

A GLANCE ON CRASH/ IMPACT STUDIES IN AERO ENGINES

A glimpse into the crash analysis in Aero Engines to help engineers assess, and refine current designs and materials for improved sustainability.



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Abstract

The modern world demands exponential growth across all sectors, with transportation playing a critical role in achieving these targets. Aviation, as the fastest mode of commuting, relies on highly sophisticated technologies to ensure unparalleled safety. Aircraft are engineered to endure the most challenging conditions, protecting both lives and significant financial investments. At the core of aviation operations lie aero-engines, the powerhouses that drive functionality and reliability.

Since the first engine was mounted on the airframe in 1848, technological advancements have led to the evolution of various engine types, including piston engines, propeller engines and turbo engines. Among these, the rotating components of turbo-fan engines, operating at high speeds, present unique challenges for safety especially during catastrophic events.

This white paper delves into the failure scenarios of rotating components in turbo-fan engines, providing insights into the critical importance of safety in aviation engineering and exploring advanced techniques to address these challenges.

Introduction

The share of commercial air travel is rapidly increasing, driven by technological advances that have instilled confidence in safe flying. This growing sector channels billions of dollars into the global economy, with its success reliant on creating safer, more reliable aircraft. At the heart of these aircraft lies the aero-engine – a powerhouse that must overcome numerous challenges beyond producing sufficient thrust to keep planes aloft.



Here are some key figures that highlight the significance and risks of air transportation:

- Airlines transport over 4.5 billion passengers annually, generating revenues exceeding \$900 billion.
- Catastrophic events, such as bird strikes, results in losses of approximately \$1 billion each year.
- Over 80000+ lives have been lost to aviation accidents and incidents till date.
- Damages caused by air crashes account for billions of dollars globally.
- Defense Aviation remains a critical and growing sector, attracting significant investments as a cornerstone of national security.
- Research and development in the aerospace domain often align with advancements in space technologies.

Sustainable technological innovations and the adoption of advanced materials have played pivotal roles in enhancing the durability and safety of modern aircraft. Aircraft design can be broadly categorized into two main sections: – the body and the engine. While the body dictates structural and functional features, the aero-engine powers these designs with the energy and thrust required for the flight.

This paper focuses on aero-engines, marvels of engineering that combine immense power generation with stringent safety regulations to ensure the reliability of modern air travel.



Design and Construction Challenges in Aero Engines

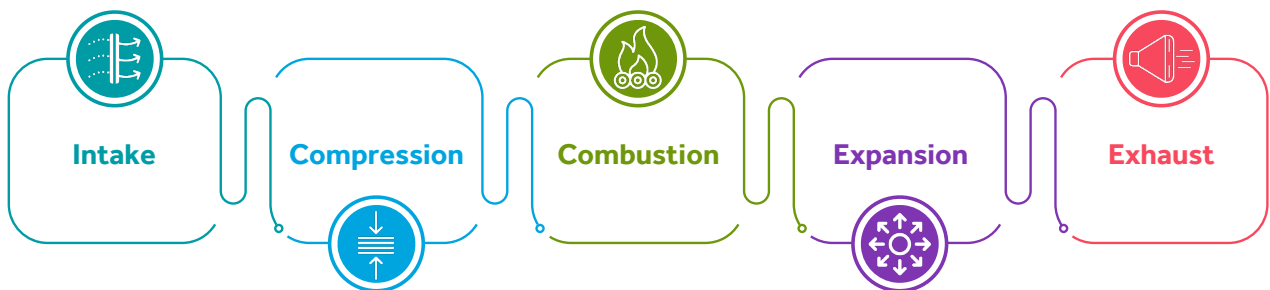
The design of aero-engines - often referred to as the "mechanical birds" of aviation-has undergone significant advancements over time, driven by evolving engineering demands. The Second World War marked a turning point, revolutionizing aero-engine technology to achieve unprecedented thrust levels and speeds.

For example, the experimental North American X-15 holds the record for a top speed exceeding 4500 miles per hour (Mach 6.7) in 1967. The Lockheed SR-71 blackbird, an iconic reconnaissance aircraft, were designed for

2200 miles per hour (Mach 3.2) at altitudes reaching 85000 feet. Achieving this remarkable speed required engines to be designed and manufactured with extreme precision and zero-error standards.

Aero engines vary significantly based on their intended purpose and the type of aircraft they power. This discussion focuses on jet engines, widely used in both commercial and military aviation. Jet engines are further categorized into subtypes such as turbo-jet, turbo-prop, turbo-fan, ramjet, scramjet and pulse jet engines.

Despite differences in their design and construction, all jet engines operate on the same fundamental principle:



Among these, the turbo-series engines (turbojet, turboprop, and turbofan) stand out for their complexity. They contain the most moving and rotating components making them more challenging to design and manufacture compared to ramjet, scramjet and pulsejet engines. These challenges highlight the need for cutting-edge engineering solutions to meet the demands of speed, reliability, and safety in modern aviation.



The thrust produced by jet-engines is universally measured in pounds force, and the aviation industry continually seeks high thrust-to-weight ratios to maximize efficiency. To achieve the desired output demanded by the aircraft manufacturers, reducing engine weight becomes a critical parameter. This drives ongoing research into exotic materials that are not only heat- and corrosion-resistant but also durable, fatigue-resistant and, manufacturable into precise shapes at lower costs – an essential focus of modern engineering innovation.

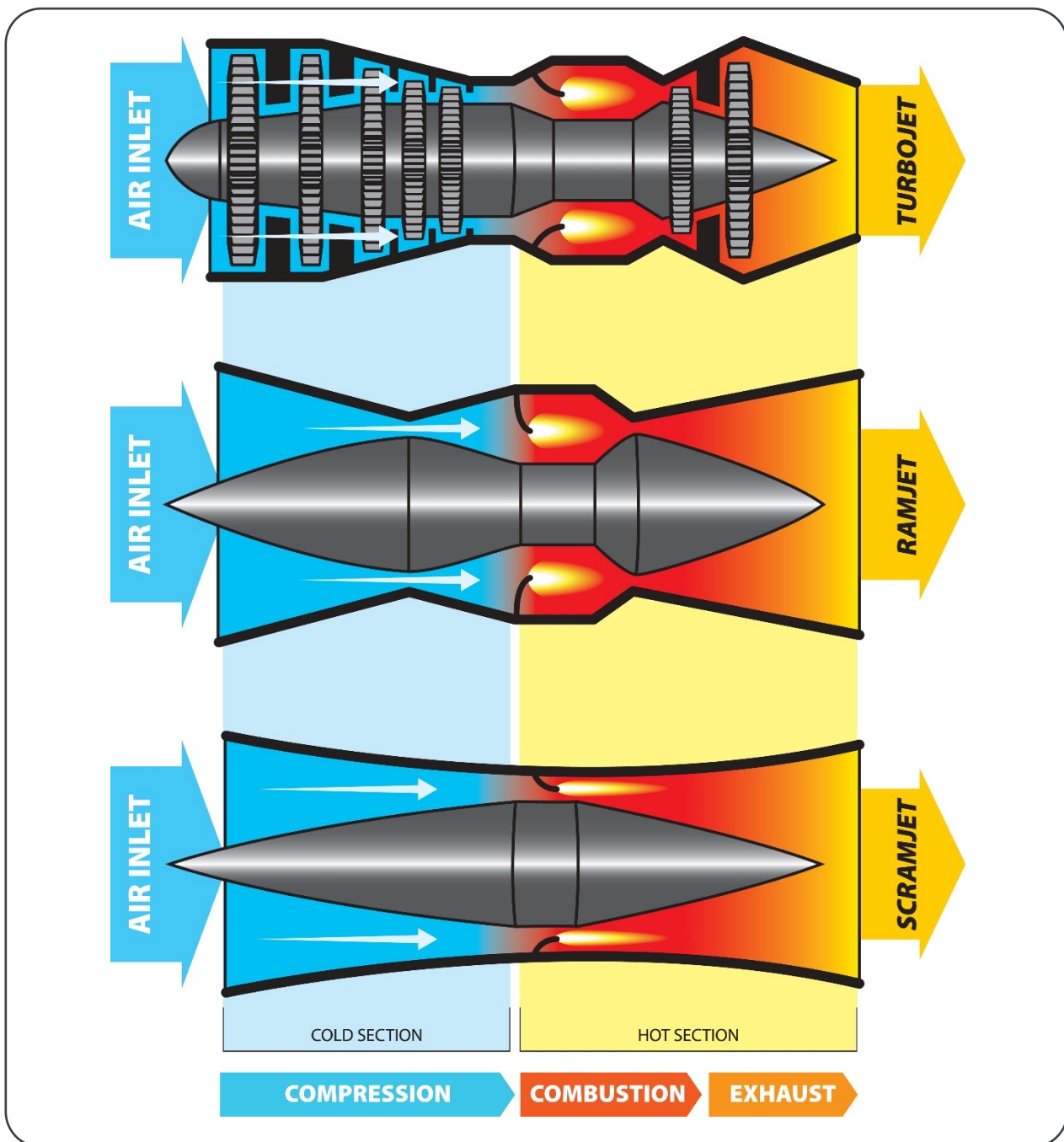
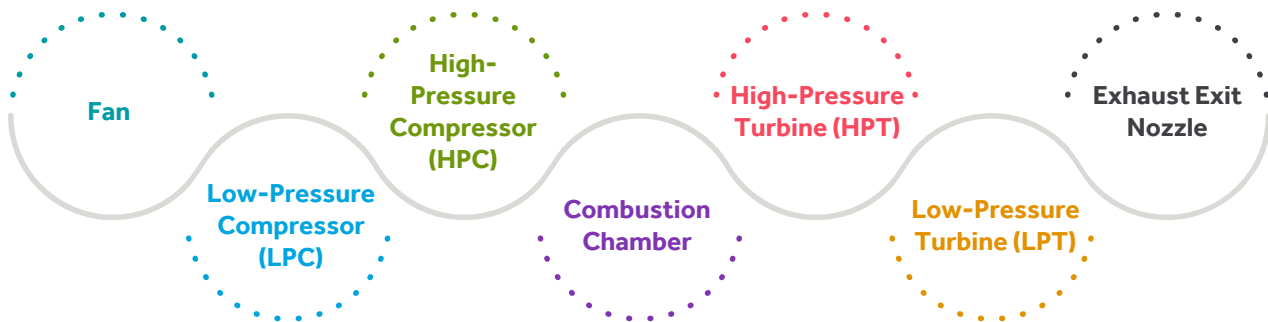


Figure 1. Types of Jet Engines

The basic construction of an engine comprises the following components



Two rotating shafts mounted on bearings connect these sections transferring rotational motions from HPT to HPC and from the LPT to the LPC and Fan. These rotating components, housed within robust casings, perform dual roles: providing structural support and containing potential damages during catastrophic events.

With rotational speeds ranging from 10,000 to 20,000 RPM, the fan blades, compressor blades and turbine blades experience extreme peripheral velocities. This makes robust engineering principles crucial to ensuring safety during air travel.

The following sections will explore critical failure scenarios in aero-engines. If not managed effectively, these scenarios could result in catastrophic losses, emphasizing the importance of meticulous design and rigorous testing in modern aerospace engineering.

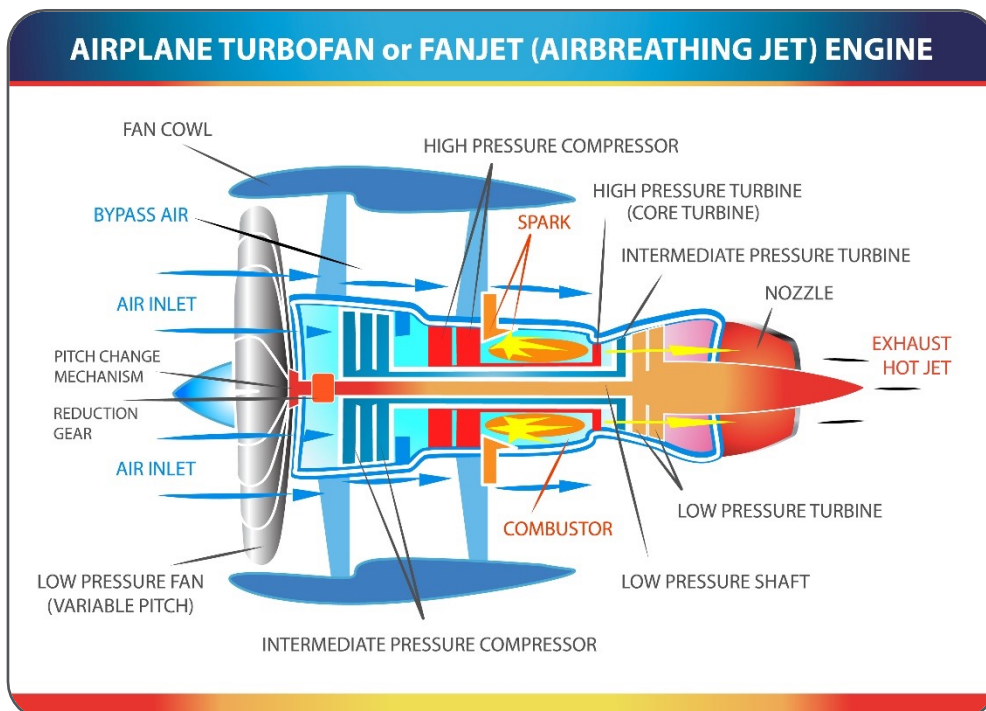


Figure 2. Main Sections of Turbo Jet Engines

Crash Impact Studies on the Aero-Engine Components and Assemblies

In addition to enduring extreme weather and fatigue loads, aero-engines must be rigorously tested for unplanned real-world scenarios such as crashes or impacts caused by foreign objects or internal failures. These stringent impact tests are mandatory for certifying engines for commercial or military use. Failure to meet these rigorous standards can result in multi-million dollar investments being grounded. Below are three critical crash scenarios commonly evaluated in aero-engine impact studies:

A

Bird Strikes on Spinner Cones and Fan Blades

B

Fan Blade Off Incidents in Optimally Operational Engines

C

Blade Outs Events in Compressor and Turbine Sections at Full Power

A. Bird Strikes on Spinner Cones and Fan Blades

The skies belongs to birds, and humans, as newcomers must contend with the risks of collision. These incidents, termed **Foreign Body Object (FBO) impacts**, pose significant challenges despite birds being much smaller than aero-engines. At high aircraft speeds, even small bird strikes can cause substantial damage due to high momentum and energy transfer.

While birds weighing under 2.5 pounds may not cause major issues, strikes from those around 5 pounds can critically impair engine performance, leading to millions of dollars in losses annually. The spinner cone and fan blades are particularly vulnerable on the engine front.



Figure 3. Partially damaged spinner cone (left) and fan blade (right) due to Bird hit

Engineering Solutions:

- **Spinner Cones:** Designed using thermoplastics or composite materials to withstand bird strikes, they are engineered to remain intact or suffer minimal damage, reducing debris entry into the engine.
- **Fan Blades:** Engineered with lightweight, high strength materials and shaped for both efficiency and resilience, these blades act as chopping mechanisms to mitigate the impact.

B. Fan Blade Off (FBO) Incidents in Operational Engines

Fan blades endure some of the most challenging conditions, being positioned at the engine's front. Factors such as creep, fatigue, FBO hits, or crack propagation can lead to midflight blade failure, potentially triggering a cascade of mechanical failures.

At high rotational speeds, the tip of these blades reach extreme tangential velocities, which can damage adjacent components. Fragments from the failed blade can enter the engine, causing severe damage to compressor sections and beyond.

Engineering Solutions:

- **Blade Design:** Modern fan blades are now lighter, stronger, and more durable.
- **Cowling:** The outer covering is designed to contain the fragments, preventing further damage.

Extensive real-world testing, involving significant investments, ensures engines can handle such scenarios before they are certified for flight.



Figure 4. Fan Blade off causing damage

(Ref. <https://aerospaceamerica.aiaa.org/departments/containing-a-blade-out/>,
https://en.wikipedia.org/wiki/Blade_off_testing)

C. Blade Out Events in Compressor and Turbine Sections at Full Power

Compressors and turbines blades face extreme fatigue loads combined with thermal stress exceeding 1000 degrees centigrade. These conditions can cause a blade to detach from its root with the help of underlying cracks/air-holes in the turbine blade, potentially creating a catastrophic blade-out event.

An ejected blade at full power behaves like a high-speed projectile, with engine casing being the only barrier to contain these detached fragments. Additional debris from secondary blade failures exacerbates the damage.

- **Advanced Materials:** Cutting-edge materials with superior thermal and mechanical properties are employed to reduce deformation and enhance containment.

These crash scenarios underline the importance of robust engineering and innovative materials in ensuring aero-engine safety. Advances in computational analysis and rigorous testing continue to drive improvements, allowing engines to meet stringent safety regulations and perform reliably under extreme conditions.

Engineering Solutions:

- **Containment Design:** Engine casings are meticulously engineered to contain damage within the affected stage, preventing propagation to other sections.



Figure 5. Uncontained blade out event caused severe disruption to engine in mid-air

(Ref. <https://www.semanticscholar.org/paper/Impact-Studies-of-Containment-Ring-during-Blade-in-Ridley/65e8569c0cb9ccf5b65bb9f3f201aa2ff6e1e63d/figure/5>,

https://www.researchgate.net/figure/A-Rolls-Royce-Trent-972-intermediate-pressure-turbine-disk-burst-accident-which-occurred_fig2_257896185)

The above crash events are meticulously evaluated before an engine is certified for take-off. Despite rigorous testing, there have been instances where previously certified engines were grounded following real-time incidents that led to fatalities. This highlights the critical importance of early-stage evaluations in the engine design process.

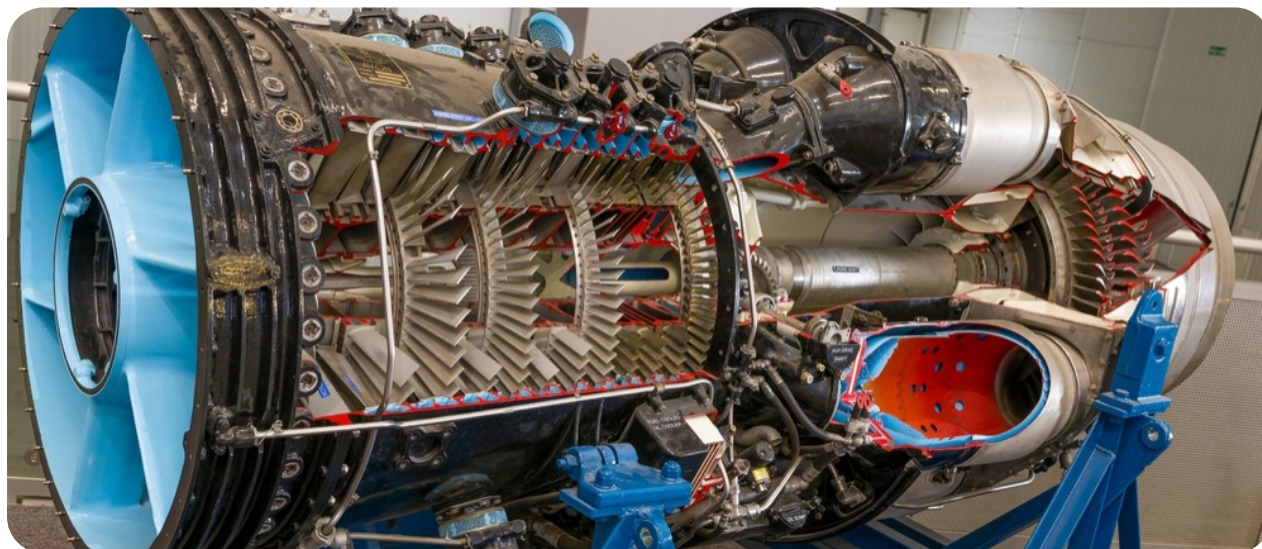
To ensure reliability, engineers focus extensively on impact scenarios during the preliminary phase, well before manufacturing begins. The advent of Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) technologies has been transformative, enabling predictive analyses for various load cases. These tools supported by numerical models for materials and physical phenomena, have helped industries save billions of dollars while enhancing safety. The next section explores the role of advanced CAE technologies and tools in creating safer, more efficient engines and fostering a new era of innovation in aviation.

Technologies and tools for Crash Finite Element Analysis (FEA)

The aviation industry relies heavily on advanced technologies and innovations to ensure the safety and efficiency of air travel. This multibillion-dollar sector demands precision and reliability throughout the manufacturing process of aero-engines, often referred to as "engineering birds." Two critical branches of engineering—**Computer-Aided Design (CAD)** and **Computer-Aided Engineering (CAE)**—play pivotal roles in turning ambitious ideas into reality.

- **CAD:** Focuses on creating innovative designs at the forefront of human imagination.
- **CAE:** Validates these designs to ensure they meet functional and safety requirements as per engineering guidelines and regulations.

Finite Elements Analysis (FEA) forms the backbone of CAE, enabling engineers to simulate and analyze scenarios related to durability, Noise, Vibration, and Harshness (NVH), Computational Fluid Dynamics (CFD) and crash analysis. Within the context of crash analysis, several commercial tools facilitate the FEA process:.



Key Tools for Crash Analysis

1. Meshing Tools



Hypermesh, ANSA, and LS-Prepost are widely used to convert CAD models into Finite Element (FE) models, ensuring detailed and precise representations for analysis.

2. Solvers



LS-Dyna, PAMCRASH, and Radios are the leading solvers for crash analysis. These tools employ rigorous algorithms to process input data, simulate impact scenarios, and generate meaningful animations and engineering insights.

3. Post-Processing Tools



The output from solvers is fed into post-processing tools like **HyperView, LS-Prepost, Animator, Metapost** to visualize results, create plots, and identify necessary adjustments to improve designs.

These advanced tools enable engineers to predict outcomes of various impact scenarios, optimize designs, and validate safety measures, all within a virtual environment. This capability has revolutionized the industry, saving billions of dollars by reducing the dependency on physical prototypes and enhancing the reliability of aviation components.



Cyient Cosmology in Aerospace

Cyient's tremendous journey with Aero-engineering

Cyient's footprint in aerospace engineering is extensive, with numerous world-renowned aviation technology corporations as delighted clients for decades. Over the years, Cyient has supported and delivered a vast number of projects across various engineering domains, including design, structural and thermal analysis, and aftermarket services for the aerospace industry.

In the past two decades, Cyient has contributed significantly to impact and crash load cases in aero-engines.

Key projects include:

- Bird strike analysis on spinner cones and stators
- Bird and hail impact studies on nosecones
- Fan Blade Off (FBO) containment in fan cases
- Turbine Blade Out containment analysis on cases and flanges
- Subsystem jolting analysis, tie-shaft failure analysis, shaft shear analysis, and meshing event simulations

Many design modifications were proposed to fine-tune components for withstanding critical crash loads, some of which have been patented. Cyient provided thoroughly investigated and validated engineering judgments, supported by functional evaluations, to assist clients in meeting certification norms for aero-engine systems.

A critical aspect of aviation engineering is data security, governed by varying legal and compliance norms across regions, given the patented and export-controlled nature of these technologies. As a global player, Cyient understands the data privacy and security obligations of its clients across geographies. It has implemented stringent security checkpoints to prevent data breaches, ensuring 100% protection of invaluable client information.

Cyient's technical competencies and adherence to business ethics, particularly in CAD/CAE, have earned the company numerous prestigious awards and recognitions from aviation corporations year after year.



Future Developments in Crash Analysis

The **digital revolution** and the integration of **Artificial Intelligence (AI)** are poised to redefine computational engineering, pushing the boundaries of crash analysis to unprecedented levels. These emerging technologies hold the potential to revolutionize the development of sophisticated material and CAE models, significantly improving the predictability of engineering problems.

Currently, available tools, when applied with the right methodologies, deliver solutions with up to 80% accuracy. However, advancements in AI and digital simulation technologies could elevate this accuracy to near 100%, reducing or even eliminating the need for costly real-time physical testing. Achieving such a milestone would mark a groundbreaking shift in engineering practices making crash analysis more efficient and reliable.

As these technologies evolve, their incorporation into commercial software is anticipated, making advanced predictive tools more accessible to engineers worldwide. This will not only enhance safety and reliability but also drive innovation in aviation and beyond. While this paper offers a glimpse into the complexities of aviation crash analysis, it is merely a starting point. The field is vast, with extensive resources available to deepen one's knowledge. Future works aim to delve further into specific crash scenarios from a CAE perspective, providing aspiring engineers with foundational insights into aero-engineering. Until then, the journey of exploration continues.

About the Author



Sathish Kumar Garala received Master of Technology in Design Engineering from IIT Hyderabad, and has over 10+ years of experience across IT & Engineering industries. He predominantly works in Crash/Impact Analysis using CAE tools to support the customers of Aero and Automotive domains. He carried out and lead projects on functional evaluations of aero engine structures like bird strikes on Spinner cones, Fan blade-off events, blade out containments in compressor/turbine sections etc. On Automotive discipline, he extensively worked on sub-system and full vehicle crash evaluations for frontal and side impact load cases for passenger cars and vans. He also takes responsibility as one of the SMEs in LS-Dyna for crash studies at Cyient. His interest lies in exploring new designs, materials and technologies that can help in building much safer aero structures and automobiles.



About Cyient

Cyient (Estd: 1991, NSE: CYIENT) partners with over 300 customers, including 40% of the top 100 global innovators of 2023, to deliver intelligent engineering and technology solutions for creating a digital, autonomous, and sustainable future. As a company, Cyient is committed to designing a culturally inclusive, socially responsible, and environmentally sustainable Tomorrow Together with our stakeholders.

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