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A Survey of Aircraft Materials: Design for Airworthiness and Sustainability

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Abstract

New developments in material science and its technologies find their best implementation areas in aircraft and space vehicles. Since the beginning of the powered flight, weight of airframes and systems are needed to be reduced. They are developed and built by light, durable and affordable materials through highly disciplined design, development, test and certification as well as manufacturing processes. Besides airframes, engineers are challenged to develop more efficient engines; both by reducing their weights and improving their aero-thermodynamic properties, sustaining higher operational and safety reliabilities along with complying stringent emission and noise restrictions. These conditions are increasing the demand for the development and the utilization of advanced lighter, stronger and durable materials and alloys, ceramic coatings and relevant manufacturing processes.

In this study, current trends and future expectations from material technologies in general; for accomplishing higher expectations for future lighter airframes, aircraft systems and engines, are reviewed.

Keywords: Advanced Materials, Aerospace Structures, Airworthiness Regulations, Concurrent Engineering and Surrogate Models.

1. INTRODUCTION

Civil Transport Aircraft (CTA) design, development, test, certification, production and related system technologies have been developed in parallel with the development levels of countries owning these technologies and industries. A typical CTA, shown as a generic design in Fig. 1, depends on several technological areas and uses various end products of these technologies as shown in Fig. 2. Production of a CTA, its roll out from the final assembly line is the end product of a highly diversified supply chain of; systems, major assemblies, components, parts and equipment depicted as a pyramid in Fig. 3.

Civil transport aircraft are first needed to be designed to fully comply with airworthiness requirements. In this perspective, present and future developments in materials are evaluated by Aircraft Structure Engineers; Designing for Structural Integrity, Fatigue and Damage Tolerance. Even at the Pre-Feasibility Phase of an aircraft project, Structure Engineers must develop master Design Documents defining several objectives, approaches and standards starting with its basic criteria for which the aircraft structure would be designed and certified to ensure compliance with airworthiness requirement, including durability, inspection interval and threshold, frequent buckling and reparability of the structure. Allowable stresses are generated by analysis supported by rigorous test evidences by the design teams. For the durability criterion, the structure must be designed to demonstrate sufficiently high fatigue endurance throughout its Design Service Goal (DSG) to achieve two durability of the structure and minimize the number of areas prone to fatigue damage.

The development and implementation of new materials and manufacturing processes for aerospace application is often hindered by the high cost and long time span associated with current qualification procedures [1]. The

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data requirements necessary for material and process qualification are extensive and often require millions of dollars and multiple years to complete. Furthermore, these qualification data can become obsolete for even minor changes to the processing route. This burden is a serious impediment to the pursuit of revolutionary new materials and more affordable processing methods for air vehicle structures. The application of integrated computational materials engineering methods to this problem can help to reduce the barriers to rapid insertion of new materials and processes. By establishing predictive capability for the development of microstructural features in relation to processing and relating this to critical property characteristics, a streamlined approach to qualification is possible [1].

Bringing a CTA Program to technical and commercial successes is not a straight forward journey and world civil aviation history may have more failure stories than the success stories. Availability of advanced materials is essential but utilizing them successfully and affordably is another further technological challenge. Integrated Product and Process Design (IPPD) and Concurrent Engineering (CE) disciplines are widely developed and are being implemented in this perspective especially in the last twenty years [2]. IPPD and CE disciplines utilizes todays advanced Product Life Cycle Management (PLM) tools, software, process, etc; a knowledge based environment help engineers to turn ideas and concepts to certified and commercially successful CTAs in to the market. Product Life Cycle Management (PLM), depicted in in Fig. 4 *(authors are thankful to Mr. Mustafa Ceren, Informatik, Turkey, for providing the figure)*, provides engineering design, analysis, documentation and the integration of the overall product information environment with tools also named as Product Development System (PDM). All of these engineering disciplines and tools do not automatically guaranties low weight and durable airframe developments. Examples for successful designs were achieved in aeronautical and space vehicles, but structural designs which are ended with catastrophic failures or overdesign structures caused transportation of excess empty weights instead of revenue generating payloads, throughout the service life of the aircraft, have become real life experiences in aviation.

Fig. 5 shows the risk matrix of seven major risk areas of a CTA design to production program and these risks are related with the phases of the program, whereas if there would be a major problem related with the corresponding risk, it is too late to cure it at that stage of the program. Right Model means that the conceptual design of a new aircraft should be better or superior than its nearest competitors both technically and commercially just from the beginning of the program and must fill a Niche Market which is clearly visible in world CTA operation environment.

First challenge to reach to the “Right Model” during Concept Design of a new CTA; the Empty Weight versus Maximum Take of Weight ratio, which is also referred as Structural Efficiency of an aircraft is needed to be minimized within the design performance goals and airworthiness compliance constraints. Fig. 5 also gives examples for the weight ratios of a group of well-known CTAs [3].

Structural Efficiency is directly related with the fuel consumption; cost of fuel plus the cost of released carbon-dioxide emission. On the other hand reducing the empty weight is inversely effect structural strength of the airframe and the aircraft must also comply with the very stringent structural strength and service life durability requirements as per civil aviation regulations. These two conflicting two challenges make the material selection, design approaches and the manufacturing techniques quite important for the airframe of a new CTA.

It is envisioned by the world civil transport aviation sector that energy efficiency and overall productivity of next generation CTAs must be improved between 60~70% by 2030~2040 as illustrated in Fig. 6 [4].

In aviation this can be made possible primarily in two ways; by reducing the overall fuel burn and by increasing the engine efficiency. Commercial aircraft are expected to be dramatically leaner, cleaner and quieter in the next 25 years, but manufacturers will have to decide how far they want to push technology, and airlines must decide how much they are willing to pay for efficiency.

NASA initiated Next Generation Aircraft Concept Design studies [4] for aircraft entering into service by 2030 - 2035 as 70% reduction in fuel burn and 70% reduction in emissions release are targeted. In these studies, the contribution of the structure to the takeoff weight of the aircraft is aimed to be reduced 5%, whereas the total empty weight is aimed to be reduced about 30%. Moreover, propulsion system’s contribution to the takeoff weight is aimed to be reduced by 3%. Besides, new propulsion systems’ specific fuel consumption must be reduced down to 14 g / [kN s]. In order to achieve these goals, new materials, new processes, utilization of integrated product and process design methods will be needed for next generation aircraft [5], [6]. NASA N+3 2030-2035 subsonic aircraft concepts are shown in Fig. 7.

2. MATERIALS: AVAILABLE AND IN DEVELOPMENT

Two completely different trends are competing against one another within the aviation industry this decade [7]. One way or the other, the issues are just too complex and the existing technologies, resources and know-how just too deeply entrenched. There has been an ongoing contest between composites and metal construction in aircraft. In a quest for distance, fuel economy, quietness, and cabin environment aircraft makers have invested billions in the use of composite materials in place of aluminum. Commercial applications, Boeing with the Dreamliner 787 that has set the standard for moving composites from use on the boundary to using them as the primary structure.

The process has initially started in military aircraft design; in 1987 the F-15 was constructed from 49% aluminum, 32% titanium and just 2% composites, by 2005 when the F22 entered service it was made from just 16% aluminum, 39% titanium and 24% composites. For commercial aircraft composites, although carrying a higher material and construction cost, it is expected to result in lower life cycle operating costs. Composites natural partner is titanium providing key structurally stressed component strength and with the rise in composite use has been a corresponding rise in titanium use. Titanium use has been on a rise.

For narrow body aircraft such as the rapidly recovering short haul and commuter jet market for 100–200 seats, metal airframes are offering considerable benefits, particularly in terms of lower development risks and lower material costs. To counter composites claims of weight reduction and with it lower operating, particularly fuel costs aluminum producers have introduced new alloys which exhibit higher strength properties allowing thinner gauges to be used and saving on weight. For example has brought out a new aluminum lithium alloy is used in fuselage skins, stringers, frames and floor beams. The alloy has been specified by Bombardier on its new C Series aircraft aimed at the 100-149 seat market [7].

Direct comparison of material properties between aluminum alloys and composites is not possible. The design drivers for the materials are significantly different, and therefore a comparison can only be made on a case-by-case basis. Detailed analyses need to be performed to determine which material is best suited for a specific structure. Scientific studies, material qualification and design implementation of new materials are continuing in aluminum and titanium alloys, composite material processing, manufacturing tools, monitoring and maintenance approaches are being continuously developed.

2.1. Chronology of Aluminum Development

The history of world aviation is closely related to aluminum and the history of creating aluminum alloys, and the more durable and reliable aluminum became, the higher, farther and safer airplanes flew [8]. The 2017-T4 Al-Cu-Mg-Mn alloy “Duralumin” was developed in Germany in the early 1900’s has been insensitively used in aviation starting with the first all-aluminum airplane, Junkers F13 manufactured in Germany in 1920. The importance of corrosion was subsequently demonstrated by the development of Alclad 2024-T3.

After the World War II, the higher strength 7178-T6 was developed and was used on the first commercially successful jetliner, Boeing 707. Material selection progressed with the desire for higher fracture toughness; Alcoa developed 7475 to fill this need. It was first flown on the Panavia Tornado, and was selected for F16. A big technical and commercial success came with the development of the T77 temper for alloy 7150. For the first time, corrosion resistance was accomplished without having to sacrifice strength. Several materials now in the early stages of development include Al-Mg-Sc alloys with better corrosion resistance, lower density, and good welding characteristics. New generation Al-Li alloy 2097 with high resistance to fatigue crack growth is being developed for the bulkheads of high performance aircraft.

Recent alloy developments have produced a new generation of Al-Li alloys which provide not only density weight savings, but also many property benefits such as excellent corrosion resistance, good spectrum fatigue crack growth performance, a good strength and toughness combination and compatibility with standard manufacturing techniques. This results in well-balanced, light-weight aluminum alloys [9]. Finally, Al-Li alloys provide many property benefits over previous Al alloys and are often competitive with the performance composites can offer for many aerospace applications. Chronology of the development Aluminum alloys and latest Al-Lithium alloys development by Alcoa Company is shown in Fig. 8.

2.2. Current Usage of Composite Materials for Airframe Structures

The use of Fiber Reinforced Composite Materials have been continuously increasing since 1990s as shown in Fig. 9 and new Boeing 787 Dreamliner and Airbus 350 XWB series aircraft are utilizing highest amount of composite materials [10].

The A350 XWB’s airframe materials were selected for their optimum qualities in uses throughout the jetliner – from composites in the fuselage, wings and tail, to advanced metallic in such major components as the landing gear, engine pylon and structural beams. Referred as intelligent airframe, Airbus’ philosophy was about using the best material for each individual application. Airbus’ extensive application of composites – comprising 53 per cent of the overall airframe (compared to 11 per cent in the A330) – benefits from the design and manufacturing advances for such lightweight, strong and durable materials. Their advantages on the A350 XWB begin with reduced development times and higher production rates on the final assembly line; while contributing to lower overall aircraft weight, along with proven in-service durability, reduced corrosion and fatigue, as well as lower maintenance costs.

Maintenance will be streamlined with Airbus' focus on improved and simplified aircraft systems for the A350 XWB – including hydraulics, electronics and power generation – which also enhance the aircraft's improved operating economics. The use of composites in the fuselage, wing and tail assumed to reduce maintenance tasks by creating a more "intelligent" airframe with increased resistance to corrosion and fatigue during the jetliner's lifetime.

Advanced metallic materials also have found their place on the A350 XWB, including low density/high performance aluminum-lithium alloys that provide increased stiffness and resistance at lower weight in floor beams, frames, ribs and landing gear bays. The latest titanium alloys are applied in main landing gear supports, engine pylons, and attachments.

The A350 XWB's major fuselage sections are created by the assembly of four large panels each, which are joined with longitudinal riveted joints. The 4-panel concept also is aimed to provide considerable weight savings, as the use of longer panels requires fewer circumferential joints and relies more on lighter longitudinal joints. This weight savings also results from better optimization of each panel for its application. The use of fewer, longer sections also means fewer joints overall – which are placed for load and weight optimization.

Another benefit is better reparability in operational service, as an individual panel can be replaced in the event of significant damage – avoiding major repair work that could require extensive composite patching. Composite material usage in A350XWB aircraft is shown in Fig. 10 [11].

Responding to the overwhelming preference of airlines around the world, Boeing Commercial Airplanes in 2004 launched the 787 Dreamliner, an all-new, superefficient airplane. An international team of top aerospace companies builds the airplane, led by Boeing at its Everett, Wash., facility near Seattle and in North Charleston, S.C. In addition to bringing big-jet ranges to midsize airplanes, the 787 provides airlines with unmatched fuel efficiency, resulting in exceptional environmental performance. The airplane uses 20 percent less fuel than today's similarly sized airplanes. The 787 also travels at a similar speed as today's fastest twin-aisle airplanes, Mach 0.85. Airlines also realize more cargo revenue capacity -- a 20 to 45 percent advantage over today's similarly sized airplanes.

Passengers also enjoy improvements on the 787 Dreamliner, from an interior environment with higher humidity to more comfort and convenience. The key to the exceptional performance of the 787 Dreamliner is its suite of new technologies and its revolutionary design. Composite materials make up 50 percent of the primary structure of the 787, including the fuselage and wing.

At the heart of the 787 design is a modern systems architecture that is simpler, more functional and more efficient. For example, onboard health-monitoring systems allow the airplane to self-monitor and report systems maintenance requirements to ground-based computer systems. Advances in engine technology are the biggest contributor to overall fuel efficiency improvements on the Dreamliner. The 787 features new engines from General Electric and Rolls-Royce companies that represent nearly a two-generation jump in technology.

The design and build process of the 787 has added further efficiency improvements. Boeing and its supplier partners have developed new technologies and processes to achieve efficiency gains. For example, manufacturing the 787 fuselage as one-piece sections has eliminated 1,500 aluminum sheets and 40,000 - 50,000 fasteners per section. More than 50 of the world's most capable top-tier supplier partners are working with Boeing to bring innovation and expertise to the 787 program. The suppliers have been involved since the early detailed design phase of the program and all are connected virtually at 135 sites around the world.

The 787 program opened its final assembly plant in Everett in May 2007 and in North Charleston in July 2011. First flight of the 787-8 Dreamliner occurred on December 15, 2009, followed by certification in August 2011. First delivery of the 787-8 took place on Sept. 25, 2011. Composite material usage in Boeing 787 aircraft is shown in Fig. 11 [12].

2.3. Titanium Alloys

Currently a greater amount of titanium is incorporated in to aircraft. This is connected with the fact that the share of the composite materials with which aluminum intensively interacts and corrodes in the new airplanes is being increased. Titanium is not subjected to these processes and results in increasing the life of components. Applications run from massive highly stressed, forged wing structures, and landing gear components, to small critical fasteners, springs and hydraulic tubing.

Titanium usage on Boeing aircraft has increased from 2% empty weight on the 737 to 17% on the 787. Titanium alloys now replace nickel and steel alloys in nacelles and landing gear components in newer airframes such as the Boeing 777, 787 and Airbus 380. Super-plastic forming/diffusion bonding has helped to increase the use of titanium alloys (Fig. 12) in new airframe designs, by lowering the cost through less machining, reworking and fewer component parts [13].

Ultra fine-grained titanium is characterised by exceptional mechanical properties, among which *high ultimate strength* and *high yield strength* are of utmost importance (Fig. 12). Classical coarse-grained titanium the relation (strength/density) varies around 70 to 120 (N·m/g) Alloy Ti6Al4V it varies around 200 (N·m/g). Ultra-grained titanium it is possible to predict the values (strength/density) = 270 (N·m/g) (Fig. 13).

2.4. Metal Bonding / Fiber Metal Laminates (FML)

The combination of metallic materials with fiber reinforced polymers into aircraft structural materials is commonly denoted as hybrid concepts or technologies. These concepts have their origin in the addition of reinforcing fibers into the bond line of thin laminated aluminum sheets [14]. Well-known examples of the FML are Arall (Aramid Reinforced Aluminum Laminates) and Glare (GLAssREinforced aluminum), aramid/glass fibers embedded in the epoxy system with aluminum layers, respectively. Glare is currently applied as skin material on Airbus A380 fuselage and as leading edges of the tail planes of this aircraft [15], [16], [17] (Fig. 14). Main advantages of FMLs over monolithic aluminum alloys are the increased fatigue and corrosion resistance. Compared to fiber reinforced polymer composites, FMLs have higher bearing strength and impact resistance and they are easier to repair. They also provide weight reduction by 15-30%.

A similar recent material is termed as CentrAl. The new, CentrAl concept comprises a central layer of FML, sandwiched between one or more thick layers of high-quality aluminum. FMLs consist of alternating layers of uni-directional impregnated fiber lamina and thin metallic sheets adhesively bonded together. This technique of coupling the metal with fiber shows improvements over the properties of both aluminum alloys and composite materials individually [18] (Fig. 15).

Aluminum metal bonding airframe structures have been widely used in Fokker70 and Fokker100 aircraft; metal bonding and intelligent use of composites have resulted with light airframe. With the proven excellent in service life; 11 million flight hours and nearly 10 million flight cycles, the structural integrity and durability which guarantee crack-free-life for 45.000 cycles, economical repair life for 90.000 cycles and superior corrosion resistance, a stretched version F120 Next Generation with new engines and complete new flight deck is being proposed. As shown in Figure 16 the proposed F120NG can have better "Structural Efficiency" even compared with new designs which are utilizing higher composite material usage. *(Authors are thankful to Mr. Rudi den Hertog and Mr. Maarten van Eeghen, NG Aircraft Company, Netherland for the information and the figure provided).*

2.5. Composite Materials for Future Airframe Structures

The use of composite materials and new concepts for the manufacturing technologies for new composite structures are expected to be increased in next generation aircraft. As examples by the improvement of 3-D Woven Pi-Preform Joints, creation of large integrated composite structures and sub-structures through composite pi-joints will be possible. It also prevents the exploitation of orthotropic properties of carbon fiber and limits out of plane failure modes. Moreover, size limitations found on pre-prep systems are removed since it is assembled in dry conditions (Fig. 17) [5]. Another concept is the Affordable Large Integrated Structures. Advancements in alloy, composite, and composite joint technology allow design flexibility toward utilized structures. The introduction of the Affordable Large Integrated Structures eliminates structural discontinuities and fastened assemblies, increasing structural efficiency, providing reduction in part count and weight (Fig. 17) [5].

Advancements in composites find their place in airplane skin too as a new skin concept is introduced. New protective skin weighs less than half of the current composite coatings with increased damage tolerance by the help of energy absorbing foam. The conductive skin over the foam protects the composite structure from lightening and also provides electromagnetic interference and environmental protection as shown in Fig. 18 [19].

Carbon nano-tubes are hexagonally shaped arrangements of carbon atoms bonded into a tube shape, sometimes with a single wall — called single-wall carbon nano-tubes or SWCNT — or multiple walls — called multi-wall carbon nano-tubes MWCNT. Carbon nano-tubes have many remarkable properties which we are only just starting to exploit. First of all, carbon nano-tubes are extremely strong, probably one of the strongest materials that is even theoretically possible. Although nano-tubes are only about a nanometer wide, they can be very long in comparison to their width, a useful property for strength (Fig. 19). Carbon nano-tubes are hexagonally shaped arrangements of carbon atoms bonded into a tube shape, sometimes with a single wall - called single-wall carbon nano-tubes or SWCNT - or multiple walls - called multi-wall carbon nano-tubes MWCNT.

Although the longest nano-tubes that have been synthesized are only a few cm in length, Nanocomp Technologies Inc. have taken a step towards making carbon nano-tubes into nano-tube fibers kilometers long. The fibers have the strength of spider silk and more than three times its shock-absorbing toughness. These fibers are both tougher and stronger than steel. The fibers have twice the stiffness and strength and 20 times the toughness of the same weight and length of steel wire [20] (Fig. 20).

2.6. New Materials in Aircraft Engines

A major effort underway in this area is the Advanced High Temperature Engine Materials Technology development which focuses on providing revolutionary high-temperature composite materials: to 425°C for polymer-matrix composites (PMCs); to 1250°C for metal-matrix / inter-metallic-matrix composites (MMCs / IMCs); and to as high as 1650°C for ceramic-matrix composites (CMCs) (Fig. 21).

Based on the preliminary designs of next generation conceptual engines, however, material temperatures approaching 1650°C are anticipated for the turbine inlet, thus requiring extensive use of CMCs throughout the combustor, turbine, and exhaust nozzle. One benefit of using CMCs is that they allow higher operating temperatures and thus greater combustion efficiency leading to reduced fuel consumption. Thanks to the low density of CMCs, compared with current technology, the use of CMCs in the hot section of the engine along with IMCs in the compressor is resulting in a 50% reduction in engine weight.

Ceramic matrix composite turbine blades and turbine materials are attractive due to their high temperature tolerance. Without the need to cool the turbine blades, compressor bleed will no longer required and higher temperatures can be achieved with the combustor.

Ceramic-matrix composites research is aimed at developing the basic and applied technologies needed to fabricate structurally reliable ceramic composites reinforced with long or continuous ceramic fibers Fig. 22. Like monolithic ceramics, these fiber-reinforced ceramics (FRCs) have lower densities, better oxidation resistance, and potential to operate at significantly higher temperatures than super alloys. However, unlike monolithic ceramics, FRCs display metal-like deformation behavior, non-catastrophic failure, and strength properties that is insensitive to processing- and service-generated flaws [21].

The use of CMCs in gas turbines would permit higher turbine inlet temperatures, which would improve turbine efficiency. Because of the complex shape of stator vanes and turbine blades, the development was first focused on the combustion chamber. A combustor made of SiC/SiC with a special SiC fiber of enhanced high-temperature stability was successfully tested for 15,000 hours [22]. SiC oxidation was substantially reduced by the use of an oxidation protection coating consisting of several layers of oxides [23].

Polymer-matrix composites (PMCs) are the lightest of the three types of composite materials under study and recent applications of PMCs in aircraft propulsion systems, such as General Electric`s F-404 engine, have resulted in substantial reductions in both engine weight and manufacturing costs. To realize the full advantages of PMCs in aircraft-propulsion systems, however, new composite materials must be developed with enhanced thermal-oxidative stability permitting their use at temperatures to 425°C [24].

Lightweight Fan / Fan Cowl can be achieved by the use of design optimization. Shape memory alloy nozzles (variable geometry nozzles) utilize a shape memory alloy actuated hinge that is able to be varied and controlled which allows for optimization of engine for given power setting and target condition. Active compressor clearance control provides higher compressor efficiencies by minimizing the blade tip losses by maintaining tip clearances which takes the form of variable, flexible surface maintained by electromagnetic actuators (Fig. 23) [5].

3. DESIGN FOR AIRWORTHINESS IN AIRCRAFT STRUCTURES

3.1. Airworthiness Regulations for CTA

In civil aircraft world; design, development, production and operation, personnel training, maintenance (MRO), air traffic control and all related sub-activities are regulated and controlled by international rules and organizations. The top regulating organization is the International Civil Aviation Organization (ICAO) established under United Nations in 7th December 1944 with Chicago Convention. Under ICAO rules several National Civil Aviation Authorities were established such as: EASA in Europe (European Aviation Safety Agency), FAA (Federal Aviation Authority) in United States. Turkey operates and maintains aircraft according to Turkish Civil Aviation Authority Regulations (DGCA-SHGM) which are fully compliant with EASA and FAA regulations. The complete Life Cycle of an aircraft; from design manufacturing and operation must be certified by the authorized organization.

Aviation Products, their Utilization and Organizations Approval (Aircrafts, Engines) Top Down Regulation Hierarchy of EASA is shown in Fig. 24 [25], [26]. Top regulations for airworthiness of civil aircraft are defined by Annex 8 of the Chicago Convention and EASA CS25 and FAA FAR25 regulations define the design and certification requirements for CTA (Large Aircraft).

3.2. Certification of Product and Parts and Appliances

3.2.1. Product

Design Organization Approval (Subpart J)

Product Organization Approval (Subpart G)

3.2.2. Aircraft (Type Certification) Certification Basis for Large Aircraft (CS25)

3.2.3 Engine (Type Certification) Certification Basis (CS-E)

3.2.4. Propeller (Type Certification) Certification Basis (CS-P)

3.2.5. Change to Type Certifications:

Design Organization Approval (Subpart j)

Production Organization Approval (Subpart G)

STC (Supplemental Type Certification)

Major Changes/Minor Changes

3.2.6. Parts and Appliances

ETSO Parts: (European Technical Standard Orders)

3.3. Reliability

The concept of Continuing Airworthiness is closely related with Reliability of aircraft and its systems. Relatively few systems are designed to operate without maintenance of any kind. For most systems there are two types of maintenance, one or both of which may be applied. In preventive or scheduled maintenance, parts are replaced, lubricants changed, or adjustments made before failure occurs. The objective is to increase the reliability of the system over the long term by preventing the aging effects of wear, corrosion fatigue, and related phenomena. Whereas, corrective or unscheduled maintenance is performed after failure has occurred in order to return the system to service as soon as possible. Such maintenance is performed at unpredictable intervals because the time to any specific unit's failure cannot be established ahead of time.

In general structural design load and damage considerations of airworthiness requirements (CS25 and FAR25) define Limit and Ultimate Loads. The Limit Load is defined as being the maximum load per life which may only cause a detectable damage to be found and repaired through maintenance. Ultimate Load is the 1.5 times of the Limit Load and it is allowed to cause only an acceptable but non-detectable damage which is referred as the Allowable Damage Limit [10].

3.4. Design Criteria for Fatigue and Damage Tolerance

The basic Fatigue and Damage Tolerance (F&DT) criteria against which the aircraft structure is designed and certified, is to ensure compliance with the airworthiness requirement, include durability, inspection interval and threshold, frequent buckling and reparability of the structure. Allowable stresses S_{allow}, are generated by analysis supported by a series of test evidences. The allowable stresses are dependent on the design geometry; the material used as well as in some cases the loading pattern. During the detailed sizing of an aircraft structure, Reserve Factors or Margins of Safety are calculated as,

$$MS - \frac{S_{allow}}{S_{equivalent}} - 1$$

Where, $S_{equivalent}$ is the maximum stress with stress ratio R that produces the same damage to the fatigue spectrum at the specific location.

Regarding the durability criterion, the structure must be designed to demonstrate sufficiently high fatigue endurance throughout its Design Service Goal (DSG), to achieve the following objectives:

- Ensure durability of the structure throughout its operational life.
- Minimize the number of areas prone to fatigue damage and development of cracking in service.

Structural detailed analysis, geometrical sizing and tests must demonstrate that the calculated fatigue life of the structure N_F is higher or equal to the DSG multiplied by an appropriate Scatter Factor (SF).

$$\boldsymbol{N_F \geq DSG \times SF}$$

The value of the SF depends on the stress (Stress Life) design data used in the analysis.

The **threshold** for initial inspection of the structure should be defined as a design objective. Design precautions will be taken for the following objectives:

- Ensure the minimum inspection threshold will be equal to the target value.
- Ensure that any damage will not reach its critical size before the first inspection occurs.

Analysis and tests must demonstrate that service life of the structure N_C is higher or equal to the design objective inspection threshold T, multiplied by an appropriate SF.

$$N_C \geq SF \times T$$

The evaluation of the inspection threshold, using initial flaw concept, must ensure that cracks will not propagate from the initial defects to the critical sizes within the inspection threshold interval. This approach is applicable to Single Load path structures and Multiple Load Path structure where it cannot be demonstrated that load path failure, partial failure, or crack arrest will be detected and repaired during normal maintenance.

The repeat inspection interval is the time between two successive directed inspections during which any damage must not propagate from the detectable size to the critical size. Design precautions will be taken for allowing objectives:

- Provide damage tolerance capability of the structure.

- Ensure that any damage will be detected before it becomes critical within the targeted inspection interval.
- Maintain airworthiness through scheduled inspections.

Repeat inspection interval is derived from period of time during which damage is detectable, and the residual strength remains above the required levels. Consequently, the structural assessment should include a calculation of the period of failure crack in the critical location of the structure to develop from the detectable size to the critical size under residual strength loads. An inspection interval is then established by applying an appropriate scatter factor to this crack growth period, in order to ensure that the crack will be detected before the residual strength of the structure is compromised.

The detectable crack size is assumed in determining the inspection interval should be consistent with the capabilities of the proposed inspection method.

The crack growth analysis and crack propagation test must demonstrate that the period n_{det} , during which the crack propagates from the detectable size to the critical size, is higher and or equal to the required repeat inspection interval I, multiplied by an appropriate SF.

$$n_{det} \geq SF \times I$$

Frequent buckling should be avoided because it has an impact on the fatigue lives of the skin and webs and/or its surrounding structure. The fatigue load spectrum should be analyzed to ensure that the buckling will not occur more than specified number during the operational life of the aircraft. The allowed numbers repeated buckling should be substantiated by test under fatigue damage to structure buckling within the fatigue load range.

Repair-ability is a characteristic of the design and related to the ability of structure to incorporate an acceptable repair with the minimum of structural modification following the occurrence of reasonable damage. Repair-ability should be considered in the geometric design and detailed sizing of the aircraft. Repair-ability is enhanced is accessibility, serviceability and standardization are maximized and corrosion requirements are minimized. In addition, the maximum use of interchangeable components becomes desirable which can facilitate rapid repair and replacement. Repair-ability concept, limit and ultimate load capability of an aircraft structure is illustrated in Fig. 25.

4. INTEGRATED PRODUCT AND PROCESS DESIGN (IPPD):

As introduced in Section 1; the current qualification procedures for the development and implementation of new materials and manufacturing processes for aerospace application is very costly and long process, selection of right materials and designs for airframe components which complies very stringent airworthiness requirements, Structural Engineers often feel as surrounded with too many constraints. It is a very difficult challenge to minimize the empty weight by accomplishing too many conflicting objectives and highly bounding constrains. But on the other hand, structural engineers now have methodologies and tools which enable them to generate innovative solutions to these challenges.

Integrated Product and Process Design (IPPD), Concurrent Engineering (CE) and Product Life-Cycle Management (PLM) tools (Fig. 4) and methodologies are well developed for robust, integrated and optimized design solutions [1999]. As being one example, Aerospace Systems Design Laboratory (ASDL) at Georgia Institute of Technology, Atlanta, USA, has been continuously improving these IPPD methodologies as well as implementation of new available tools through various research and design activities [27].

An exceedingly large number of scientific and engineering fields are confronted with the need for computer simulations to study complex, real world phenomena or solve challenging design problems. However, due to the computational cost of these high fidelity simulations, the use of neural networks, kernel methods, and other surrogate modeling techniques have become indispensable. Surrogate models are compact and cheap to evaluate, and have proven very useful for tasks such as optimization, design space exploration, prototyping, and sensitivity analysis. Consequently, in many fields there is great interest in tools and techniques that facilitate the construction of such regression models, while minimizing the computational cost and maximizing model accuracy. Reference [28] presented a mature, flexible, and adaptive machine learning toolkit for regression modeling and active learning to tackle these issues.

As being an instructive study to implement IPPD and CE methodologies as well as to utilize PLM tools, a CTA floor beam structural design and analysis conducted by reference [29] will be presented as an example.

4.1. Problem Definition

3-D view of the floor beams in the fuselage and simplified beam section are shown in Figure 25. Major design variables are selected as section dimensions shown in Figure 26 along with the material type (Aluminum/Titanium) and manufacturing method (NC/Sheet Metal). The Overall Evaluation Criteria (OEC) constructed to represent the overall expectations from the design is formulated as:

$OEC= \alpha (W/W_{BL}) + \beta (C/C_{BL}) + \gamma$ (Shape Criteria)

Where α, β and γ are weighting parameters for weight, cost and geometric constrains respectively. W and C are weight and cost of the component and W_{BL} and C_{BL} are baseline values to normalize weight and cost respectively.

The ultimate goal is to determine the values of design variables that minimize OEC while satisfying static structural constraints. Structurally it is required to ensure that the beams do not fail under the loads which they will be exposed during their complete life cycle. The constraints are defined as:

$Min (MS_i) > 0$ $i = 1,2,3,4,5,6$

Max Deflection > defined values

Where MS_i is margin of safety due to any of six primary static stress failure criteria selected as:

- Shear buckling
- Bending buckling
- Combined shear-bending buckling
- Shear stress
- Axial stress
- Crippling

Deflection constraint has been rewritten so as to make it “higher than zero” constraint like MS, and it has been assumed as seventh MS.

4.2. Implementation of DOE-RSM Approach

Having selected weight, cost, OEC, and minimum and norm of the margins of safety – including deflection constraint – as responses, Design of Experiment (DOE) and Response Surface Method (RSM) have been realized by using JMP, a statistic software by SAS Institute, NC, and a 128-experiment custom model has been constructed by JMP commercial software [30]. Engineering simulations and modeling are performed by CATIA, MSC PATRAN/NASTRAN and several in-house structural analyses codes (representing the PLM environment). In this preliminary study, a simplified parametric cost model has been used [31]. Formulation is written for particular design as;

$C = W a \cdot b + W \cdot c / Q$

where C is manufacturing cost including material acquisition cost, W is weight, a, b, and c are parameters dependent upon material type and manufacturing method, and Q is production quantity.

Response Surface Designs (RSD) [32] are based on the assumption that complex relationships between design variables often examined through the use of sophisticated and time consuming codes, can be represented by a quadratic equation. This response is a function of the most important design variables and their interaction. In cases where no prior knowledge exists as to which variables are important, a Screening Test (ST) has to be performed. The ST is used to identify primary contributing factors among a set of design variables at two-level (minimum and maximum settings) during the DOE phase. The Response Surface Methodology (RSM) encompasses a set of techniques by which relationships between a set of independent variables and their dependent functions can be studied empirically. The “response” is the outcome of each individual experiment and the response values are then used to create surface equation fits based on the various independent parameters. The surface fit equations are selected as with the form:

$Y = \alpha0+\sum i\alpha iXi+\sum i\alpha iiXi2+\sum i\leq j\alpha ijXiXj$

The coefficients of this equation are determined through a three-level DOE. Since an equation involving too many variables is impractical, the number of variables must be reduced to a manageable size. Sensitivities and responses to the design variables are given in Fig. 27.

Response surface for the objective OEC of the beam design in this example is the Surrogate Model of the beam structural and geometrical design. With todays advanced PLM environment (Fig. 4) and tools, engineers can utilize Parametric Design and Surrogate Models connected as several serial and parallel design sub-activities and can perform optimization procedures for iterating and selecting the Best Affordable Design Solutions [28].

5. DISCUSSIONS AND CONCLUSIONS

As being one of the major and initial challenges in the design and development a new CTA, assuring a desired Structural Efficiency is quite complicated engineering process. Top decision makers give strategic decisions step by step during Pre-Feasibility, Concept Exploration, Preliminary Design and Concept Definition phases of the new CTA Program. They should be provided with precise solutions and clear alternatives in the decision making processes.

Authors evaluate that difficulties and risks, which are addressed in Section 1, can be turned to new challenges and opportunities if correct approaches will be used. First of all, structural design is a team work and good results can be achievable by common and well shared intelligence. Structural design teams first must respect the vast experiences of senior engineers and on the other hand young engineers must be knowledgeable and competent in using advanced methodologies and tools in a fast and accurate way. Innovative thinking can give results with disciplined and systematic design iterations but right modeling always depends on real life experiences.

As outlined in Section 2, development new and affordable materials for aircraft structures will lead structural engineers to design and manufacture lighter and durable airframes. Reversely, aircraft industry will be seeking and demanding for new materials and processes for new airframe design applications. Aircraft structures will continue to utilize metallic and composite materials with different forms of design and manufacturing processes for near decade. Airplanes are always multi-material and the use of aluminum in aerospace is projected to grow along with the usage of composite materials.

In section 3 it is emphasized that CTA airframe designs are strictly regulated to ensure the continued airworthiness of the aircraft throughout its life cycle as long as it operates. Aircraft structural engineers must well understand certification aspects of the structural design even down to very detailed component and small parts level. On the other hand regulators must also ease the qualification processes for new materials, with a parallel utilization of new technologies and processes by which these new materials and processes will be developed.

Aviation is expected to grow 6% annually and aircraft replacements can be realized earlier than expected. There will be a continuous demand for good structural engineering. As briefly explained in Section 4 available and continuous developments in IPPD, CE, PLM and all other engineering design tools and methodologies will enable structural engineers to develop better solutions and intelligent designs.

APPENDICES

Figure 1 - A generic CTA, is the end product of a diversified materials equipment and industrial/technical knowhow supply chain.

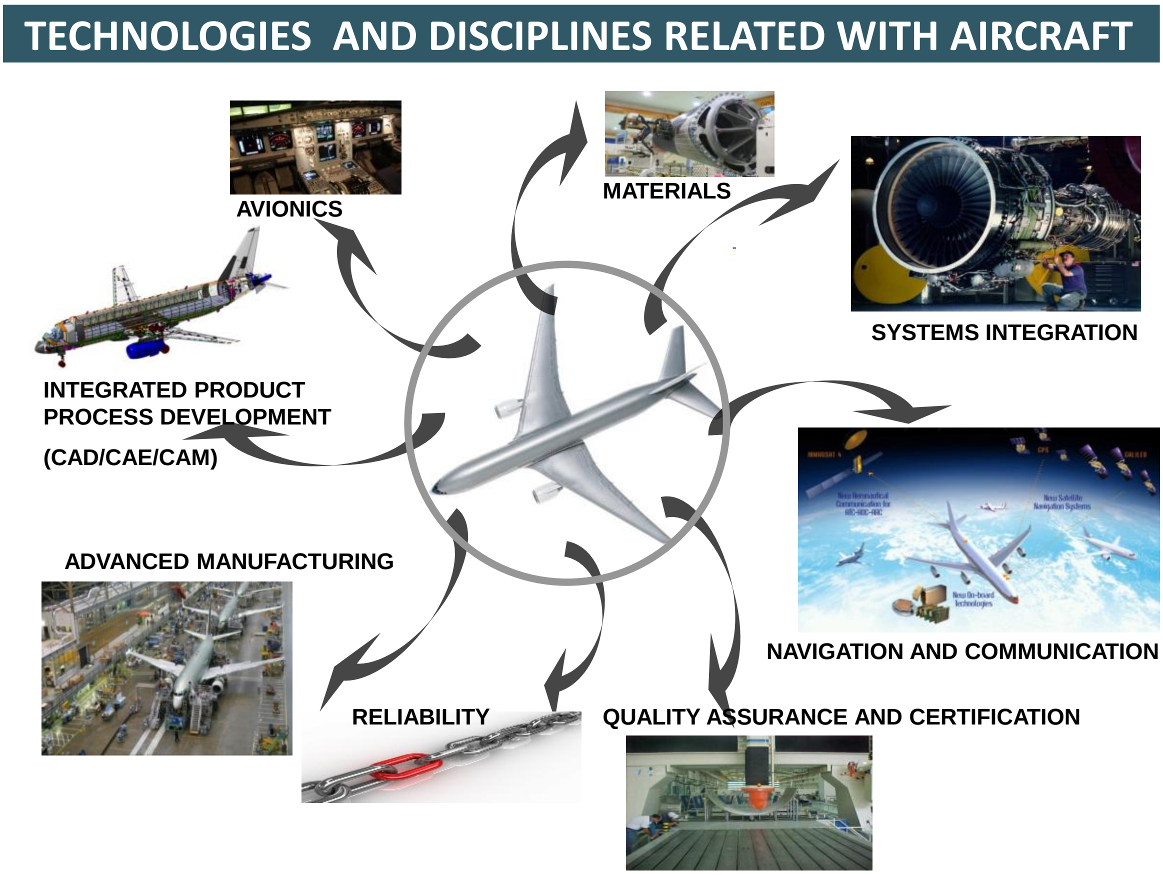


Figure 2 - Commercial Transport Aircraft Design, Development, Certification, Production and Operation (Life Cycle) utilizes several technologies and disciplines which are mainly developed as spin-off technologies of aerospace industry itself in decades.

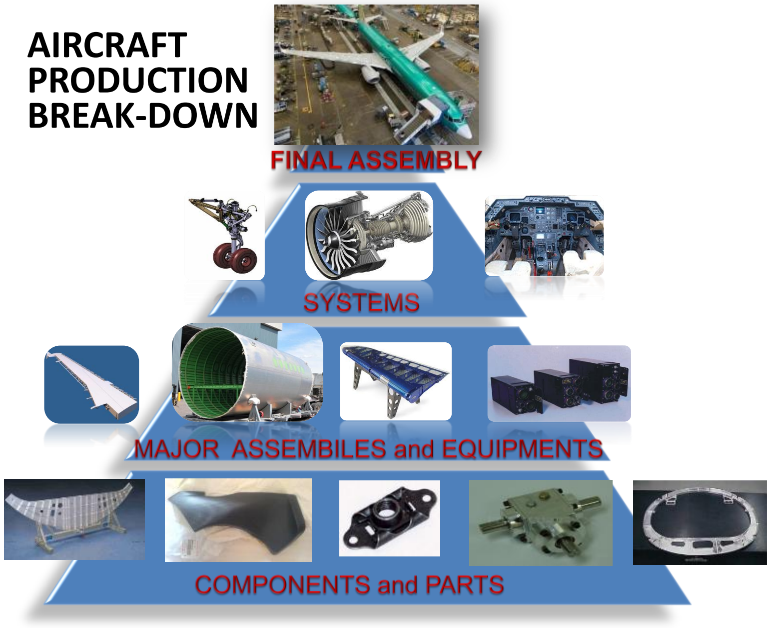


Figure 3 - The pyramid of the highly diversified supply chain of systems, major assemblies, components and parts of CTA production.

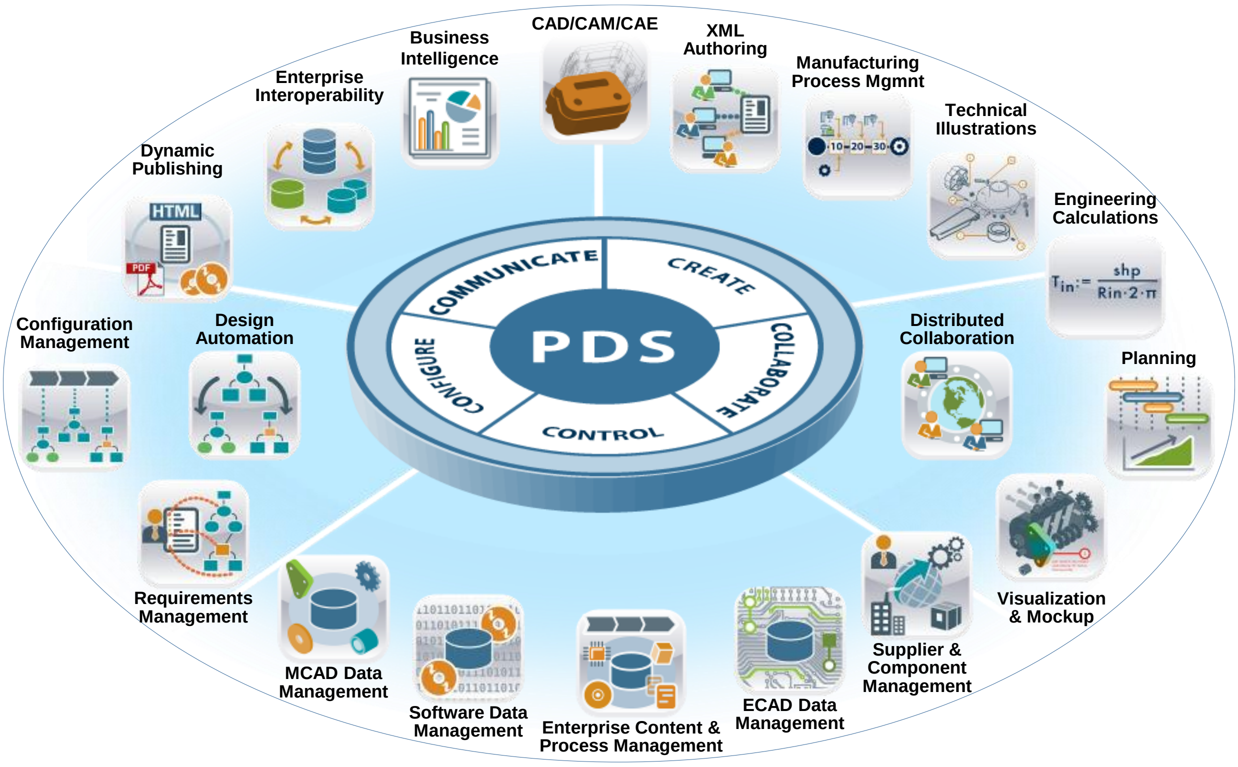
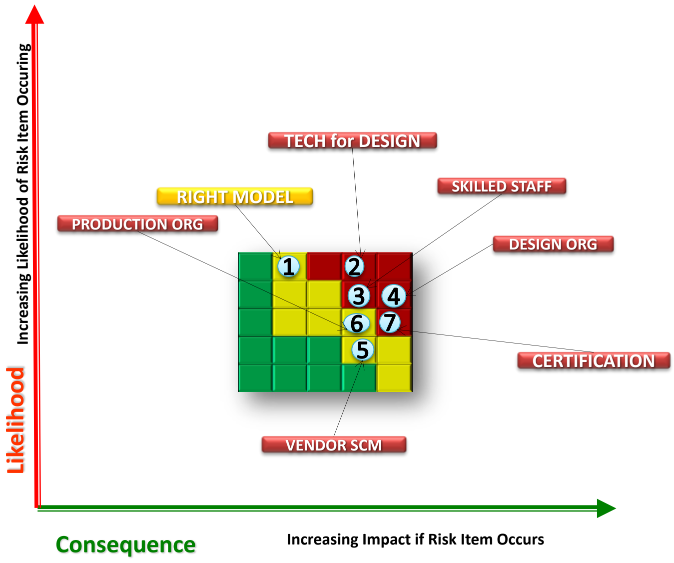


Figure 4 - Product Life Cycle Management (PLM) provides engineering design, analysis, documentation and the integration of the overall product information environment with tools also named as Product Development System (PDM) (Provided by Mr. Mustafa Ceren, Informatik, Turkey).



Selected Models	"Structural Efficiency" Ratio of Empty Weight to Max Take-off Weight
Concorde	0.425
777-200LR	0.426
A340-500	0.460
777-300ER	0.473
787-8	0.482
787-9	0.464
767-300ER	0.482
747-8	0.482
F-100 Tay 650	0.561
F120NG *Proposed*	0.535

Figure 5 - CTA Design, Development, Certification and Production Program 7 Major Risk Areas for A New Indigenous Design and "Structural Efficiency" of the Selected CTAs [3].

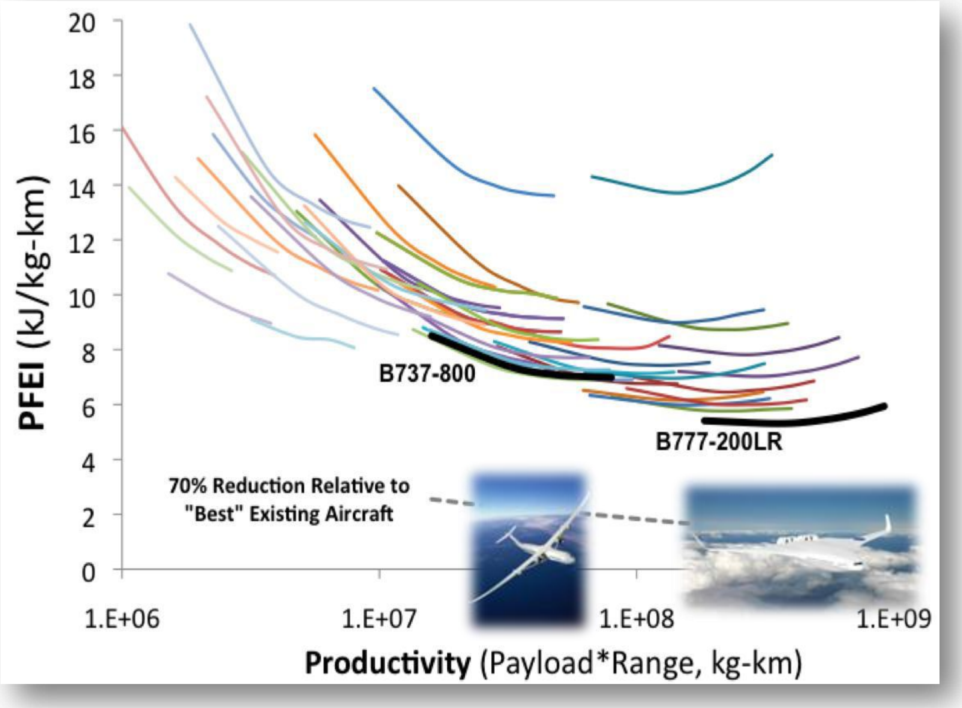
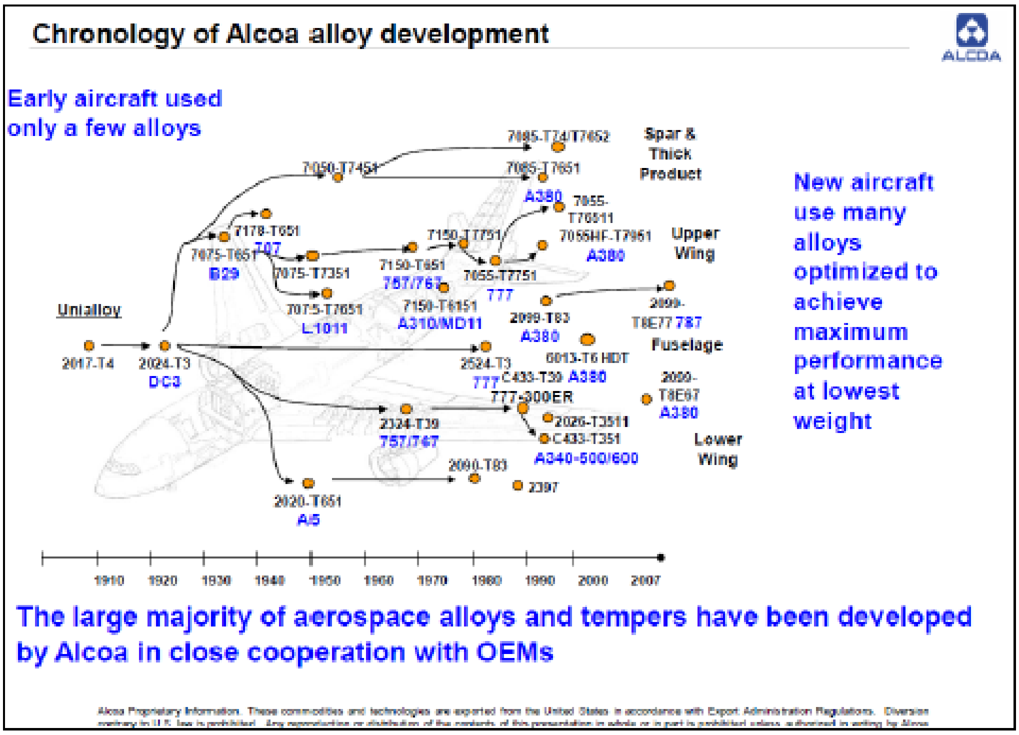


Figure 6 - Commercial Transport Aircraft Fuel Burn Goals for 2030-2035 70 % reduction in total fuel burn per seat-mile [5], [6].

Figure 7 - Future Aircraft Concepts NASA N+3 for 2030-2035 [5], [6].

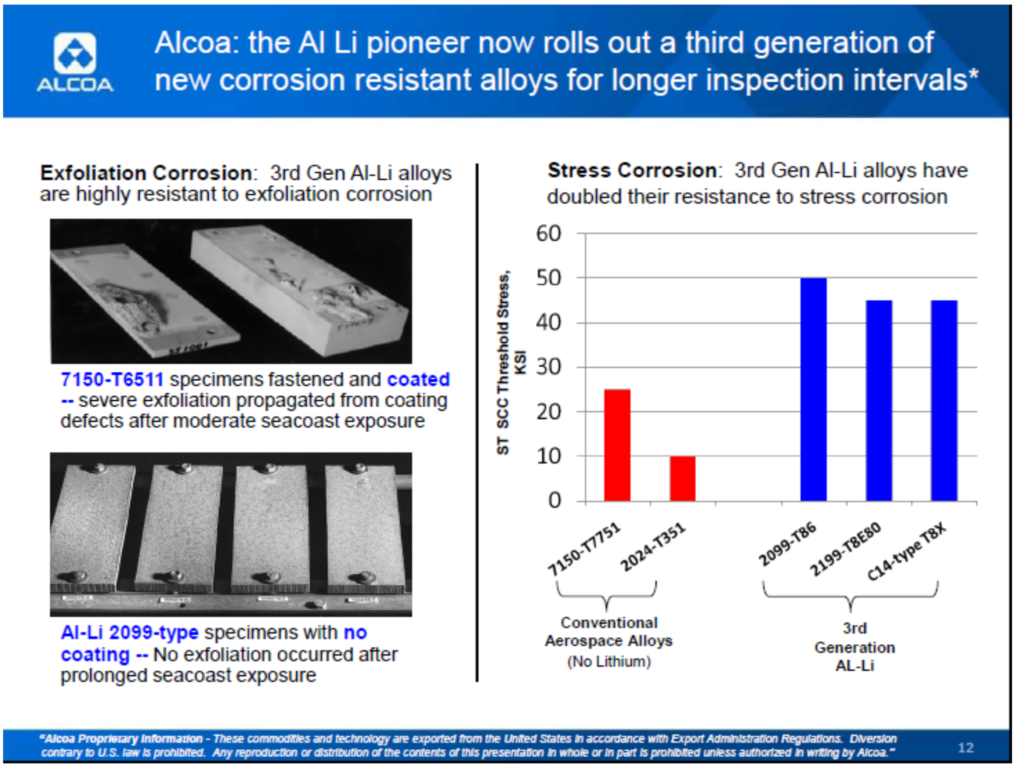


Chronology of Alcoa alloy development

Early aircraft used only a few alloys

New aircraft use many alloys optimized to achieve maximum performance at lowest weight

The large majority of aerospace alloys and tempers have been developed by Alcoa in close cooperation with OEMs



Alcoa: the Al Li pioneer now rolls out a third generation of new corrosion resistant alloys for longer inspection intervals*

Exfoliation Corrosion: 3rd Gen Al-Li alloys are highly resistant to exfoliation corrosion

7150-T6511 specimens fastened and **coated** -- severe exfoliation propagated from coating defects after moderate seacoast exposure

Al-Li 2099-type specimens with **no coating** -- No exfoliation occurred after prolonged seacoast exposure

Stress Corrosion: 3rd Gen Al-Li alloys have doubled their resistance to stress corrosion

Figure 8 - Chronology of Aluminum Alloys Development and Aluminum Lithium Alloys (Copyright of Alcoa Company).

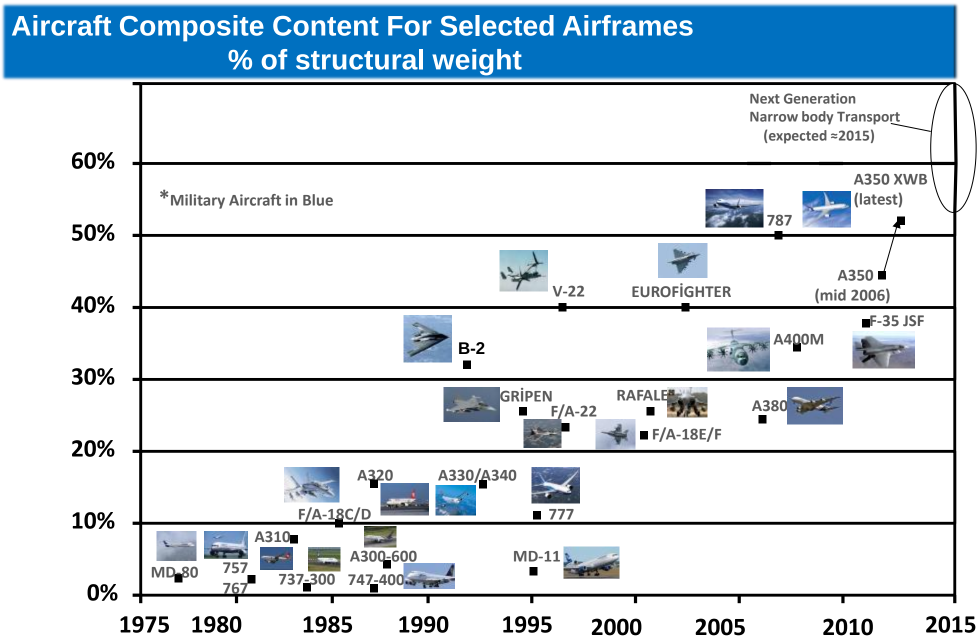


Figure 9 - Chronology of Composite Material Usage in Aircraft (Reproduced as based on [10]).

Figure 10 - Composite Material Usage in Aircraft Industry, Airbus A350 XWB Aircraft, Copyright of Airbus [11].

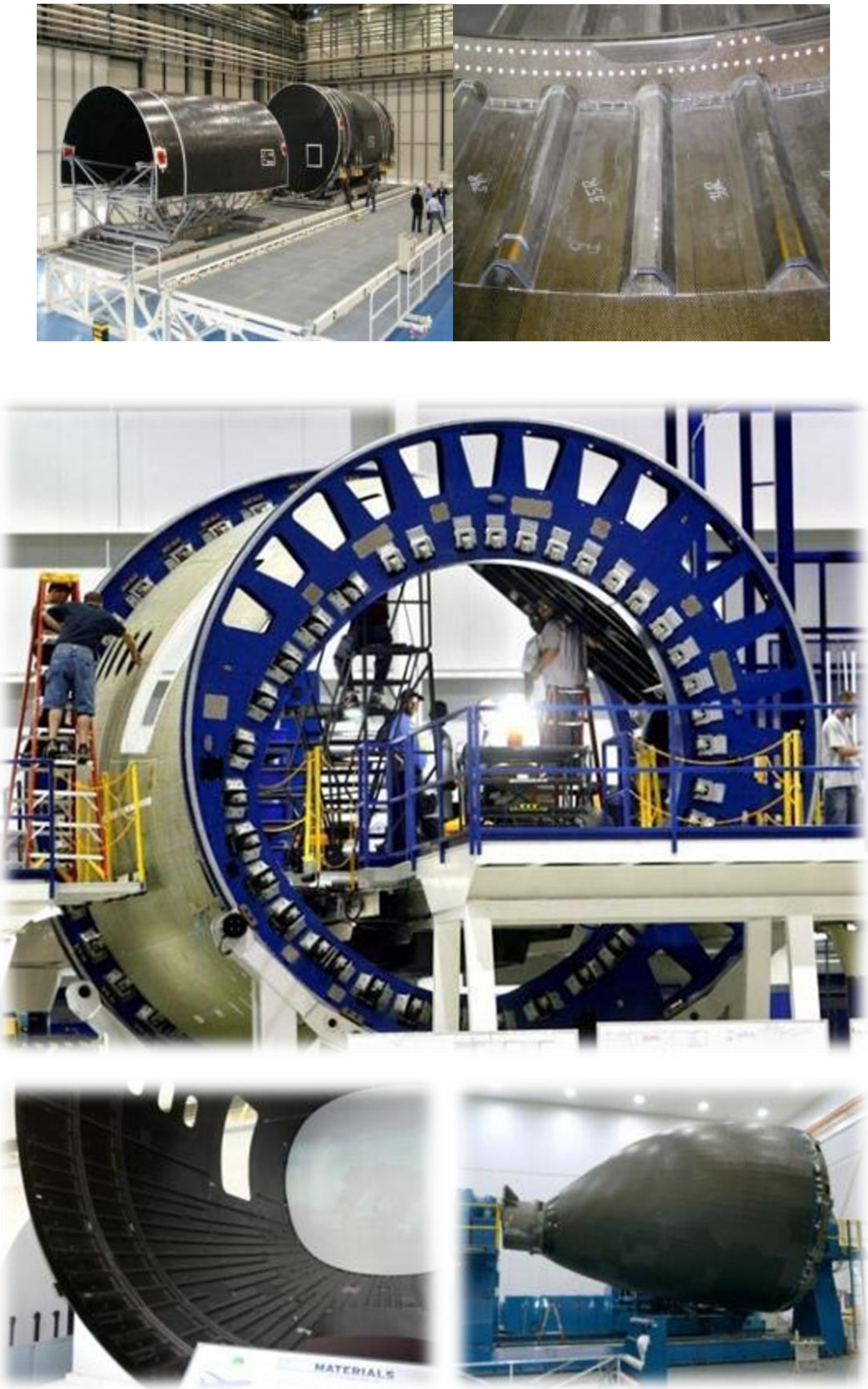


Figure 11 - Composite Material Usage in BOEING 787 Aircraft, Copyright of Boeing Commercial Airplanes, [12].

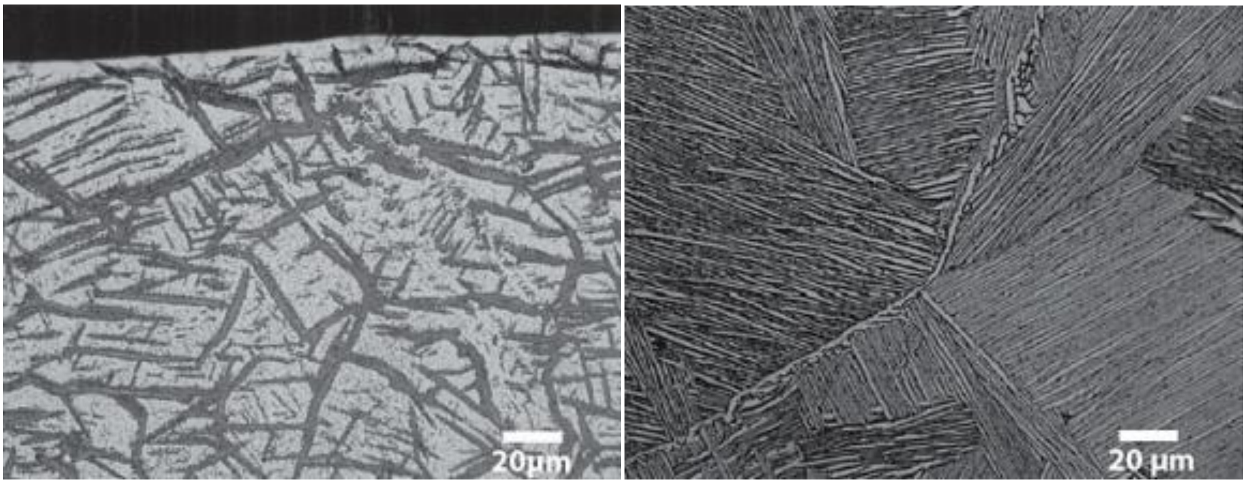


Figure 12 - Titanium Alloy Development [13].

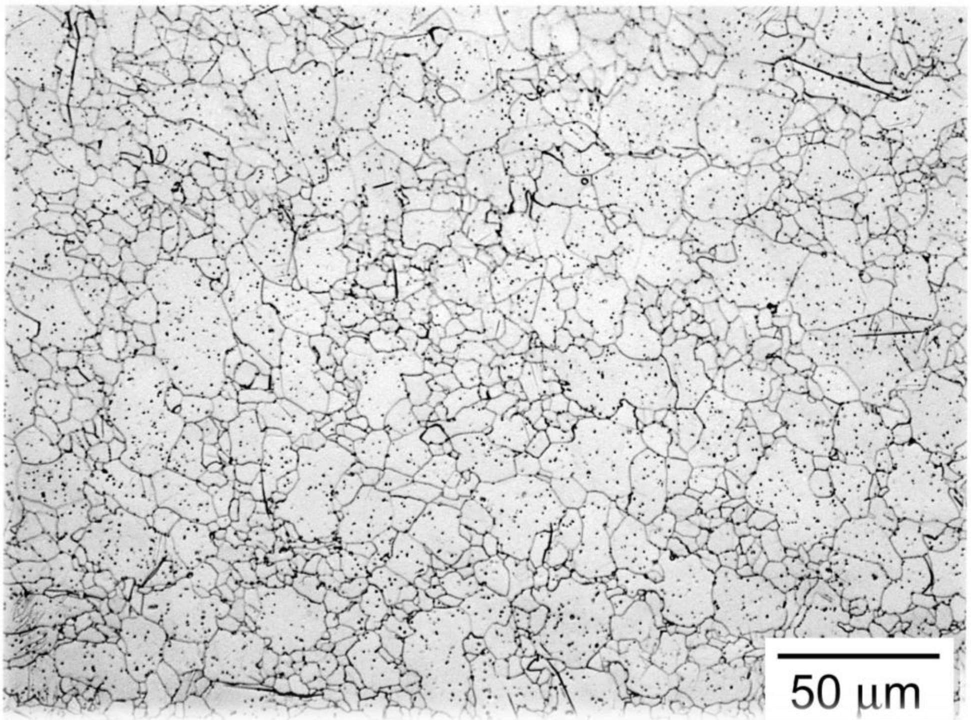
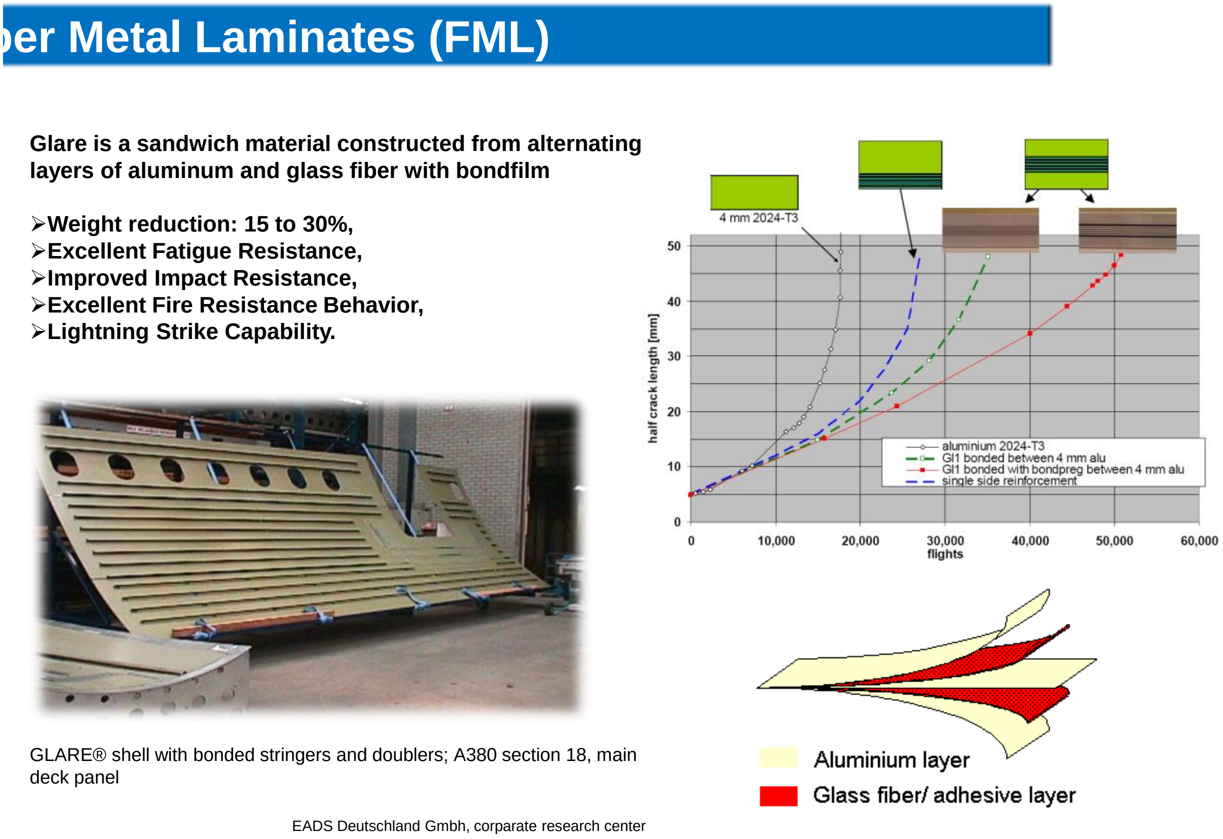


Figure 13 - Titanium Alloy Development [13].



ber Metal Laminates (FML)

Glare is a sandwich material constructed from alternating layers of aluminum and glass fiber with bondfilm

- **Weight reduction: 15 to 30%,**
- **Excellent Fatigue Resistance,**
- **Improved Impact Resistance,**
- **Excellent Fire Resistance Behavior,**
- **Lightning Strike Capability.**

GLARE® shell with bonded stringers and doublers; A380 section 18, main deck panel

EADS Deutschland Gmbh, corparate research center

Figure 14 - Glare Fuselage Panel Usage in A380 Aircraft [16], [17].

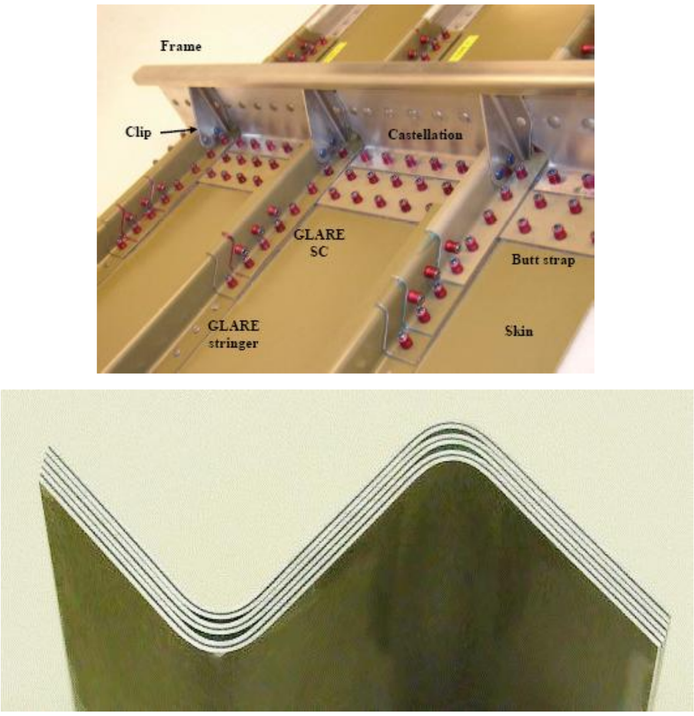


Figure 15 - Laminated Al components [18].

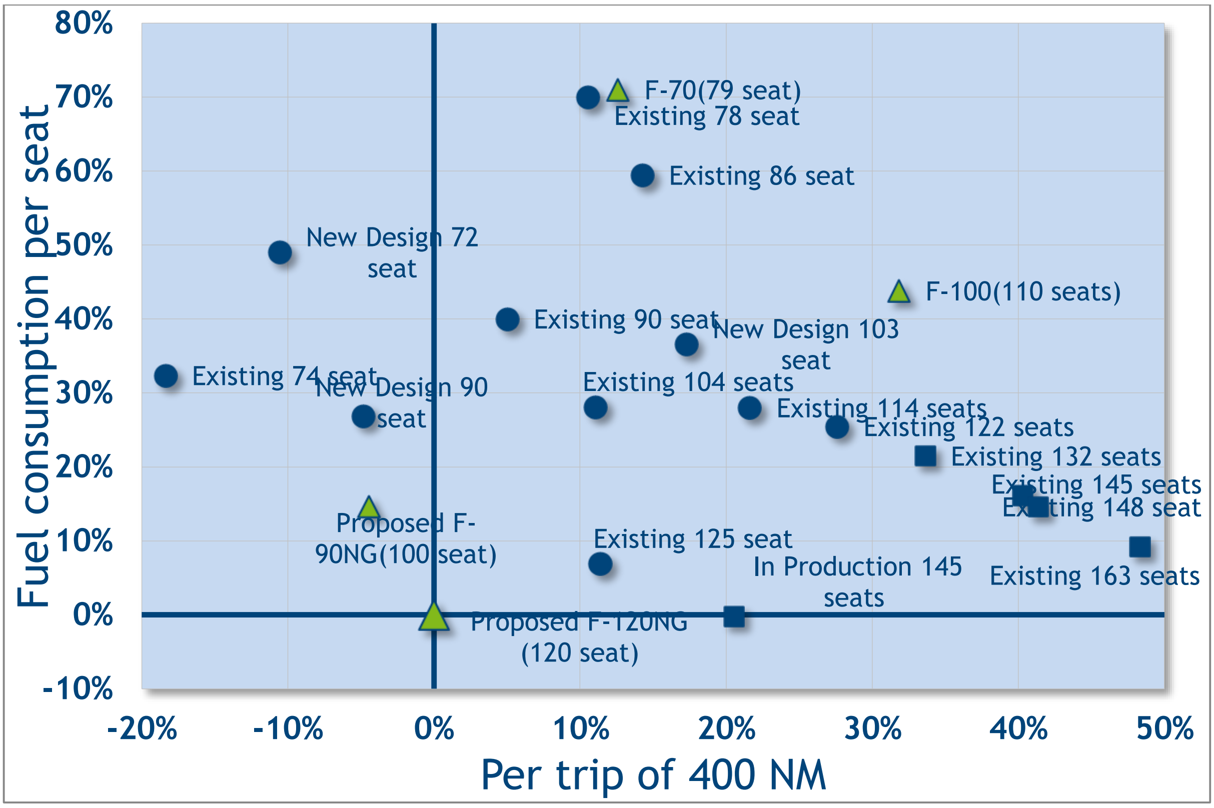
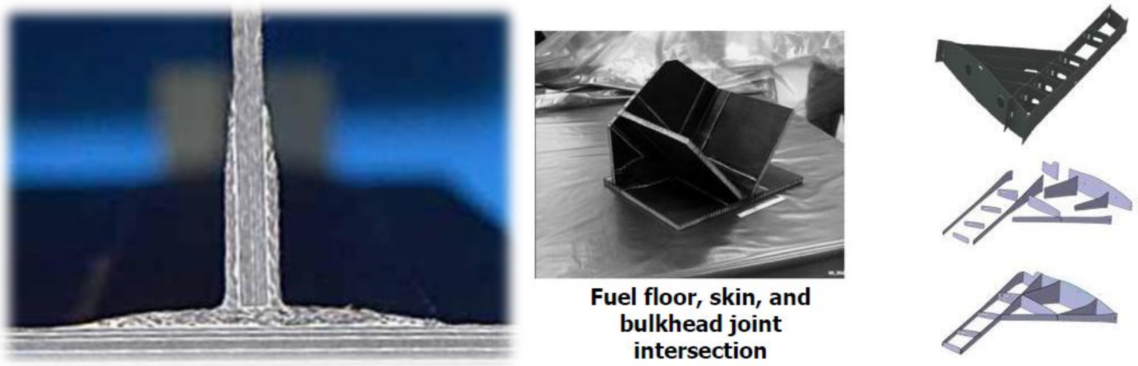


Figure 16 - Proposed F120 Aircraft to be developed as based on F100 (Authors are thankful to Mr. Rudi den Hertog and Mr. Maarten van Eeghen, NG Aircraft Company, Netherland for the information and the figure provided).



Fuel floor, skin, and bulkhead joint intersection

Figure 17 - 3-D Woven and Pi-Preform Joints and Large Integrated Composite Structure [5].

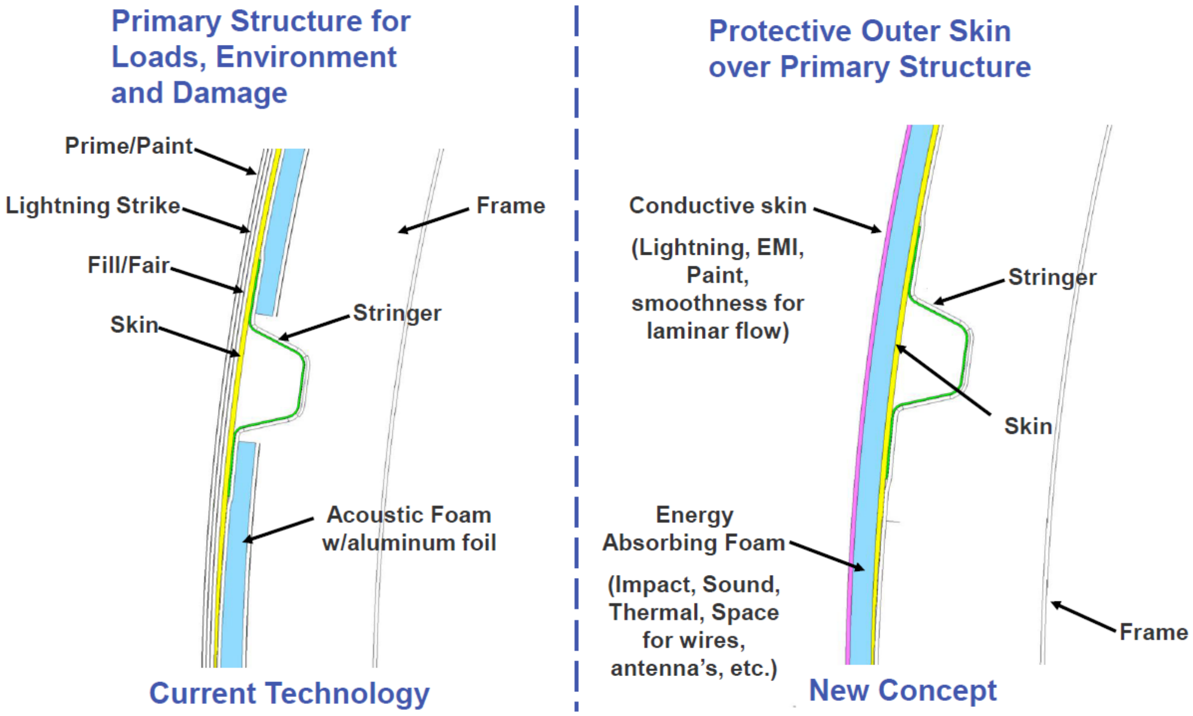


Figure 22 - New Composite Conductive Skin-Stringer Concepts with Energy Absorbing Foam [19].

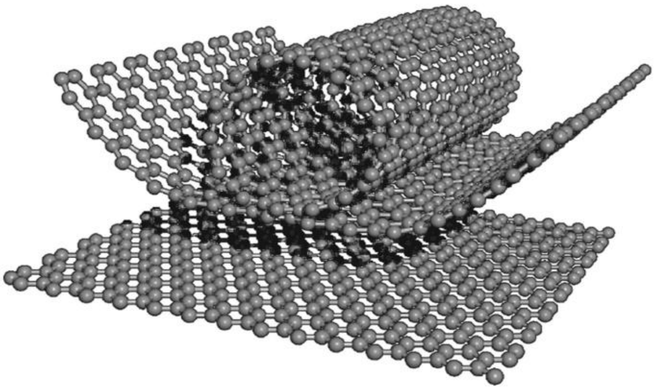


Figure 19 - Carbon Nano-tubes hexagonally shaped arrangements of carbon atoms bonded into a tube shape [20].

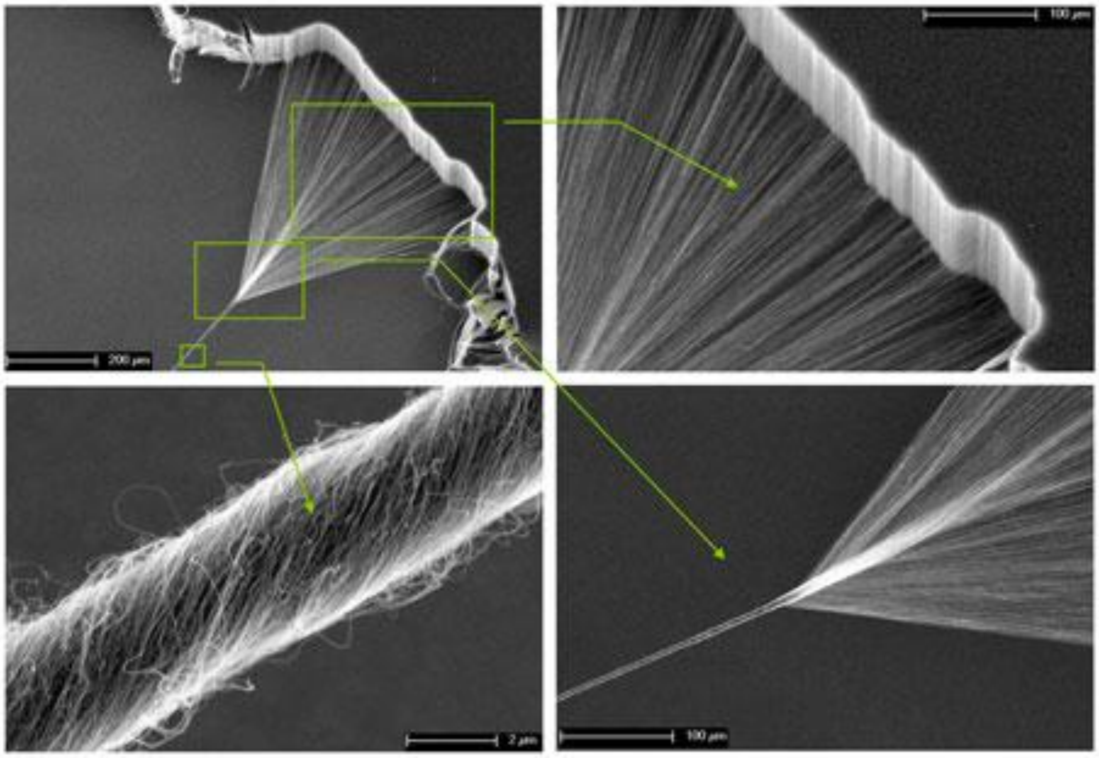
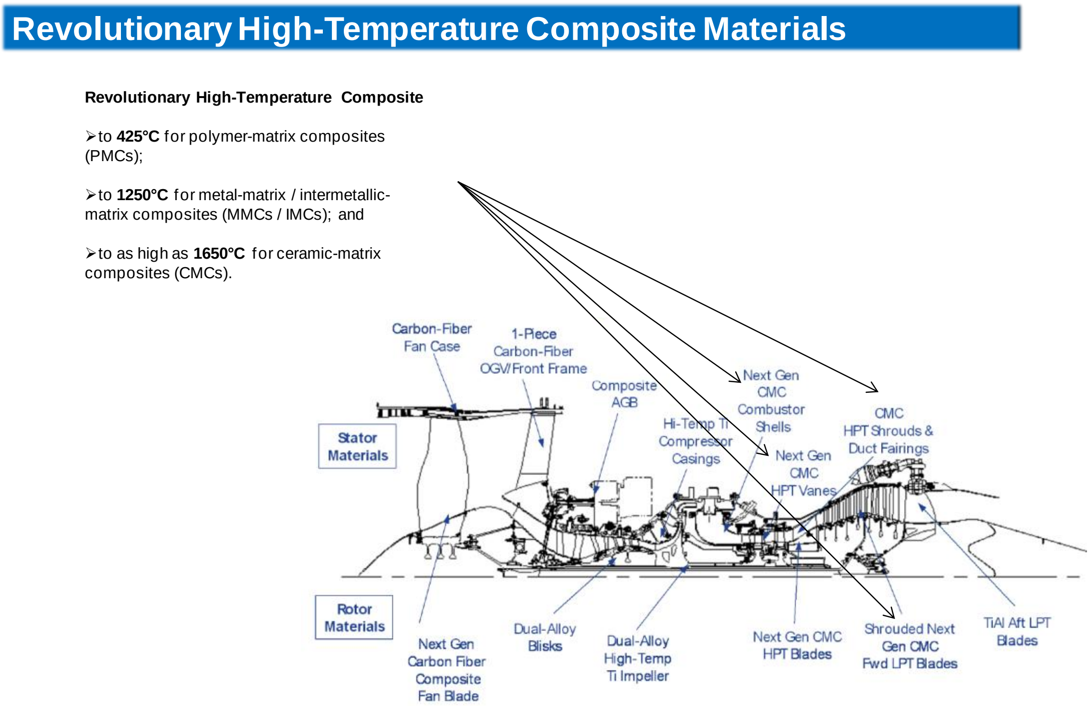


Figure 20 - From Nano-tubes to nano-fübers (Nanocomp Technologies Inc., Reference [20]).



Revolutionary High-Temperature Composite Materials

Revolutionary High-Temperature Composite

➢to **425°C** for polymer-matrix composites (PMCs);

➢to **1250°C** for metal-matrix / intermetallic-matrix composites (MMCs / IMCs); and

➢to as high as **1650°C** for ceramic-matrix composites (CMCs).

Figure 21 - Advanced High Temperature Engine Technology Development [23].

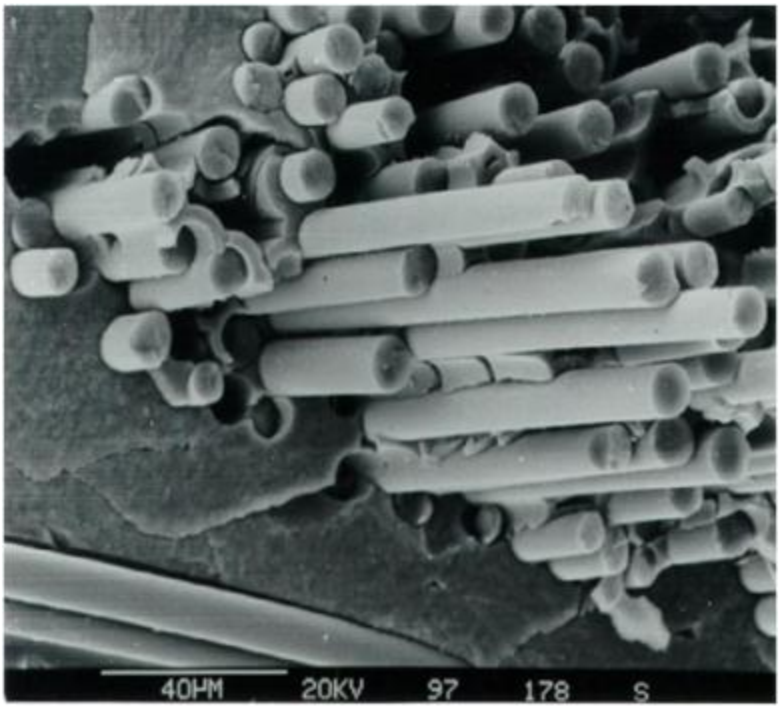
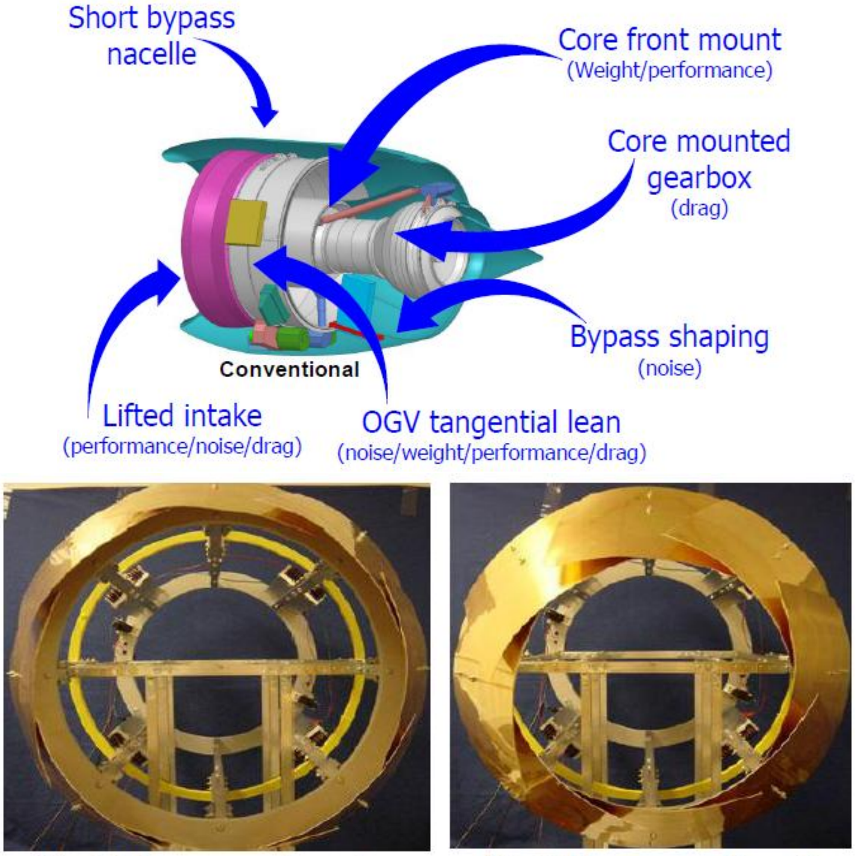


Figure 22 - Ceramic Matrix composites, ceramic composites reinforced with long or continuous ceramic fibers [21].



Variable-area exhaust nozzle: fully open

Variable-area exhaust nozzle: reduced area

Figure 23 - Shape Memory Alloys (variable geometry nozzles for Light Weight Fan / Fan Cowl [5].

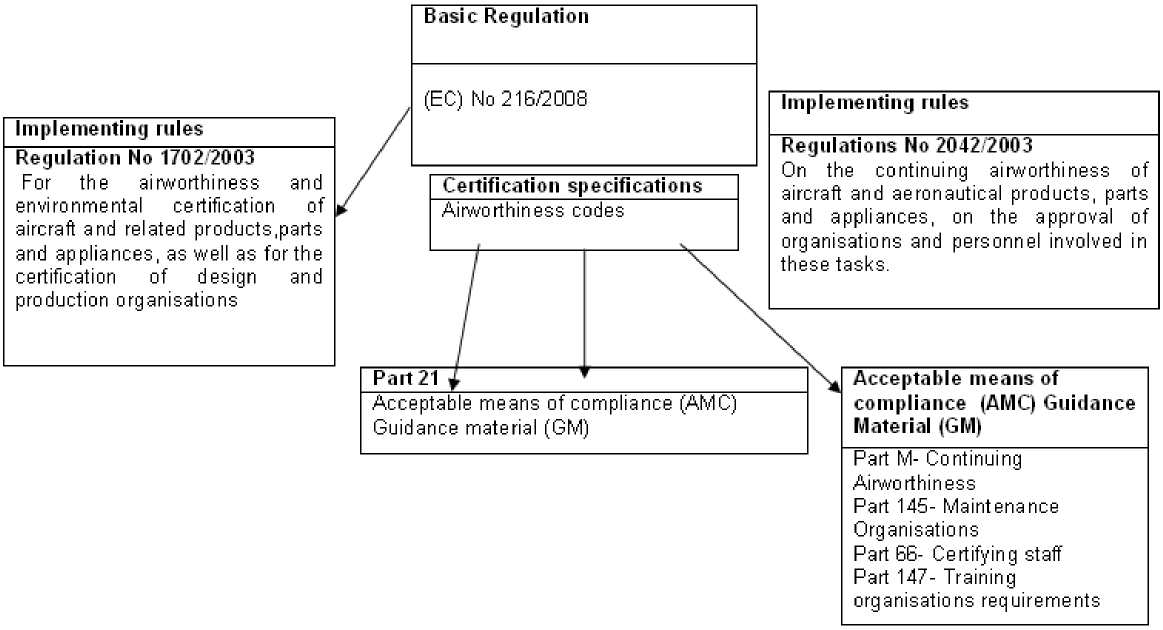


Figure 24 - Top Down Hierarchy of EASA Civil Aviation Regulations Covering the Complete Product Life Cycle of an Aircraft.

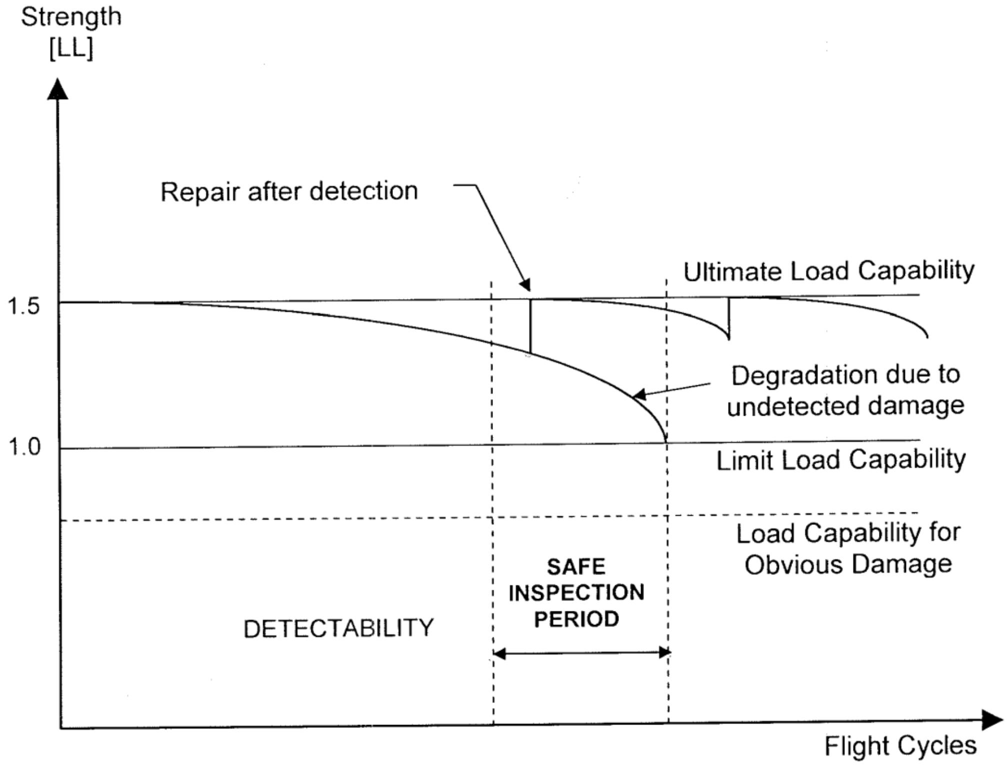


Figure 25 - Aircraft Structures Loading, Damage Detection, Inspection; Repair-ability Illustration.

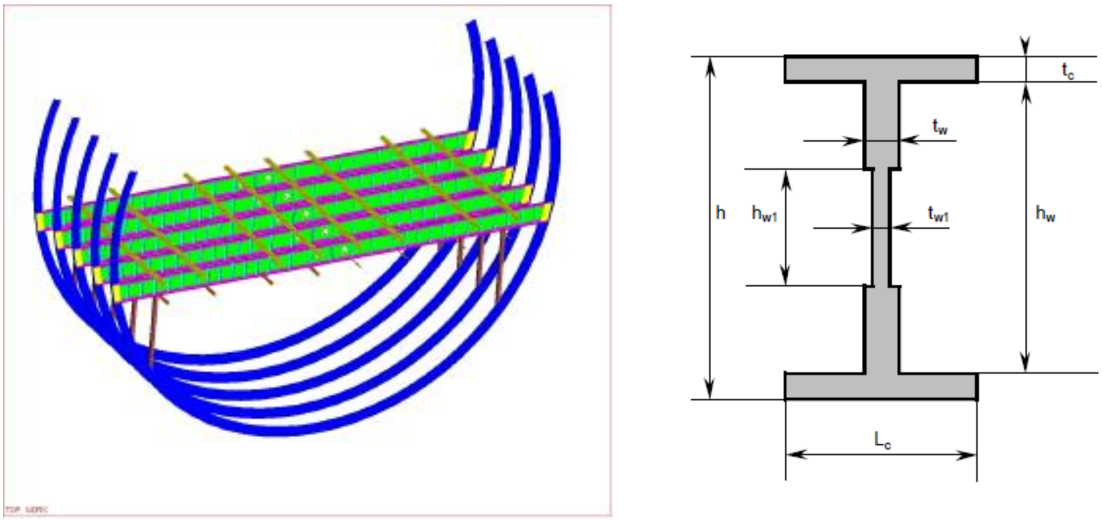


Figure 26 - 3-D view of The Floor Beam Structures and Cross Sectional Dimensions for Design Iterations [29].

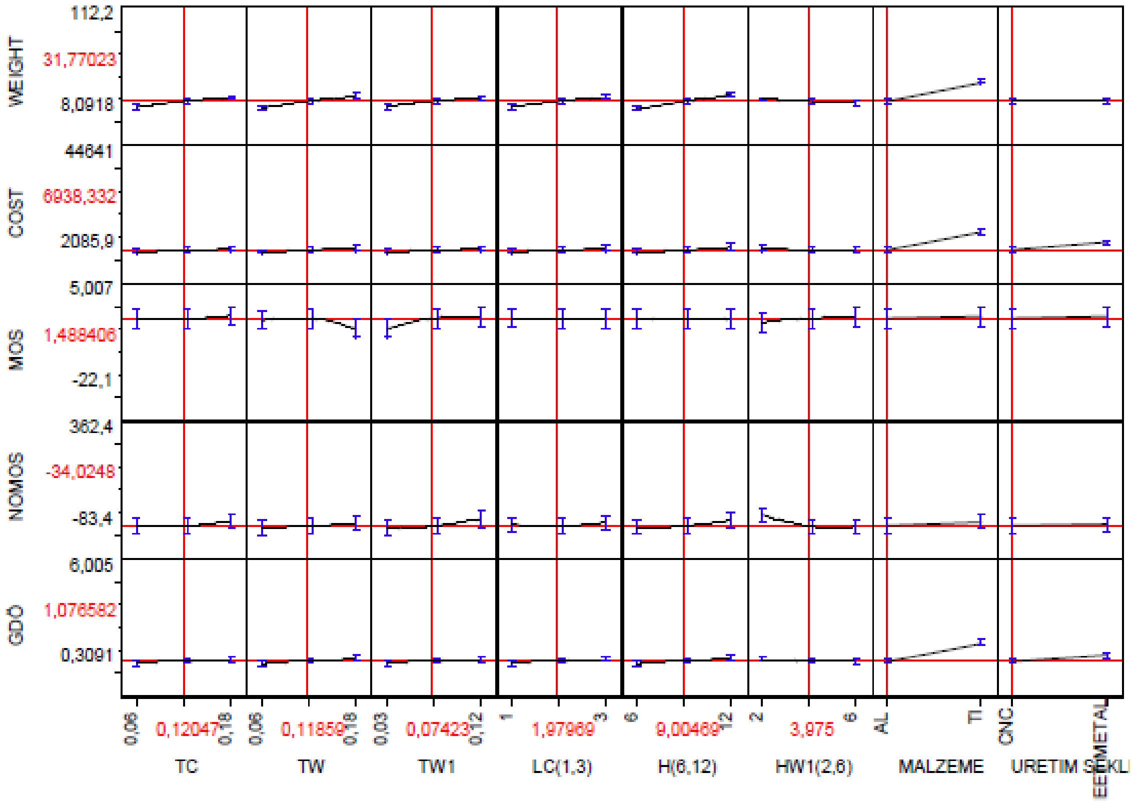


Figure 27 - Sensitivities and responses to the design variables for the floor beam design [29].

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