation industry: rubber boots, pneumatic boot systems, fluid freeze point, and bleed based anti-icing systems. In addition, two new types of icing systems are tested for the new generation of aeroplanes; these are electro expulsive system and electrically powered systems. Some of the commercial aeroplane manufacturers use the electrical anti-icing technology in their aeroplanes at present.

Figure 4.3 Schematic illustration of the anti-icing system A320 [16]

The bleed-based anti-icing systems are commonly used to prevent ice forming on the wing structures of the commercial aeroplanes. Figure 4.3 and 4.4 illustrate the anti-icing instalment for a commercial aeroplane (Airbus A320). It is clear that required heat (steam) is obtained from the engines of the aeroplane and conducted through the leading edge slats by the help of pipes. Having pipe installment inside slat brings drawbacks for installation of the electromechanical actuators. Fortunately, new generation of anti-icing systems use electrical current instead of pipes. In this manner, required space allocation for the EMA is obtained.
4.3 Peculiar Electromechanical Actuators

While deciding the right actuator, some parameters play crucial role: the weight, stroke, and the force. It is observed that these parameters bring a wide range of alternatives and there are plenty of possible actuators on the market today. Space restriction and deformation analysis’ results proved that finding the most suitable EMA is a difficult problem for the adaptive slats. The most feasible actuator selection is performed as close as possible to FEM analysis results from the market. According to space and force restrictions, we also designed the best possible peculiar actuator.

![Displacement vs. reaction force](image)

**Figure 4.4 Displacement vs. reaction force**

The above graph illustrates the slat displacement and corresponding reaction forces under the aerodynamic force and pre-applied displacement conditions. FEM analysis resulted in maximum displacement of 0.092 m and this displacement structurally created the 58.841 kN reaction force for maintaining the maximum slot closure. (Fig 4.4) These results clearly guided us for finding the right EMA from the perspective of reaction force. Commonly used electromechanical actuators’ property comparison is presented on in table 4.2. Figure 4.5 gives some hints and dimensional restrictions for the slat structure about the suitable EMA choice. It is clear that allocating space is quite narrow for some standard EMA in the market.

For example, actuator 1, 2 and 3 have highly long extended length compared to the free space of the slat (Table 4.2 – Fig 4.5). Since the reaction force is 27 kN/m span, and maximum distance between leading edge and back side of the slat is 270 mm, the nominal design is a good choice; but, minimum four actuators installation per slat is needed obtain the required force for this slat’s state. In the next chapter, exact number of actuators is going to be defined.
by some different kinds of structural designs and we are going to observe different types of structural designs which will reduce the number of actuators.

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Stroke (mm)</th>
<th>Nominal Force (kN)</th>
<th>Weight (kg)</th>
<th>Diameter (mm)</th>
<th>Length Retracted (mm)</th>
<th>Length Extended (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator 1</td>
<td>100</td>
<td>12.73</td>
<td>6.4</td>
<td>123.5</td>
<td>383.5</td>
<td>483.5</td>
</tr>
<tr>
<td>Actuator 2</td>
<td>100-150</td>
<td>11.8</td>
<td>7.2</td>
<td>23 x 35</td>
<td>217</td>
<td>317</td>
</tr>
<tr>
<td>Actuator 3</td>
<td>50</td>
<td>12</td>
<td>12.5</td>
<td>120</td>
<td>293</td>
<td>343</td>
</tr>
<tr>
<td>Actuator 4</td>
<td>30</td>
<td>0.4</td>
<td>5</td>
<td>46 x 80</td>
<td>72</td>
<td>102</td>
</tr>
<tr>
<td>Nominal Design</td>
<td>18</td>
<td>17.6</td>
<td>11-13</td>
<td>99</td>
<td>75</td>
<td>93</td>
</tr>
<tr>
<td>Best Design</td>
<td>22.8</td>
<td>27.5-29.5</td>
<td>8-10</td>
<td>115-125</td>
<td>75</td>
<td>97.8</td>
</tr>
</tbody>
</table>

Table 4.2 Actuator properties and types

A suitable EMA may be available on market; we will still try to find the best one for given parameters and restrictions. In this manner, an EMA was designed by the properties of 20-30 mm stroke, 27.5 – 29.5 kN force and 8-10 kg weight. It is clear that two actuators are enough to compensate the gap closure but structural stress insensitivity must be considered more detailed for two actuator application in the leading edge slat.

New technology methods are always necessary for obtaining the required results using the most efficient system’s development. Fortunately, experts have recently been working on the various projects. One of them is a slat designing with electrical anti-icing systems that provides
much more free space for the higher volume actuators; and another improvement might be piezoelectric actuators. Some results however show that piezoelectric actuators cannot provide enough force with their current designs.
5. STRENGTH ANALYSIS

In this section, we consider stress and strain analyses for adaptive slat structure. As is well known, “for rigid components the loading is described by forces and moments. When a deformable body is considered, forces and moments still control the motion and deformation” [7]. Since the ADP and actuator forces cause the stress and the strain on the slat structure, performing strength analysis to examine the response of the composite structures under various load conditions is essential.

Firstly, the actuators were located and marked on the back of the slat structure; then, required displacements were applied. After executing the FEM calculation, post processor results showed that stresses were getting intensive near vicinity of the actuator acting points. Such a deformation and stress insensitivity around the actuator acting points were unwanted results as these indicated that possible damage risks were high; to prevent the possible any damages on the structure, additional composite layers with holes and actuator pistons’ connection could be assigned by the designing aluminium hinges. Further, strengthening the composite gave raise to another consideration: curing the new composite layers to the structure and installing Aluminium hinges by different assembly methods such as adhesive and bold joints.

The ADP and actuator forces caused some kind of waviness due to the strains on the trailing edge of the slat; this was interesting and concern structural and/or CFD engineers in their studies further. At the end of the section different displacements for different types of designs were compared for flexible parts.

Figure 5.1 Sample strength post processing [22]
5.1 Post Processing

A series of results were obtained in post processing: such as stresses, strains, and reaction forces. These results were expected to give new ideas about the actuator numbers and structural strengthening methods. Failure criterions also play important roles in understanding as to when the structure is damaged under the aerodynamic and actuator forces. Two different methods available for performing damage analysis to visualize the stresses on the structure; are first one is writing APDL commands for the puck failure criterion on the post processing section of the workbench, and using the special module of the Ansys, the “Composite Pre-Post”. We have used the composite pre-post module has been used to visualize the possible damage regions on the slat structure for different kinds of designs.

5.1.1 Failure Criterions (Puck) and the Factor of Safety

Since the slat structure consists of composite materials, available post processing methods for determining damage are not valid anymore on the ANSYS workbench. The composite materials have orthotropic material properties; namely, all mechanical properties are different in different directions. So, looking at the von misses stress is not a logical approach because the von misses stress is valid only for the isotropic material properties. On the other hand, while VM stress gives to maximum stress results in different directions, the failure criterions are to give maximum stresses just before the structure is damaged. Various methods are available for performing the damage analysis: Tsai-Wu, Maximum Stress, and Puck failure criterion. We have used the puck failure criterion in the damage analysis section; the puck failure criterion gives the fiber-matrix failure time of the composite laminates under the influence of the forces. (Appendix C)

Another important parameter is the “Factor of Safety”. The Federal Aviation Authority (FAA) is to publish the factor of safeties for different sections of the aeroplane structures. For instance, while the factor of safety of fuselage design becomes 2, the design safety factor of wing structure is to be 1.5. Simply, the maximum stresses and deformations are to be reduced 1.5 times to obtain standard and safe structures during the design process.

5.1.2 Direct EMA application to the Composite

During the geometry modification process, CATIA V5 surface design properties such as extrude/cut properties are to be applied for the additional composite layer. After the geometry creation step, the slat geometry is transferred to the ANSYS/Workbench and the whole of FEM properties such as ADP, BCs, and material definitions like in the deformation analysis section are applied. (Fig. 5.2). In the second step, defined composite layers are to be pointed symmetrically for obtaining exact locations and required deformations of the actuator pistons. Besides, the slat geometry is to be modified by adding fiber directions and plies on the ANSYS composite pre-post. In this way, all thicknesses and composite material properties are defined by adding glass fiber failure constants of puke.
Post processing results show that the most intensive stresses and relative strains are found around the actuators acting points on the back of the slat. These results also proved that, direct application of the EMAs to the side of the structure can cause early structural failure; therefore, other design methods were considered to increase the composite sections’ strength on the back of the slat. Also, factor of safety requirements have to be fulfilled during the whole design process. (Fig 5.3 and Table 5.1)
<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puck Failure Criterion</td>
<td>1-1.13</td>
</tr>
<tr>
<td>Strain (%)</td>
<td>0.33</td>
</tr>
<tr>
<td>Deformation (m)</td>
<td>0.097</td>
</tr>
</tbody>
</table>

Table 5.1 Stress and strain results on the back side of the slat

5.1.3 Additional Composite Layers

In the second design process, 4mm thick composite layer is cured for the whole wideness of slat; FEM results show that intensive stresses are decreased around the back of the slat due to the first design. It is clear that red regions illustrate the pistons’ acting points and max stresses on the back of the slat structure. Also, by adding the new layer, we try to reduce the EMA number; it is observed that two actuators compensated the required deformation instead of four. (Fig.5.4)

![Figure 5.4 4 mm additional composite layer and strains](image)

Table 5.2 and Figure 5.4 illustrate that additional 4 mm composite layer. New additional composite layer gave rise to stiffness of the slat and created higher reaction force for obtaining the required total deformation. However, local stresses’ insensitivity is to diffuse the whole structure on the back side of the slat to fulfill the factor of safety requirement of FAA. At the end of the second design process, failure and strain results showed that, the second method is much more efficient, defining 4 mm composite layer on the back of the slat. (Fig. 5.4 and
Fig. 5.5 illustrates the most intensive and risky areas for the possible damage on the slat structure; these are around the actuator acting points. Although the second design becomes much more efficient than the first one, it still does not fulfill the factor of safety requirements. Therefore, another conceptual idea is needed to minimize the stresses.

<table>
<thead>
<tr>
<th>Puck Failure Criterion</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain (%)</td>
<td>0.596</td>
</tr>
<tr>
<td>Deformation (m)</td>
<td>0.097</td>
</tr>
</tbody>
</table>

Table 5.2 Stress and strain results on the back side of the slat

5.1.4 Additional Composite Layer and Solid Hinges

In this section, we studied the design of additional composite layers and Aluminium hinges inside the leading edge slat. In the geometry creation process, CATIA V5 part design module was used and solid bodies were created using extrusion and cut properties. Another major concern was space allocation during the design process. Since we have narrow area in the slat structure, dimensions of the Aluminium hinges were decided critically. After geometry creation process, design carried out the FEM software and two identical, symmetric actuator displacement applied. After executing the solver, results obtained showed that stress and strain intensiveness evidently reduced on the back side of the slat; namely, stress intensiveness was absorbed by the Aluminium hinges. Figure 5.6 and 5.7 show the strains and failure regions on the back side of the slat, respectively. When we consider the rainbow scale, the back side of the slat...
slat structure is totally blue. It is also an evidence for the right factor of safety band from the safety perspective of structural design factor.

Finally, three different types of designs and their strain results are compared in Table 5.4. The results prove that hinge design is to reduce the local strains, while the other results intensify around the actuator acting points on the composite back side of slat.

Figure 5.6 Additional composite layer and hinges (Strain)

Figure 5.7 Stress and strain on the back side of slat (Puck)
Finally, three different types of designs and their strain results are compared in Table 5.4. The results prove that hinge design is to reduce local strains, while the other results intensify around the actuator acting points on the composite back side of slat.

<table>
<thead>
<tr>
<th>Design</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Actuator Application</td>
<td>0.33</td>
</tr>
<tr>
<td>Additional Composite Layer</td>
<td>0.596</td>
</tr>
<tr>
<td>Additional Composite Layer and Hinges</td>
<td>0.159</td>
</tr>
</tbody>
</table>

Table 5.4 Strain results comparisons

### 5.1.5 Trailing Edge Waviness and Flexible Section Strains

The trailing edge of the slat is to tend the structural waviness with respect to strains; and this situation also affects the fluid flow during the flight operation. The results in this project bring the need for further explorations of trailing edge waviness in slat aerodynamics to the attention of CFD engineers. (Fig.5.8 & Table 5.5)

![Figure 5.8 Locational Composite layers and strain regions](image)

During the process, series of nodes were picked on the trailing edge of the slat and post processing results obtained with respect to total deformation of the slat structure. The results proved that the trailing edge of the slat also deforms symmetrically and differently with minor displacements for different designs (Figure 5.9-11-13).
Figure 5.9 Locational Composite layers and strain regions

Figure 5.10 Locational Composite layers and strain regions
Figure 5.11 Locational Composite layers and strain regions

Figure 5.12 Locational Composite layers and strain regions
The three different design results were compared by the bending differences on the flexible part of the leading edge slat. Results showed that various designs have different structural bending on the flexible region of the slat.

Table 5.5 Trailing edge elastic strains

<table>
<thead>
<tr>
<th></th>
<th>Maximum Elastic Strains (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Actuator Application</td>
<td>0.04</td>
</tr>
<tr>
<td>Additional Composite Layer</td>
<td>0.05</td>
</tr>
<tr>
<td>Additional Composite Layer and Hinges</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figure 5.13 Locational Composite layers and strain regions
Fig.5.14 Flexible sections’ displacement comparisons

Fig.5.15 represents different bending for different types of designs such as slat deformation without positioning electromechanical actuator, with additional composite layer and hinge connections. It is clear that by applying EMA and hinges, the slat structure’s flexible composite sections bend steadily when compared to additional composite layer and non-positioning EMA designs.
5.2 Joining of Composite Structure and Aluminum Hinge

Air frame structures consist of assembly elements to form a load transmission which include stiffeners, frames, skins and spars. The connections are potentially the weakest sections in the airframe and they must be determined critically and efficiently. In the aviation industry, the most important considerations are minimum number of complexities of joints and minimum weight and cost. Since the composite materials provide better assembly facilities, they are mostly preferable structures for the airframe building. Because of the complexities of the aeroplanes, composite materials like aluminums and steels are to be combined. This chapter is concerned with the joints used to connect structural elements. Airframe structural joints are distinguished as;

- Mechanically fastened joints (Bolts and Rivets) joints, and
- Adhesively bounded (Polymer, Epoxy Adhesives) joints, and
- Mechanical and Adhesives together.

In this thesis, we perform film adhesive joints and mechanically fastened joints between aluminium hinges and glass fiber reinforced plastic material. During the design and analysis process, we found some widely used commercial epoxy adhesives from the market and compared mechanical properties of them; also, a standard bolt was designed to assemble Al-GFRP material layers. In the geometry application process, thin layers were created and contacted between aluminium hinges and composite layers. Since we had obtained the displacements and reaction forces and boundary conditions earlier, all of these properties were defined on the sub structure, easily. In the second process, we tried to find optimum thickness of the film adhesive between the structures with respect to Von Misses stress. In this way, stress intensiveness and critical layers were tested between composite structure-epoxy and aluminium hinge–epoxy. To apply all properties, sub model FE calculation was performed on the force acting hinges and composite layers instead of the whole of the slat.

5.2.1 Epoxy Film Adhesive and Mechanical Properties

There are two different types of adhesives: the paste and the film epoxy. We focus on the film adhesives because of their excellent advantages; also, glue application and its optimum thickness are tested. Generally, Film adhesives provide much higher strengths than the corresponding paste adhesives. Some other important advantages include:

- Ease with which the adhesive can be placed on the adherent surface,
- Avoidance of the need for accurate weighing and mixing,
- Avoidance of mess (compared with paste adhesives),
- Minimization of entrapped air and volatile materials (from solvent residues), and
- Ability to hold adherents in position during cure.
In addition, film adhesives assure a higher level of process and therefore quality control. Disadvantages of film adhesives include high cost, the need for relatively high pressures (compared with single-component paste adhesives) to ensure adhesive flow, high temperatures for cure, and the need for low-temperature storage. Cure temperatures, depending on the hardener system, vary from ambient to around 180 °C, and pressures from zero for paste adhesives to 100-700 KPa for film adhesive.[1] After a market research, a popularly used film epoxy adhesive was selected for aluminium - composite bounding; and the properties were are defined below. (Table 5.6)

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Young Modulus(GPa)</th>
<th>Possion’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Modulus Adhesive</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Low Modulus Adhesive</td>
<td>0.12</td>
<td>0.3</td>
</tr>
<tr>
<td>Conventional Film</td>
<td>0.34</td>
<td>0.43</td>
</tr>
<tr>
<td>Epoxy</td>
<td>0.72</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 5.6 Isotropic film epoxy adhesive material properties [11]

5.2.2 Strength Analysis of Bounded Composite and Al Hinge

Sub model geometry was created from the global slat geometry; then, the composite backside, additional composite layers, film adhesive layers and aluminium hinge were defined on FEM software. In the second step, boundary conditions and known displacements and reaction forces were applied to the sub model geometry. Since the contact problem occurred between the materials, all layers and their contact properties were defined carefully. Subsequently, suitable meshes such as map mesh for adhesive layers and composite layers, and solid mesh were defined for the aluminium hinges on ANSYS Workbench. (Fig 5.14)

![Figure 5.16 Sub Model](image)

In the first design process, only polymer based epoxy glue is pasted between the Al – GFRP layers, and optimum thickness of the glue material was tested. During the thickness optimization process, the results showed that there were no big differences from 0.1mm to
0.3mm thick epoxy. However, just after 0.3mm, the stress and strains dramatically increased (Figure 5.16-5.17-5.18 and Table 5.7). All these high stress and strain intensiveness showed that glue application only between the layers was not enough to obtain reliable assembly; because, there were high level of strain, stress and displacement. Therefore, other commercial and commonly used adhesive bounding methods were investigated and tested.

![Stress vs Thickness](image1)

![Equiv VM Strain Front](image2)

Figure 5.17 Epoxy thickness vs Stress, strain
In the second assembly process, adhesives and conventional films were applied between the AL-GFRP materials and a sandwich film adhesive structure was obtained by applying film and adhesive layers (Fig. 5.16 and Fig. 5.17).

![Figure 5.18 Epoxy thickness vs deformation](image)

### Table 5.7 Epoxy thickness vs stress, strain, deformation results

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Eqv. VM stress (Pa)</th>
<th>Eqv. VM Strain (%)</th>
<th>Total Deformation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2.06 \times 10^8</td>
<td>6.70 \times 10^{-3}</td>
<td>2.52 \times 10^{-6}</td>
</tr>
<tr>
<td>0.2</td>
<td>2.33 \times 10^6</td>
<td>3.20 \times 10^{-3}</td>
<td>2.43 \times 10^{-6}</td>
</tr>
<tr>
<td>0.3</td>
<td>1.47 \times 10^6</td>
<td>2.00 \times 10^{-3}</td>
<td>2.44 \times 10^{-6}</td>
</tr>
<tr>
<td>0.4</td>
<td>1.14 \times 10^7</td>
<td>6.60 \times 10^{-3}</td>
<td>5.98 \times 10^{-6}</td>
</tr>
</tbody>
</table>

 ![Figure 5.19 Sandwich Design](image)
In order to build a sandwich material, all layer thicknesses and material properties were defined writing APDL commands on ANSYS/Workbench like in the leading edge slat composite layers building.

Film-Adhesive design results proved that sandwich film-adhesive bounding is much more efficient than only epoxy application. When obtained results between two applications were compared, we observed that equivalent stresses reduced three times (3.4 %) between the Al hinges and adhesive layers. Also, critical regions (layer separation location) were found on the corner and edge of the sandwich layers.

In addition, layer thickness optimization was performed for the epoxy-film adhesives. Results and corresponding graphs illustrated that maximum stress, strain and displacement was found on 9 layered adhesive sandwiches while the minimum was on 5. However, the best result was obtained from the 5 layered epoxy-film sandwiches (Fig. 5.19 and 5.20).

**Figure 5.20 Epoxy and film layers [11]**

**Figure 5.21 Stress distributions on epoxy-film layer**
Figure 5.22 Number of layers vs VM Stress
After obtaining the best film-epoxy adhesive sandwich design result, we considered another installation method: that is, mechanically fastened joints (Bolts and Rivets) between the GFRP and Al structures. In this design process, we had to consider different parameters compared to adhesive bounding joints. For instance, when a bolted single lap joint was considered between composite and aluminium materials, damage risk increased on the composite layer; this was because higher strength bolt head could damage while the nut was fastening the aluminium structure. In order to prevent such a possible damage risk, special joint element was used between the bolt head and composite structure like washer. Finally, film-epoxy adhesive + bolt (mechanically fastened joints with adhesive) connections were defined. It was observed that using washer can reduce the bolt head stress by 10%. (Fig. 5.21)

<table>
<thead>
<tr>
<th>Layer Numbers</th>
<th>Eqv. VM Stress (Pa)</th>
<th>Eqv. VM Strain (%)</th>
<th>Total Deformation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.60 x 10^6</td>
<td>9.40 x 10^-4</td>
<td>2.63 x 10^-6</td>
</tr>
<tr>
<td>5</td>
<td>5.80 x 10^5</td>
<td>3.70 x 10^-4</td>
<td>2.34 x 10^-6</td>
</tr>
<tr>
<td>7</td>
<td>2.69 x 10^6</td>
<td>1.50 x 10^-3</td>
<td>3.00 x 10^-6</td>
</tr>
<tr>
<td>9</td>
<td>4.17 x 10^6</td>
<td>2.45 x 10^-3</td>
<td>3.76 x 10^-6</td>
</tr>
</tbody>
</table>

Table 5.8 Film and epoxy layers vs stress, strain, deformation results

Figure 5.23 Film-Epoxy + Bolt connection design
Finally, in the last design, we obtained $6.93 \times 10^{-5}$ strain and $5.03 \times 10^{-7}$ m deformation between composite layer and aluminium hinge; the best results among the three different designs. We observed the stress increment on the adhesive layers in last design; this stress increment came from the bolt joint. When the nut and bolt fastened, aluminium hinge and composite layer compressed the adhesive layers and total stress increased.

### Table 5.9 Film adhesive + bolt connection

<table>
<thead>
<tr>
<th>Design</th>
<th>Eqv. VM Stress (Pa)</th>
<th>Eqv. VM Strain (%)</th>
<th>Total Deformation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt+Adhesive</td>
<td>$1.92 \times 10^6$</td>
<td>$6.93 \times 10^{-5}$</td>
<td>$5.03 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

In the last section, we detected maximum tensile strength properties of material to understand whether film epoxy adhesive was applicable. Commercial film epoxy adhesives are abound for our assembly conditions under tensile loading. We have chosen the best with mechanical properties: 8.96 MPa\[^{11}\] (Max.Tensile Strength) at 22 C\(^0\).

$$1.92 \times 10^6 < 8.96 \times 10^6 \quad \text{(Safe)}$$
6. CONCLUSIONS

In this thesis, applications of the leading edge slat and adaptive system technologies have been studied. During the design and analysis process, assessments and the feasibility of the structures of 3-D finite element modeling methods and their compatibilities are studied. Three distinct steps were performed to reach our goals: deformation analysis, decisions on adaptive systems, and designs and structural strength analysis.

In the first step, the slat structure was built using computer aided design and the software for the finite element method; further, all engineering properties due to the realistic conditions were applied to the geometry on the computer simulation ambient. Expected results were achieved by performing, the generic geometry study. The study of generic geometry provided various advantages: the dependencies of the structure for the follow up steps were detected and thus material thicknesses (composite layers) and properties, meshing and boundary conditions were easily defined. After the generic study, possible actuator positions and aerodynamic pressure application were performed on the structure, and requested deformations between the wing box and the slat structure were obtained by utilizing from the generic geometry. In the last step of the compatibility study, all properties were carried out from generic geometry to the realistic slat structure geometry.

During the second step, comparisons of adaptive systems and designs were studied. At first, the possible positions of the actuators in the slat structure were defined; then, different types of actuators were searched and an assessment was performed about the type of applicable actuators. We focused on the linear and the rotational actuators; this is because the motional properties of these two types actuators compensated the desired displacement. Different types of actuators and their properties were also evaluated and properties of available mechanical actuators from the market were compared. Comparisons and researches showed that some electromechanical actuators provided the desired dimensions, stroke and force. However, there was still the need to design the best electromechanical actuator; and subsequently, the most feasible peculiar electromechanical actuator was designed for the slat structure.

Having designed the slat structure and actuators, the strength analysis was performed in the last step; strength analysis was needed because aerodynamic forces and actuator forces caused the structural deformations, stresses and strains on the slat structure. Strain and stress analyses their dependencies were examined, and strengthening and actuator assembly methods were assessed to prevent possible structural damage, two different methods, the additional composite layers with actuator holes and additional composite layer with Aluminium hinges were designed, and gradually reducing the stress, intensiveness was obtained. All of these properties were incorporated into the software of composite pre-post. Installation of the hinges was studied with adhesives and bolt connections and optimum installation methods of different materials were defined. Finally, all data were gathered together and necessary comparisons were performed to achieve the best results.
The top side of the slat structure is to be flexible and this flexibility is to provide required gap closure between the wing box and the slat structure by the electromechanical actuator forces. Recent technological developments and scientific research have proved that piezoelectric cells will be used in both the flexible part of the composite sections and the actuators in near future.

Figure 6.1 Piezoelectric cells [21]
ACKNOWLEDGMENTS

My supervisor’s guidance and the love of family and friends provided my inspiration, and have been my driving force during my study of this much enjoyed research work that culminated in the thesis in your hands. The time and energy put into this work were all worth the while: completing this work is, I know, a milestone in my career development; hence the joy and satisfaction are great.

I would like to express my special thanks, Prof.Dr.Per-Lennart Larsson; Professor Larsson guided me with his invaluable technical knowledge and experiences during my MSc. studies at Kungliga Tekniska högskolan - Royal Institute of Technology (KTH) and followed my progress.

My special thanks go also to Dipl.Ing.Anton Rudenko who enriched incredibly contributed my scientific knowledge about the aviation beyond measure, tirelessly answered my questions, and gave directions me for my future career at Deutsches Zentrum für Luft - und Raumfahrt (DLR).

Now, it is time to thank my invaluable supporters while I am walking on my way in my life more confidently with each achievement. I would like to thank Prof.Dr.Ufuk Taneri for helping me to realize my dreams from my early days in higher education. She was more than a Mathematics professor and guided me through difficult times. It would not be possible without her support to continue my MSc studies either; I would like to thank her for her confidence in me.

Finally, I would like to thank to Assist.Prof.Dr.Hasan Hacışevki too; His guidance and technical knowledge during my BSc studies brought me to MSC Studies.

Thank you all for your trust in me, and your invaluable contributions academically. I will continually build on the knowledge and expertise I have gained with your support.
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APPENDIX A: FIBER GLASS REINFORCED PLASTIC (GFRP) and ORTHOTROPIC MATERIAL PROPERTIES

In this section, strain, stress and engineering constants’ formulation have been represented. S is a compliance matrix as inverse of stiffness matrix C. “For an orthotropic material, the compliances are generally expressed by three E-moduli, six poisson’s ratios and three shear moduli.” [7]

\[ \varepsilon = S\sigma \] Eqn. A1

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{xy} \\
\gamma_{yz} \\
\gamma_{xz}
\end{bmatrix} = 
\begin{bmatrix}
\frac{1}{E_1} & -\frac{\nu_{12}}{E_2} & -\frac{\nu_{13}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{12}}{E_2} & \frac{1}{E_2} & -\frac{\nu_{23}}{E_3} & 0 & 0 & 0 \\
-\frac{\nu_{13}}{E_3} & -\frac{\nu_{23}}{E_3} & \frac{1}{E_3} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{23}}
\end{bmatrix} 
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{xy} \\
\tau_{yz} \\
\tau_{xz}
\end{bmatrix} = S\sigma \] Eqn. A2

If the compliance matrix is symmetric according to Eq.A2 there are three relations between the poisson’s ratios.

\[ \frac{\nu_{21}}{E_2} = \frac{\nu_{12}}{E_1} \quad \frac{\nu_{31}}{E_3} = \frac{\nu_{13}}{E_1} \quad \frac{\nu_{32}}{E_3} = \frac{\nu_{23}}{E_2} \] Eqn. A3

Some data represented as example in table A.1 and a comparison performed between carbon fiber reinforced plastic and glass fiber reinforced plastic from the material constant perspective. Such as elastic, shear modulus and poisson’s ratio.[7]

<table>
<thead>
<tr>
<th></th>
<th>( E_L/\text{GPa} )</th>
<th>( E_T/\text{GPa} )</th>
<th>( G_{LT}/\text{GPa} )</th>
<th>( \nu_{LT} )</th>
<th>( \nu_{TT} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP</td>
<td>200</td>
<td>10</td>
<td>7</td>
<td>0.28</td>
<td>0.3</td>
</tr>
<tr>
<td>GFRP</td>
<td>40</td>
<td>8</td>
<td>4</td>
<td>0.25</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table A.1 Stiffness Properties of CFRP and GFRP [7]
Glass and epoxy resin properties represented below separately.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>E-Glass</th>
<th>Epoxy Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus in longitudinal direction(N/mm$^3$)</td>
<td>73000</td>
<td>35000</td>
</tr>
<tr>
<td>Elastic modulus in transverse direction(N/mm$^3$)</td>
<td>73000</td>
<td>35000</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.22</td>
<td>0.35</td>
</tr>
<tr>
<td>Shear Modulus (N/mm$^3$)</td>
<td>30000</td>
<td>1300</td>
</tr>
</tbody>
</table>

*Table A.2 Stiffness Properties of Glass and Epoxy Resin* [12]
APPENDIX B: LAMINATE THEORY

A laminated structure is composed of several thin layers that are bonded to each other. Lamination of plies can in many conditions be used to improve the mechanical properties of a structure.[7]

- $t_i =$ thickness of ply
- $Z = 0,$ Middle surface in the $z$ direction.
- $Z_{i-1}$ and $Z_i,$ $Z$ coordinates of the bottom and top surface respectively.

The average stress $\sigma_y$ over the thickness of the laminate;

$$\sigma_y = \frac{1}{t} \sum_{i=1}^{N} t_i \sigma_y^i$$  \hspace{1cm} \text{Eqn. B1}

The plane stress stiffness matrix $C_{ps}$ is obtained from inversion of compliance matrix for an orthotropic material with the material symmetry axis.

$$C_{ps} = \begin{bmatrix} \frac{E_1}{1-\vartheta_{12}\vartheta_{21}} & \frac{\vartheta_{21}E_1}{1-\vartheta_{12}\vartheta_{21}} & 0 \\ \frac{\vartheta_{12}E_2}{1-\vartheta_{12}\vartheta_{21}} & \frac{E_2}{1-\vartheta_{12}\vartheta_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix}$$  \hspace{1cm} \text{Eqn. B2}

The average plane stress stiffness is defined by Eqn.B3.

$$C_{ps} = \frac{1}{t} \sum_{i=1}^{N} t_i C_{ps}^i$$  \hspace{1cm} \text{Eqn. B3}
APPENDIX C: PUCK FAILURE CRITERION

Reserve Factor

The reserve factor (RF) indicates margin to failure. The applied load multiplied by the reserve factor gives the failure load:

\[ RF \times F_{\text{applied}} = F_f \quad \text{Eqn. C1} \]

Reserve factor values greater than one indicate positive margin to failure and values less than one indicate negative margin. The values of reserve factors are always greater than zero. The critical values of reserve factors lie between zero and one, whereas the non-critical values range from one to infinity. Whether the results are shown in numeric form or as contour plots, the non-critical values tend to be emphasized in comparison to critical values. Therefore, the inverse reserve factor (IRF) is often preferred in practical use:

\[ RIF = \frac{1}{RF} \quad \text{Eqn. C2} \]

The non-critical values of IRF range from zero to one and the critical values from that on. The margin of safety (MoS) is an alternative for the reserve factor in indicating margin to failure. The margin of safety is obtained from the corresponding reserve factor with the relation

\[ Mos = RF - 1 = \frac{1}{RF} \quad \text{Eqn. C3} \]

A positive margin of safety indicates the relative amount that the applied load can be increased before reaching failure load. Correspondingly, a negative margin of safety indicates how much the applied load should be decreased. Margins of safety are typically expressed as percentages.

Failure Criterion Function

The strength of materials and material systems under multi-axial loads can be predicted based on different failure criteria. Failure criteria relate the material strength allowable, defined for uniaxial tension-compression and shear, to the general stress-strain state due to multi-axial loads. Typically failure criteria are presented as mathematical expressions called failure criterion functions \( f \):

\[ f = \text{function(stress(or strain), material strength)} \]

Where \( f \geq 1 \) indicates failure.

The values of failure criterion functions change with load similarly as the inverse reserve factor (values below one are non-critical and one indicates failure). However, the values are generally not equal except at the failure point. Only the reserve factor RF (IRF, MoS) tells the actual
distance to the failure point from the point represented by the applied load. Typically a numeric line search method is used for determining the value or RF (IRF, MoS) based on the selected failure criterion, stresses and strains due to the applied load, and material strength allowable.

**Puck Failure Criteria**

**Simple and Modified Puck Criterion**

The two elder Puck failure criterion formulations are the so called simple Puck and the so called modified Puck. Both criterions consider failure due to longitudinal loads and matrix failure mode due to transverse and shear loads separately [Puck1969a] [Puck1969b]

For both, simple and modified Puck criterion, failure in fiber direction is calculated the same way as in the maximum stress criterion:

\[ f_f = \left| \frac{\sigma_1}{X} \right| = \frac{1}{RF} \]  \hspace{1cm} \text{Eqn. C4}

The matrix failure is calculated differently for each formulation as illustrated in Equation below for simple Puck. As shown in Equation below tensile or compressive failure stresses are used depending on the stress state.

\[ f_m = \left( \frac{\sigma_2}{Y} \right)^2 + \left( \frac{\tau_{12}}{S} \right)^2 = \frac{1}{RF} \]  \hspace{1cm} \text{Eqn. C5}

\( \sigma_1 \geq 0 \Rightarrow X = X_t; \sigma_1 < 0 \Rightarrow X = X_c \)

\( \sigma_{21} \geq 0 \Rightarrow Y = Y_t; \sigma_2 < 0 \Rightarrow Y = Y_c \)

The modified Puck criterion differs from the latter one only in the formulation for matrix failure:

\[ f_m = \frac{\sigma_2^2}{Y_tY_c} + \frac{\tau_{12}}{S} + \left( \frac{1}{Y_t} + \frac{1}{Y_c} \right) \sigma_2 = \frac{1}{RF} \]  \hspace{1cm} \text{Eqn. C6}

Just like in Hashin failure criterion the failure occurs for either \( f_f \) or \( f_m \) reaching the value one, so the failure criterion function is

\[ f_{max} = (f_f, f_m) = \frac{1}{RF} \]  \hspace{1cm} \text{Eqn. C7}

Despite being called ‘simple’ in the failure criteria configuration in the ACP “Failure Criteria Definition”-dialog for Puck the modified version is actually implemented and the name is referring to the simplicity of that criterion in comparison to Puck’s action plane strength criterion.
Puck’s Action Plane Strength Criterion

Fiber Failure (FF)
As is simple Puck one option for evaluating fiber failure is to use the maximum stress criterion for that case

$$\frac{\sigma_1}{X_t} = 1 \text{ for } \sigma_1 > 0 \text{ or } \frac{\sigma_1}{X_c} = 1 \text{ for } \sigma_1 < 0 = \frac{1}{RF} \text{ Eqn. C8}$$

And similarly a maximum strain criterion.

$$\frac{\varepsilon_1}{X_{Ec}} = 1 \text{ for } \varepsilon_1 > 0 \text{ or } \frac{\varepsilon_1}{X_{Ec}} = 1 \text{ for } \varepsilon_1 < 0 = \frac{1}{RF} \text{ Eqn. C9}$$

A more complicated version for FF criterion was as well presented by Puck for the World Wide Failure Exercise, but the maximum stress criterion is considered sufficient for the case of FF.

Inter-Fiber Failure (IFF)

Plane Stress-State
Inter-fiber failure, or inter-fiber fracture according to can be explained in the cutting plane for which the principal stress $\sigma_1$ of an UD layer.

FigureC1 Fracture Curve [13]
Fracture curve in \((\sigma_1, \tau_{21})\) space for \(\sigma_1 = 0\). Three different fracture modes A, B, C are distinguished.

The curve consists of two ellipses (modes A and C) and on parabola (mode B). Generally Puck’s action plane strength criterion is formed utilizing the following 7 parameters, \(R_{\perp \parallel}^{(+)}, \ R_{\perp \parallel}^{(-)}, \ p_{\perp \parallel}^{(+)}, \ p_{\perp \parallel}^{(-)}, \ p_{\perp \parallel}^{(\pm)}, \ p_{\perp \parallel}^{(\pm)}\), where \(R\) stands for fracture resistances and for slope parameters of the fracture curves. The symbols \(\parallel\) and \(\perp\) denote the reference to direction parallel to the fibers and transverse (perpendicular) to the fibers. The values for \(R_{\perp \parallel}^{(+)}\) and \(R_{\perp \parallel}^{(-)}\) define the intersections of the curve with \(\sigma_2\)-axis, as well as \(R_{\perp \parallel}^{(\pm)}\) for the intersection with \(\tau_{12}\)-axis. The slope parameters \(p_{\perp \parallel}^{(\pm)}\) are the inclinations in the latter intersections.

The failure conditions for IFF are:

\[
\sqrt{\left(\frac{\tau_{21}}{R_{\perp \parallel}}\right)^2 + \left(1 - p_{\perp \parallel}^{(+)} R_{\perp \parallel}^{(+)}\right)^2 \left(\frac{\sigma_2}{R_{\perp \parallel}^{(\pm)}}\right)^2 + p_{\perp \parallel}^{(+) \cdot \sigma_2}} = 1 = \frac{1}{RF} \quad \text{Eqn. C10}
\]

For mode A \((\sigma_2 \geq 0)\)

\[
\frac{1}{R_{\perp \parallel}^{(\pm)}} \left(\sqrt{\tau_{12}^2 + (p_{\perp \parallel}^{(-)} \sigma_2)} + p_{\perp \parallel}^{(-) \cdot \sigma_2}\right) = 1 = \frac{1}{RF} \quad \text{Eqn. C11}
\]

For mode B \((\sigma_2 < 0 \text{ and } 0 \leq \left|\frac{\sigma_2}{\tau_{21}}\right| \leq \frac{R_{\perp \parallel}^{(\pm)A}}{\tau_{21c}}\)\)

The superscript A denotes that the fracture resistance belongs to the action plane.

\[
\left[\left(\frac{\tau_{21}}{2(1+p_{\perp \parallel}^{(-)} R_{\perp \parallel}^{(-)}) R_{\perp \parallel}^{(-)}}\right)^2 + \left(\frac{\sigma_2}{R_{\perp \parallel}^{(-)}}\right)^2\right] \frac{R_{\perp \parallel}^{(-)} \cdot \sigma_2}{(-\sigma_2)} = 1 = \frac{1}{RF} \quad \text{Eqn. C12}
\]

For mode C \((\sigma_2 < 0 \text{ and } 0 \leq \left|\frac{\tau_{21}}{\sigma_2}\right| \leq \frac{|\tau_{21c}|}{R_{\perp \parallel}^{A}}\)\)

The assumption

\[
p_{\perp \parallel}^{(-)} = p_{\parallel}^{(-)} \frac{R_{\perp \parallel}^{(\pm)A}}{R_{\parallel \parallel}} = \frac{1}{RF} \quad \text{Eqn. C13}
\]

is valid here and leads to
\[ R_{\perp}^A = \frac{R_{\perp}^A}{2p_{\perp}(-)} \left( \sqrt{1 + 2p_{\perp}(+) \frac{R_{\perp}(-)}{R_{\perp}}} - 1 \right) = \frac{1}{RF} \quad \text{Eqn. C14} \]

Also Equation (47) is valid.

\[ \tau_{21c} = R_{\perp} \sqrt{1 + 2p_{\perp}(-)} = \frac{1}{RF} \quad \text{Eqn. C15} \]

As the failure criterion functions and the functions for their corresponding stress exposure factors \( f_E \) are the same, they can be written as follows given the equations below.

\[ f_E, \text{Mode A} = \frac{1}{R_{\perp}} \left( \sqrt{\left( \frac{R_{\perp}(+)}{R_{\perp}(-)} - p_{\perp}(+) \right)^2 \sigma_2^2 + \tau_{21}^2 + p_{\perp}(+) \sigma_2} \right) = \frac{1}{RF} \quad \text{Eqn. C16} \]

\[ f_E, \text{Mode B} = \frac{1}{R_{\perp}} \left( \sqrt{\tau_{21}^2 + (p_{\perp}(-) \sigma_2)^2} \right) = \frac{1}{RF} \quad \text{Eqn. C17} \]

\[ f_E, \text{Mode C} = \frac{\tau_{21}}{4R_{\perp}^2 (1 + p_{\perp}(-))^2} \left( \frac{R_{\perp}(-)}{R_{\perp}(+)} - (\sigma_2) \right) = \frac{1}{RF} \quad \text{Eqn. C18} \]

### 3D Stress-State

While the latter formulations have been a reduced case working in \((\sigma_2 - \tau_{21})\)-stress space, the 3D stress-state can be described with Equations below;

\[ \sigma_n \geq 0: f_E = \sqrt{\left[ \left( \frac{1}{R_{\perp}(+)} - \frac{p_{\perp}^{(+)} R_{\perp}^{(+)}}{R_{\perp}^{(+)}} \right) \sigma_n \right]^2 + \left( \frac{\tau_{nt}}{R_{\perp}} \right)^2 + \left( \frac{\tau_{n1}}{R_{\perp}} \right)^2 + \frac{p_{\perp}^{(+)} R_{\perp}^{(+)}}{R_{\perp}^{(+)}} \sigma_n} = \frac{1}{RF} \quad \text{Eqn. C19} \]

\[ \sigma \leq 0: f_E = \sqrt{\left( \frac{\tau_{nt}}{R_{\perp}^{(+)}} \right)^2 + \left( \frac{\tau_{n1}}{R_{\perp}} \right)^2 + \left( \frac{p_{\perp}^{(-)} R_{\perp}^{(-)}}{R_{\perp}^{(-)}} \right) \sigma_n + \frac{p_{\perp}^{(-)} R_{\perp}^{(-)}}{R_{\perp}^{(-)}} \sigma_n} = \frac{1}{RF} \quad \text{Eqn. C20} \]

Where

\[ \cos^2 \psi = 1 - \sin^2 \psi = \frac{\tau_{nt}^2}{\tau_{nt}^2 + \tau_{n1}^2} = \frac{1}{RF} \quad \text{Eqn. C21} \]
As can be seen from the equations above the failure criterion function is formulated in the fracture (action) plane using the corresponding stresses and strains. The formulations for the stresses $\sigma_n$, $\tau_{nt}$, and $\tau_{n1}$ in an arbitrary plane with the inclination angle $\theta$ are

\[
\sigma_n = \sigma_2\cos^2\theta + \sigma_3\sin^2\theta + 2\tau_{23}\sin\theta\cos\theta = \frac{1}{RF}
\]

\[
\tau_{nt} = (\sigma_3 - \sigma_2)\sin\theta\cos\theta + \tau_{23}(\cos^2\theta - \sin^2\theta) = \frac{1}{RF}
\]

\[
\tau_{n1} = \tau_{31}\sin\theta + \tau_{21}\cos\theta = \frac{1}{RF}
\]

To find the stress exposure factor $f_E$ one has to iterate the angle $\theta$ to find the global maximum, as the failure will occur for that angle. An analytical solution for the fracture angle is only available for plane stress-state by assuming

\[
\frac{p^{(-)}_{\perp\perp}}{R^{(-)}_{\perp\perp}} = \frac{p^{(-)}_{\perp\|}}{R^{(-)}_{\perp\|}} = \frac{1}{RF}
\]

which leads to formulations for the exposure factor

\[
f_E(\theta) = \begin{cases} 
\arccos \left( \sqrt{\frac{-R^{\perp\perp}_{\perp\perp}}{-\sigma_2}} \right), & \text{for } \sigma_2 < -R^{\perp\perp}_{\perp\perp} = \frac{1}{RF} \\
0, & \text{for } \sigma_2 \geq -R^{\perp\perp}_{\perp\perp}
\end{cases}
\]  

\[
\begin{align*}
\frac{p^{(-)}_{\perp\perp}}{R^{(-)}_{\perp\perp}} &= \frac{p^{(-)}_{\perp\|}}{R^{(-)}_{\perp\|}} = \frac{1}{RF} \\
\sigma_n &= \sigma_2\cos^2\theta + \sigma_3\sin^2\theta + 2\tau_{23}\sin\theta\cos\theta = \frac{1}{RF} \\
\tau_{nt} &= (\sigma_3 - \sigma_2)\sin\theta\cos\theta + \tau_{23}(\cos^2\theta - \sin^2\theta) = \frac{1}{RF} \\
\tau_{n1} &= \tau_{31}\sin\theta + \tau_{21}\cos\theta = \frac{1}{RF} \\
f_E(\theta) &= \begin{cases} 
\arccos \left( \sqrt{\frac{-R^{\perp\perp}_{\perp\perp}}{-\sigma_2}} \right), & \text{for } \sigma_2 < -R^{\perp\perp}_{\perp\perp} = \frac{1}{RF} \\
0, & \text{for } \sigma_2 \geq -R^{\perp\perp}_{\perp\perp}
\end{cases}
\end{align*}
\]
Puck illustrated in [Puck1996] that the latter criterion can be used as a criterion to determine delamination, if an additional weakening factor for the interface $f_w^{(1/f)} \approx 0.8 \ldots 0.9$ is applied, finally resulting in:

$$\frac{1}{f_w^{(1/f)}} \sqrt{\left[ \left( \frac{1}{R^+} - \frac{p_{\psi}}{R^A_{\psi}} \right) \sigma_3 \right]^2 + \left( \frac{\tau_{32}}{R^A_{\perp}} \right)^2 + \left( \frac{p_{\psi}}{R^A_{\psi}} \sigma_3 \right)^2} = 1 \text{ for } \sigma_3 \geq 0 = \frac{1}{RF} \quad \text{Eqn. C29}$$

$$\frac{1}{f_w^{(1/f)}} \sqrt{\left( \frac{\tau_{32}}{R^A_{\perp}} \right)^2 + \left( \frac{\tau_{31}}{R^A_{\perp}} \right)^2 + \left( \frac{p_{\psi}}{R^A_{\psi}} \sigma_3 \right)^2} = 1 \text{ for } \sigma_3 < 0 = \frac{1}{RF} \quad \text{Eqn. C30}$$

Different default values for the coefficients are set for carbon and glass fiber plies to:

**Carbon**

$$p_{\perp | |}^{(+)} = 0.35 \quad p_{\perp | |}^{(-)} = 0.3 \quad p_{\perp | \perp}^{(+)} = 0.25 \quad p_{\perp | \perp}^{(-)} = 0.2 = \frac{1}{RF}$$

**Glass**

$$p_{\perp | |}^{(+)} = 0.3 \quad p_{\perp | |}^{(-)} = 0.25 \quad p_{\perp | \perp}^{(+)} = 0.2 \quad p_{\perp | \perp}^{(-)} = 0.2 = \frac{1}{RF}$$

Those values are compliant with recommendations given in [Puck2002a].

**Influence of Fiber Parallel Stresses on Inter-Fiber Failure**

To take into account that some fibers might break already under uniaxial loads much lower than loads which cause ultimate failure (which can be seen as some kind of “degradation”), one can introduce weakening factors $f_w$ for the strength parameters. Puck has formulated a power law relation in [Puck1996]

$$f_w = 1 - \left( \frac{\sigma_1}{\sigma_{1d}} \right)^n = \frac{1}{RF} \quad \text{Eqn. C31}$$

Where; $\sigma_{1d} = \xi X_t (\text{or} - \xi X_c)$ respectively; $\xi$ and $n$ can be experimentally determined.

Different approaches exist to handle that problem numerically. The function given in Equation (62) can be replaced by an elliptic function.

$$f_w = \left\{ \begin{array}{ll} \sqrt{1 - c(|\sigma| - sX)^2} & \text{for } |\sigma_1| > s \cdot X = \frac{1}{RF} \\ 1, & \text{for } |\sigma_1| \leq s \cdot X \end{array} \right. \quad \text{Eqn. C32}$$
Where

\[ c = \frac{1-M^2}{(1-s)^2} \quad 0 \leq M \leq 1 \quad and \quad 0 \leq s \leq 1 = \frac{1}{RF} \]  
Eqn. C33

Where \( M \) and \( s \) are so called “degradation” parameters.

In ACP the stress exposure factor is calculated by intersecting the weakening factor ellipse with a straight line defined by the stress vector using the parameters

\[ c_{\text{Line}} = \frac{f_{E0}}{|a_s/X|} \quad a_{\text{Ellipse}} = \frac{(1-s)}{\sqrt{1-M^2}} = \frac{1}{RF} \]  
Eqn. C34

\[ q = \frac{s}{(1+(a_{\text{Ellipse}}c_{\text{Line}})^2)} + \sqrt{\left(\frac{s}{(1+(a_{\text{Ellipse}}c_{\text{Line}})^2)}\right)^2 - \frac{s^2-a_{\text{Ellipse}}^2}{1+(a_{\text{Ellipse}}c_{\text{Line}})^2} = \frac{1}{RF} \]  
Eqn. C35

\[ f_E = \frac{\sigma_s/X}{q_{f}} \quad for \quad \frac{|\sigma_s/X}{f_{E0}} > s \cdot X \quad = \frac{1}{RF} \]  
Eqn. C36

Otherwise the fiber failure criterion determines the stress exposure factor \( f_E \}

Default values for the “degradation” parameters are \( M=0.5 \) \( s=0.5[13] \)
APPENDIX D: SINGLE LAP JOINT and BOLT PRE-TENSION

Let us now consider what happens when an external tensile load $P$, as in Fig. 8–13, is applied to a bolted connection. It is to be assumed, of course, that the clamping force, which we will call the preload $F_i$, has been correctly applied by tightening the nut before $P$ is applied. The nomenclature used is:

$F_i =$ preload
$P =$ external tensile load
$P_b =$ portion of $P$ taken by bolt
$P_m =$ portion of $P$ taken by members
$F_b = P_b + F_i =$ resultant bolt load
$F_m = P_m - F_i =$ resultant load on members
$C =$ fraction of external load $P$ carried by bolt
$1 - C =$ fraction of external load $P$ carried by members
$\delta =$ E elongation
$k_b, k_m =$ Stiffness of bolt and members

The load $P$ is tension, and it causes the connection to stretch, or elongate, through some distance $\delta$. We can relate this elongation to the stiffness by recalling that $k$ is the force divided by the deflection.

Thus;

$$\delta = \frac{P_b}{k_b} \quad \text{and} \quad \delta = \frac{P_m}{k_m} = \frac{1}{RF} \quad \text{Eqn. D1}$$

or

$$P_m = P_b \frac{k_m}{k_b} = \frac{1}{RF} \quad \text{Eqn. D2}$$

Since $P = P_b + P_m$ we have

$$P_b = \frac{P_k_b}{k_b + k_m} = CP = \frac{1}{RF} \quad \text{Eqn. D3}$$

And

$$P_m = P - P_b = (1 - C)P = \frac{1}{RF} \quad \text{Eqn. D4}$$
Where

\[ C = \frac{k_b}{k_b + k_m} = \frac{1}{RF} \quad \text{Eqn. D5} \]

is called the stiffness constant of the joint. The resultant bolt load is

\[ F_b = P_b + F_i = CP + F_i \quad \text{Eqn. D6} \]

Of course, these results are valid only as long as some clamping load remains in the members; this is indicated by the qualifier in the equations.[8]

**Bolt Preload Measurement**

\[ K = \frac{T L}{E A \Delta D} \quad \text{Eqn. D7} \]

Where;

- \(T\) = Bolt installation torque,
- \(L\) = Bolt grip length,
- \(E\) = Bolt modulus of elasticity,
- \(A\) = Bolt cross-sectional area,
- \(D\) = Bolt nominal shank diameter,
- \(\Delta\) = Measured bolt elongation in units of length.
- \(K\) = Torque coefficient [8]