Arslan Mahmood

Review of composite structures in aeronautic applications part 3

Master Dissertation
European Master Advanced Structural Analysis and Design using Composite Materials

Work developed under the supervision of
Professor Doctor Bruno CASTANIÉ

Funded by the European Union

September 2023

DECLARATION

Name: Arslan Mahmood

Email: engr.arslanmahmood@gmail.com

Title of the Thesis: Review of composite structures in aeronautic applications part 3

Supervisors:

Professor Doctor Bruno CASTANIÉ

Year of Conclusion: 2023

Master Course in Advanced Structural Analysis and Design using Composite Materials

University of Toulouse III Paul Sabatier, 04/09/2023

Signature: Arslan Mahmood

ACKNOWLEDGEMENTS

The author thanks the cooperation of Supervisor Professor Doctor Bruno CASTANIÉ for his guidance and continuous support during the production of the thesis document. The author also thanks Professor Doctor Christophe Bouvet for proof-reading a part of the document.
In general, I am grateful to entire FRP++ team.

RESUME

L'objectif des travaux de réparation de la structure composite des avions est de restaurer la structure altérée à au moins 80 % de sa capacité en tenant compte des performances fonctionnelles, de la résistance, de la rigidité, de la durabilité, du cycle de vie en service et de l'esthétique. Étant donné que l'utilisation de matériaux composites avancés s'est étendue des composants structurels secondaires d'un avion aux structures primaires, il est crucial de disposer de techniques de réparation avancées. Actuellement, les techniques de réparation de composites disponibles comprennent la réparation par injection de résine (RIR), la réparation par fibres coupées (CFR), la réparation collée et la réparation boulonnée. Ces techniques ont leurs avantages et leurs limites, mais leur application peut entraîner une restauration de la rigidité structurelle et de l'intégrité, permettant ainsi une durée de vie prolongée des composants structurels composites de l'avion.

Le concept de tolérance aux dommages a été développé dans les années 1960 pour les composants structurels d'un avion afin d'améliorer la fiabilité des opérations aériennes continues et d'assurer un cycle de vie durable de l'avion. Pendant les opérations aériennes, un avion tolère la corrosion, les détériorations liées aux impacts, la fatigue et la dégradation de l'environnement. Le concept de tolérance aux dommages améliore la sécurité en vol de l'avion en intégrant une conception à sécurité intégrée dans les principaux composants structurels porteurs de l'avion. De plus, les composants structurels composites sont insensibles aux cycles de fatigue, tandis que les dommages causés par l'impact et la compression après l'impact sont des facteurs déterminants dans la conception de structures composites tolérantes aux dommages.

L'utilisation de composants structurels composites dans l'industrie de l'aviation civile et leur évolution des composants secondaires aux pièces principales de la cellule sont examinées au chapitre 3. Les matériaux composites typiques largement utilisés dans l'aviation commerciale sont la fibre de verre, la fibre de carbone, les structures sandwich renforcées de carbone, les structures à noyau en nid d'abeille. et les plastiques thermodurcissables. L'utilisation commerciale de composants structurels composites a évolué du secteur aérien commercial à la navigation et à l'exploration spatiales. Le développement d'une technologie avancée de matériaux composites permet des missions spatiales sur la Lune, sur Mars et au-delà.

L'utilisation de matériaux composites avancés est très demandée par les avions militaires en raison de leurs qualités uniques, de leur facilité d'application et de leurs coûts de fabrication inférieurs, de leurs coûts d'exploitation et de maintenance inférieurs et de la production d'avions furtifs de nouvelle génération. L'intégration de composants composites dans les avions militaires est passée de 5 % dans les années 1960 pour les avions de 3e génération à 35 % en 2020 dans les avions furtifs de 5e génération. Les matériaux composites avancés présentent une excellente efficacité pour répondre aux exigences des cellules de nouvelle génération (5e génération et au-delà). Le chapitre 4 donne un aperçu de l'application de structures secondaires et primaires à base de composites aux avions de combat militaires et de l'intégration de technologies composites avancées dans la production d'avions de combat de nouvelle génération.

KEYWORDS : Réparations composites, Tolérance aux dommages, Structures sandwich renforcées de carbone, Matériaux composites, avions furtifs

Review of composite structures in aeronautic applications part 3

ABSTRACT

The composite aircraft structural repair works objective is to accomplish the restoration of impaired structure to at least 80% of the capability considering functional performance, strength, stiffness, durability, service life cycle and aesthetics. Since the utilization of advanced composite materials has expanded from secondary structural components of an aircraft to the primary structures, it is crucial to have advanced repair techniques. Currently, the available composite repair techniques include resin injection repair (RIR), chopped fiber repair (CFR), bonded repair and bolted repair. These techniques have their advantages and limitations but their application can result in structural stiffness and integrity restoration, allowing extended service life of the composite structural components of the aircraft.

The damage tolerance concept was developed in the 1960s for the structural components of an aircraft to improve reliability of continuous aircraft flight operations and ensure sustainable life-cycle of the aircraft. During flight operations, an aircraft tolerates corrosion, impact deteriorations, fatigue, and environmental degradation. The concept of damage tolerance enhances the in-flight safety of the aircraft incorporating fail-safe design into the primary load bearing structural components of the aircraft. Moreover, the composite structural components are insensitive to fatigue cycles while impact damages and compression after impact are critical governing factors in the design of damage tolerant composite structures.

The utilization of composite structural components in civil aviation industry and their evolution from secondary components to primary airframe parts are reviewed in chapter 3. The typical composite materials widely used in commercial aviation business are fiberglass, carbon fiber, carbon reinforced sandwich structures, honeycomb core structures, and thermosetting plastics. The commercial utilization of composite structural components has evolved from commercial airline business to space navigation and exploration. The development of advanced composite material technology is enabling space missions to moon, mars and beyond.

The utilization of advanced composite materials is in high demand with military aircraft owing to their unique qualities, ease of application and lower manufacturing cost, lower operational and maintenance cost, and production of next generation stealthy aircrafts. The integration of composite components into the military aircraft has risen from 5% in the 1960s 3rd generation aircraft to 35% by 2020 in 5th generation stealthy aircraft. The advanced composite materials are exhibiting excellent effectiveness in achieving the sheer demands of next generation (5th generation and beyond) airframes. Chapter 4 provides insight into the application of composite based secondary and primary structures to military fighter crafts and integration of advanced composite technologies into the production of next generation fighter crafts.

KEYWORDS: Composite repairs, Damage tolerance, Carbon reinforced sandwich structures, Composite materials, Stealth aircrafts

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AFP	AUTOMATED FIBER PLACEMENT
ATL	AUTOMATED TAPE LAYING
BVID	BARELY VISBLE IMPACT DAMAGE
CFR	CHOPPED FIBER REPAIR
CFRP	CARBON FIBER REINFORCED POLYMER
CV	CARRIER VARIANT
CTOL	CONVENTIONAL TAKEOFF AND LANDING
JSF	JOINT STRIKE FIGHTER
LBW	LASER BEAM WELDING
NDT	NON DESTRUCTIIVE TESTING
ODD	OBVIOUSLY DETECTABLE DAMAGE
RCS	RADIAL CROSS-SECTION
RIR	RESIN INJECTION REPAIR
SLS	SPACE LAUNCH SYSTEM
STOVL	SHORT TAKEOFF AND VERTICAL LANDING
VID	VISIBLE IMPACT DAMAGE

Symbols

ε_l^{comp}	COMPRESSIVE STRAIN
ε_l^{res}	LONGITUDINAL RESIDUAL STRAIN
r_{lt}^{res}	LONGITUDINAL SHEAR STRAIN

THIS PAGE WAS INTENTIONALLY LEFT BLANK

1. 1. INTRODUCTION

Aircraft sections (metallics / composites) experience ageing damages in service from fatigue / stress corrosion [3], manufacturing damages, accidental damages from fire, engine failure, loading and unloading at hangers from ground equipment - as depicted in Figure 1.1 - which explains percentage of impact by zones and mapping of impact energy, and environmental damages from hail, debris, bird strike and lightning strike as depicted in Figure 1.2. The classification of damages includes scratches, gouges, dents, skin delamination, de-bonded stringer, skin perforation, honeycomb core depression / perforation, and mud and paint cracking as visualized in Figure 1.3. The manufacturing defects in materials from poor production techniques and in service cracking from pitting corrosion leads to local stress accumulation which eventually causes cracking initiation / propagation in aircraft parts [3]. The substitution of damaged parts is costly, time consuming and losing aircraft access. Thus, repairs in aircraft faulty sections have been adopted in industry to improve structural competence and longer fatigue cycles [4].

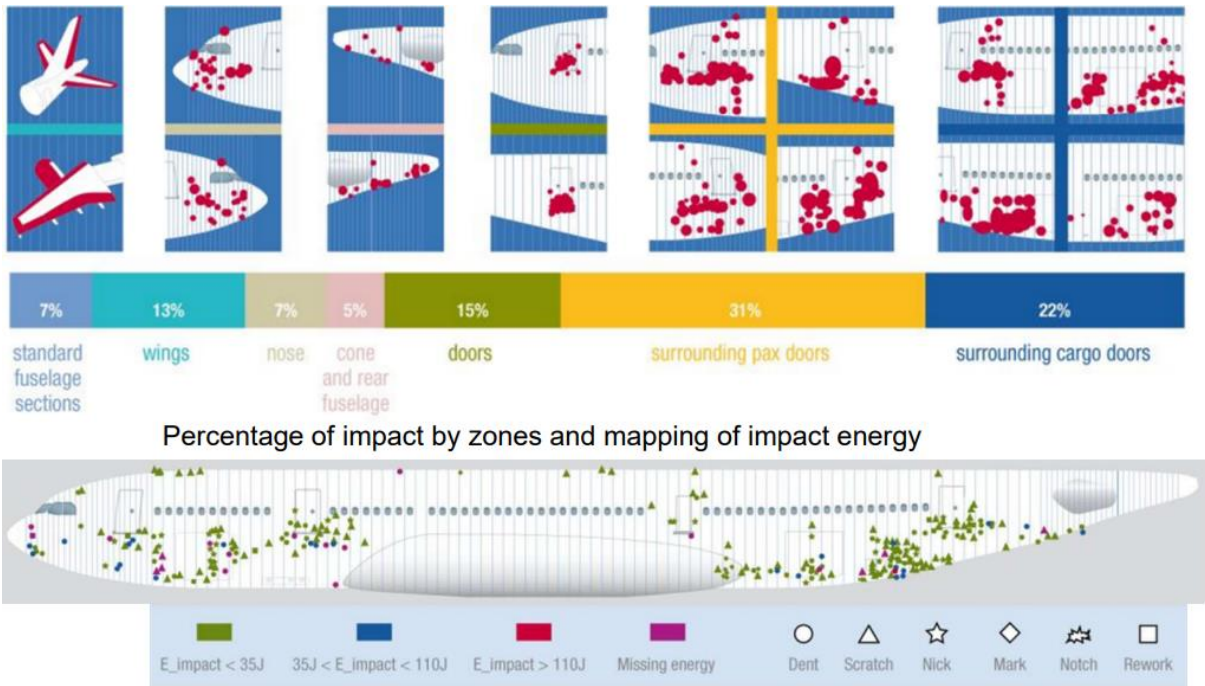


Figure 1.1: Percentage of impact by zones and mapping of impact energy [16]

Figure 1.2: Lightening strike damages on the body of aircraft [16]

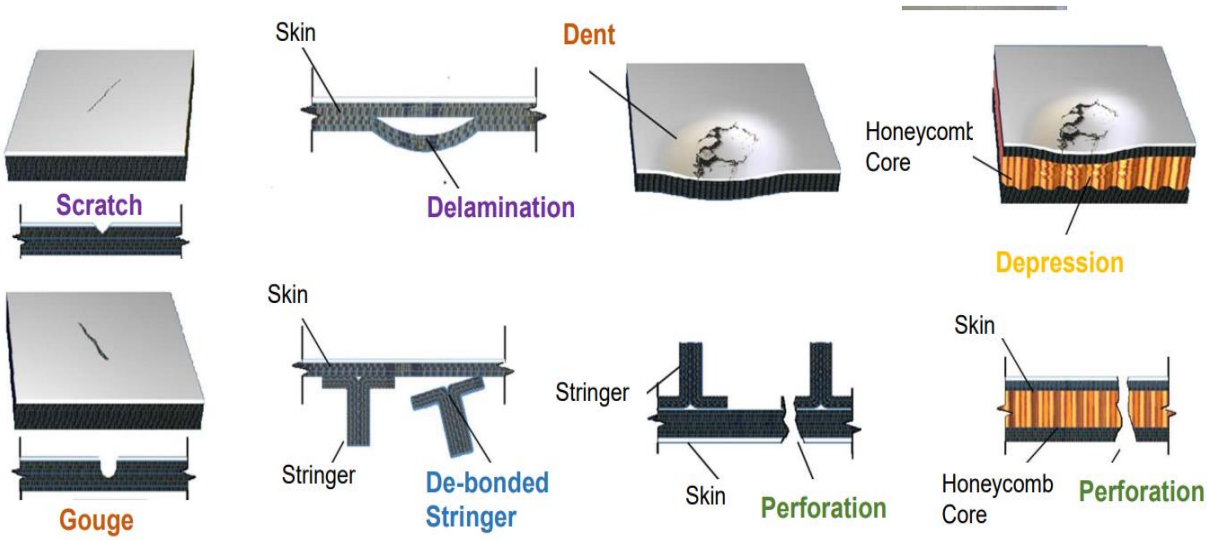


Figure 1.3: Classification of damages [16]

The objective of an aircraft composite repair work is to ensure structural integrity and restore bearing capacity (ultimate limit state and serviceability limit state). The main criteria for selecting the type of repair are the effective load transfer mechanism (stiffness compatibility with the parent section), shorter time span, minimum cost, least extra weight, aerodynamic evenness, minimum technical challenges, and determination of the exact repair spot. Based on satisfactory career and successful implementation, adhesively bonded patch, and mechanically bolted patch; the two aircraft repair types are generally used. However, the first type is structurally more efficient than the second [5] for highly loaded structures. The purpose of both composite reinforcements is to diminish stress concentration (crack patching) where the sectional components experience fatigue / stress corrosion cracking, solidify under-designed components to enhance static stability and suppress flutter, deflection, and fatigue elongation at stress intensifier; and reconstruct residual rigidity after crack eradication [5].

The conventional methodology for executing repair work is utilizing several rivets / bolts to integrate reinforcement with the concerned damaged portion of the aircraft. However, the traditional method has become ineffective as the extra bolt holes introduce considerable stress concentrations into the aero-vehicle structural component, while the hole drilling itself poses threat to the interior of the structure. Thus, the traditional repair mechanisms can end up encouraging damage into the airframe. To resolve the issue, advanced repair technologies have emerged to conduct composite repair works in more efficient and cost-effective applications. These advanced repair technologies include Resin Injection Repair (RIR), Chopped Fiber Repair (CFR), Bonded Repair etc. Moreover, the damage evaluation using NDT (non-destructive testing) includes ultrasonic (Figure 1.5) for measuring sub-surface damages, thermography (Figure 1.6) for assessing material defects and shearography (Figure 1.4) for exterior deformation quantification [15].

Figure 1.4: NDT via Shearograhy

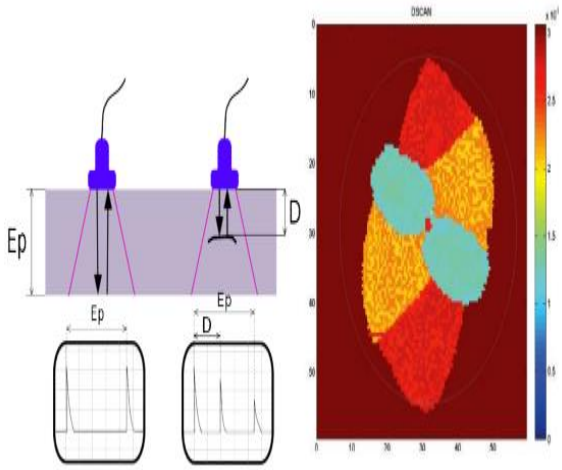
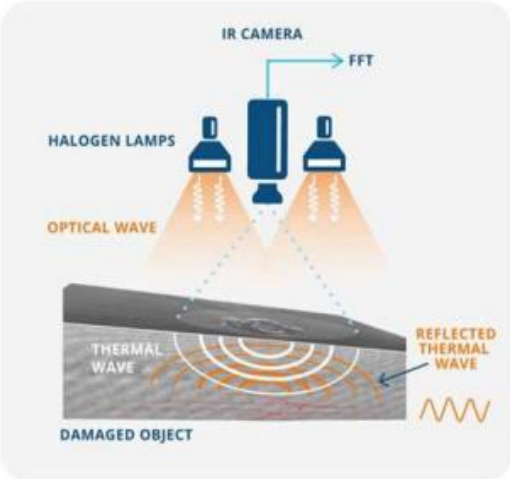


Figure 1.5: NDT via Ultrasonic



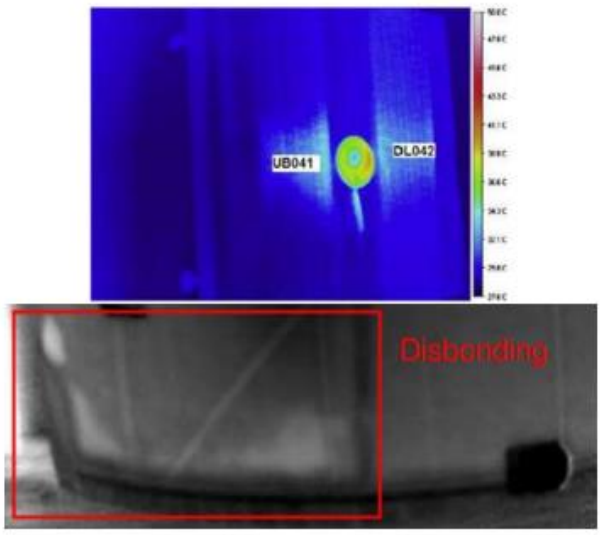


Figure 1.6: NDT via Thermography

1.2. COMPOSITE REPAIR TECHNOLOGIES

1.2.1. RESIN INJECTION REPAIR (RIR)

The technique is used for repairing delamination of plies composing a laminate or de-bonded skins of honeycomb composite structural parts of aircrafts. The RIR ensures the achievement of local stiffness and adherence. Typically, two small, drilled holes upon the laminate structure are executed where viscous resin flows through one or many holes, and vacuum port through the other. The principle of Resin Injection repair to refill laminate damages can be visualized in Figure 1.7. However, precaution is necessary in the execution of holes as they can lead to additional cracks and damage to the airframe laminate composite structure [6], [17], [1].

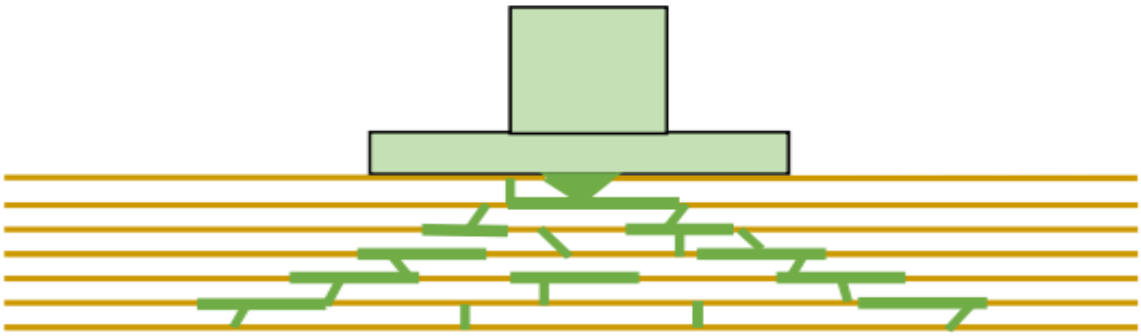


Figure 1.7: Principle of Resin Injection repair to refill laminate damages [16]

1.2.2. CHOPPED FIBER REPAIR (CFR)

The flawed drilling of holes, during assembly / manufacturing stage, in the composite laminate structural component can lead to error in geometric endurance, loose and misaligned holes. The CFR technique, mostly used for secondary structural parts, is exercised to deal with such flawed holes were chopped composite fibers and system of epoxy resin effectively treat the damaged portion of laminate keeping the structural integrity intact [1].

1.2.3. BONDED REPAIR

The bonded repair formation consists of external / internal patch - single or two-sided dual strips – as visualized in Figure 1.8, and scarf / stepped - scarp strips bonded to the cracked structural component as visualized in Figure 1.9 [15]. However, both structural sides are not available for bonded repair work unless the structure is dismantled. Moreover, some researchers believe that scarf joint supplies better stress distribution theoretically than stepped joint [1].

Figure 1.8: Bonded external patch, single side and both sides [16]

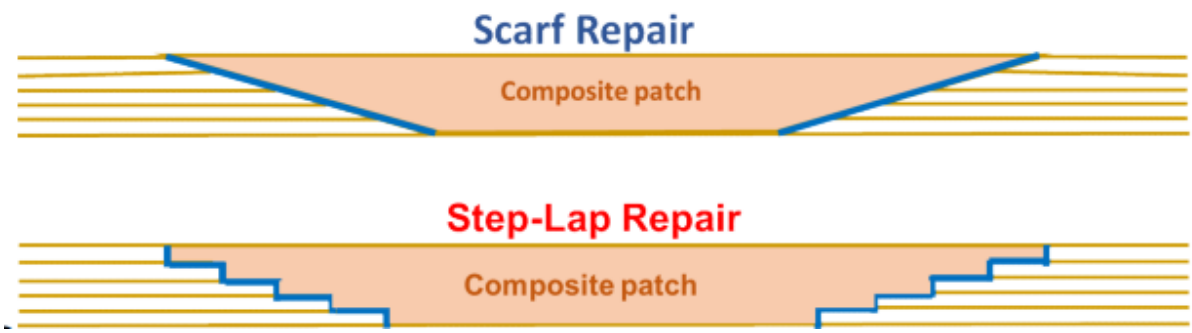


Figure 1.9: Typical exhibition of Scarf repair and Stepped Lap repair [16]

Bonded strips repairs are very suitable for thin structural cross-sections, where removal of material and finished smooth surface is not necessitated [22]. Scarf patches are utilized in thick structural cross-sections for long-lasting repair works [13]; however, the technique necessitates skilled labor to exercise structural repair code and skillful application technique [13]. Scarf bonding and stepped bonding can be exercised with only one side of cracked section ; provides potent stress transmission and aerodynamic surfacing [15].

Figure 1.10 detail a flowchart for the typical bonded repair process phases. The specific damage details of primary and secondary structural components of an aircraft certainly enhance the efficiency of bonded repair works. Then, the repair mechanism phase (automated / manual) for bonded composite repairs starts, involving skillful manner to execute crack computation, material expulsion, surface training, reinforcement assembly and curing treatment with temperature and pressure [2].

The material expulsion is executed using composite machining of 3 major types, which are conventional, laser and abrasive waterjet machining. The conventional machining of composites is indicated with intermittent micro-fractures, generated from the heterogeneous response of fibers and polymer matrix to the applied forces [7]. The fibers and polymer matrix have different heat sensitivity resulting residual stresses, and difference in moisture absorption ratio when heat coolant is applied, adversely affecting the machined surface quality The composite structures having heterogeneity, abrasiveness, poor heat conductivity, anisotropic nature, and thermal sensitivity are difficult to handle using conventional machining [20]. However, complex apparatus is necessitated to mechanize automatic laminate scarfing for bonded composite repair works [23].

Machining of composites using lasers provides accurate scarfing and damaged surface removal. It is a mechanical non-contact machining process, can be used with complex heterogeneous geometries, and does not necessitate material distortion during machining [20]. However, laser machining may result in the development of heat affected zones, which depends upon the quality of fiber and polymer matrix material [14].

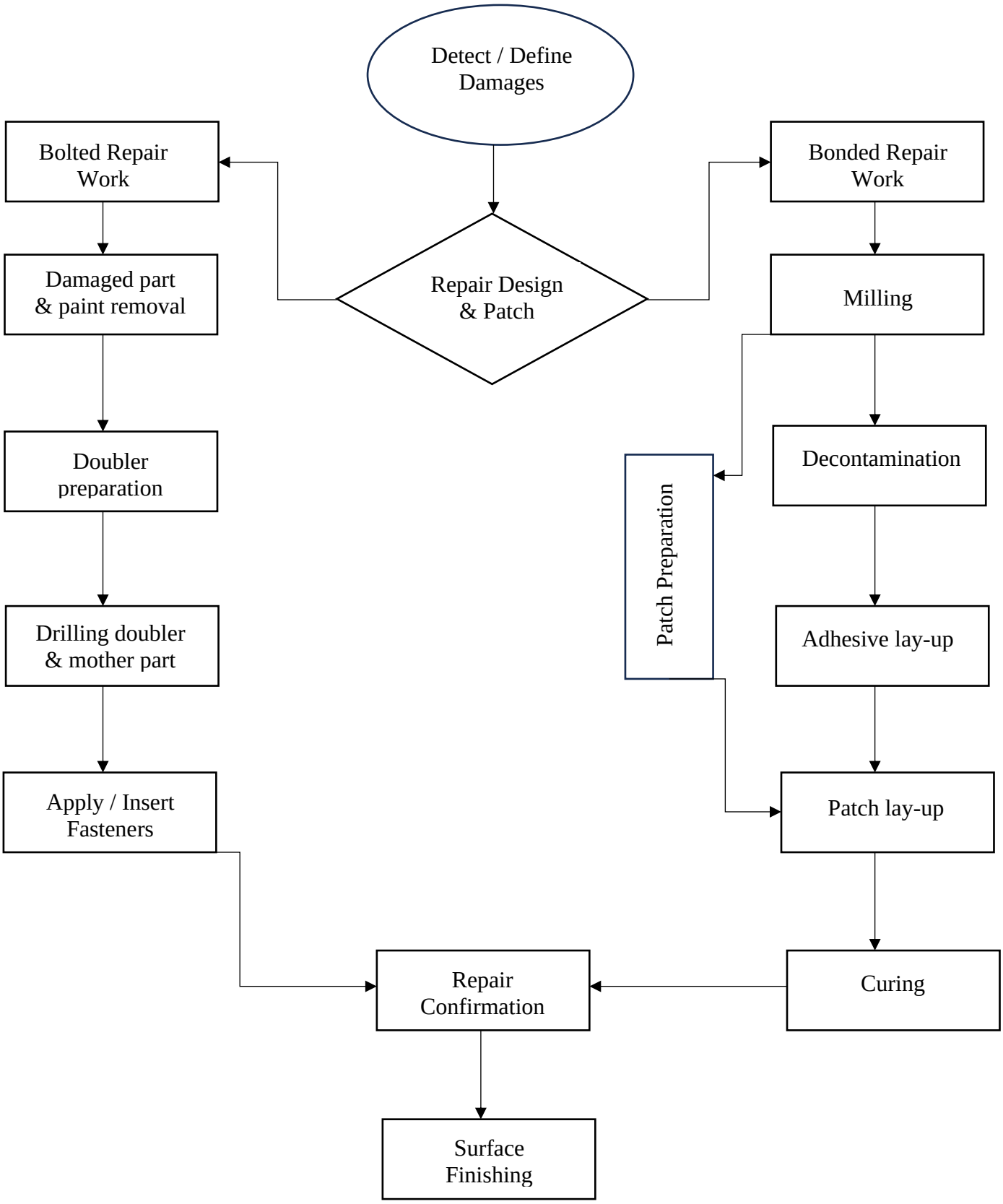


Figure1.10: Typical repair process flowchart for bolted repair works and bonded repair works.

The abrasive water jet (AWJ) machining depends on hydro pressure and motion rate, mixing pipe specifications, abrasive material and particle specification and motion rate, inclination gradient, stand-off interval etc. [21], [20]. AWJ machining is a clean process [20], used for complicated scarf surfaces [10] and may result in delamination [18].

The surface preparation of composites for damaged structural parts is used to enhance the adhesion between the interface bonding surfaces. Factors governing the interface adhesion are surface preparation and adjacent contact [12]. Ordinary surface preparation can stain the surface, thus advanced treatments (atmospheric plasma treatment and laser ablation) are exercised for bonded composite repair works [15].

Appropriate reinforcement materials and adhesive resins along with sophisticated curing conditions are crucial for patching strong & reliable composite reinforcement [9]. The patching of scarf cavity is executed using hard patch or soft patch. The hard patch is pre-cured, bonded to original aircraft part with application and curing of the adhesive resin at low / high temperature depending on the material utilized for the adhesive and the parent part, while the soft patch is in-situ wet layup with application and curing generally at low / high temperature and high pressure to achieve patch cementing [19]. Moreover, curing temperature and pressure can affect the quality of consolidated patch, while optimal cure of resins requires supervised cure cycles [8].

Structurally bonded repair works, like stepped / scarf repairs, are likely to enhance stress transmission systems, patch competence and smooth surface finish. However, the technology should be repeatable and reliable in order to have cheap composite aircraft structural repairs, which involve but not limited to modern NDT for damage evaluation ; advanced composite machining for damaged material extraction ; proper finished structural interface surfaces for adhesive bonding ; supervised curing conditions for hard / soft patch construction ; precise damage assessment and patch design for standard repairs ; result supervision and automation for certified repeatable repair works [15].

1.2.4. BOLTED REPAIR

This repair technique is generally used for thick structural composite components and consists of external / internal patch constructing single / double shear joints. The bolts bear the shear stress load, and the patch bears the in-plane loading, where applied double patch reduces the transfer load eccentricity in the repaired structural part [1]. The bolted repair procedure flowchart is explained in Figure 1.10.

The composite joints demand high quality composite, stainless steel, titanium, or monel fasteners, with special arrangements to avoid corrosion. The typical procedural steps consist of surface and patch preparation, parent surface markings to prepare for holes, adjust patch with the parent skin, carefully drilling pits in the parent skin and the applied patch, check alignment of drilled holes between the patch and skin, patch installation, bolts installations in the drilled pits, and sealing the bolts. The repair design should ensure even distribution of loads among all bolts, which is not possible with multiple rows of bolts as it depends upon bolt intra spacing and diameter, and patch configuration. Thus, proper design engineering is to be exercised for complex bolted repair works with the help of approved repair procedures like TM, SRM, TO etc. [1].

The bolted repair configuration can consist of bolted internal doubler, external patch with backup plates, and external patch with blind fasteners. The bolted internal doubler approach requires access to both sides of the repaired part, continuous doubler to transmit load in all directions and filler. The second approach configures a composite patch bolted to the repaired structural part. The third approach is like the second one except backup plates are not used [1]. The failure analysis of the bolted joint involves variables such as composite laminate thickness, layup configuration and material [1]; and bolt stiffness to be determined by proper testing. Moreover, the failure analysis of the parent part of the bolted joint is to be exercised to investigate bearing ratio and laminate failure configurations. The detailed analysis technique is provided in volume 3 of Military Handbook 17.

1.2.5. APPLICATIONS OF BONDED REPAIR VERSUS BOLTED REPAIR

The repair criteria depend upon aircraft segment configuration and engineering complexity for practical purposes. The bonded repair is used for thin laminates and bolted repair for the thicker ones. The bonded repairs offer better stress distribution, efficiency and higher fatigue resistance; and allow constructing thin laminates achieving aerodynamic surfaces, least stress concentrated areas, minimal addition of weight and better aesthetics. The bolted repairs are readily available with mature technology, skill and tools accessible worldwide. Engineering is simpler, allowing confidence in design and execution phases. The general criteria as per Evans [11] and Archer [1], bolted repairs should be used for laminates greater than 8 mm thickness and practically up to 3 mm thickness of the laminates.

The disadvantages of bonded repairs highlight difficult surface preparation, complexity in materials, skills, and time consumption. The NDT (non-destructive testing) enhances the consumption of cost, time, skill and resources. Moreover, all the processes from design to execution and curing are complex and require highly skilled labor. The disadvantages of bolted

repair include difficulty in the design and execution for thin laminates and sandwich structures. The fasteners may experience environmental deterioration while issues related to strength / stiffness discrepancy and thermal stresses add to the disadvantages of this technique. Moreover, the structural component weight addition, poor finishing and compromised surface aerodynamics, and fastener hole breakout are common issues with the bolted technique.

Bonded repair works are common with honeycomb structures and secondary structural components of an aircraft. However, bonded repairs are not completely certified for primary aircraft structures as the finished repair strength and durability can only be assessed with destructive examination, which adds to the complexity and cost of the finished product.

THIS PAGE WAS INTENTIONALLY LEFT BLANK

2. 1. INTRODUCTION

The conceptualization of damage tolerance for aeronautical applications is decisive in controlling the failure mechanisms of primary structural components. Research proves that aircraft structural parts undergo fatigue failure, much earlier than the design life. Thus, safe life concept where structural component replacement is cheap / easy (not feasible) and fail-safe design with redundant structural components (anomaly) in the body of aircraft, were introduced. The fail-safe design employs damage tolerance analysis for assessing damaged structural portions of components with respect to failure impact and airframe service life. The expression of damage tolerance regarding fail-safe airframes is difficult and can be executed according to USAF MIL-A-83444 [48]. The importance of damage tolerance can be understood from the fuselage failure of the Comet leading to loss of life, where pressurized fuselage damage tolerance was underestimated, as shown in Figure 2.1.

Figure 2.1: Comet Jet Crash, Rome 1952

The damage tolerance analysis ensures the aircraft structural safety during its useful lifespan, that can be compromised from structural deformation and failure, transpiring from corrosion, fatigue, or disaster [50]. It is conducted to investigate structural strength and detect parts deteriorations. The purpose is damage detection to avoid operational hazards by accepting the capability of composite structure to sustain sufficient loads within failure strains [28].

2.2. PROJECTILE IMPACT DAMAGES

The structural integrity of a composite aircraft is decisive in computing physical vulnerability, which can be compromised from damaging mechanisms such as bird strike, engine

fragmentation, manufacturing defects and poor fatigue tolerance. The damage tolerance evaluation of aircraft composite structures necessitates in-depth analysis of failure mechanisms and threat (external / internal) induced response modes of composite structures. The description of projectile threats is categorized into exploding / non-exploding projectiles and engine debris. An exploding projectile is accompanied with blast effects on impact with aircraft while a non-exploding projectile remains intact on hitting the aircraft structural component. The rotating engine components failure in-flight generates engine debris, if breakout from the engine casing, which can compromise the structural integrity of composite structural parts. The projectile damage on composite laminates is compromised from fiber ductility, interlaminar strength and plies orthotropic stiffness, and results in fiber fracture, peeling, gouging, perforation, and delamination [27].

The encounter parameters of a projectile striking the body of aircraft involve velocity, altitude, fragment impact density and obliquity angle. The striking velocity is a relative velocity relationship at the instant of clash between the flying machine and projectile and measured for composite structures as the ratio between velocity and ballistic limit velocity. The projectile altitude ranging from 0-degree to 90-degree, is the angle between projectile flight path and longitudinal axis, influencing the lateral structural damage with projectile penetration. The fragment impact density in the number of fragments colliding per unit area. The greater fragment impact density imparts greater composite structural deterioration and fracture. The obliquity angle is between the projectile flight path and normal to the impact outer and it greatly influences the damage size in fiber composites structural laminate ([27]).

The projectile damage results in considerable out-of-pane composite structural deformity with cracks, holes, and dents. The lateral damage and transverse lateral damage measurement techniques are used for damage tolerance vulnerability analysis of composite aircraft.

Composite structural design engineers have conducted broad research to evaluate residual strength of the damaged / impact -damaged structure and the damage propagation rate. The methods used to conduct residual strength analysis are Inglis, C. E. [43] analysis [53], Griffith's A. A. [38] energy approach [53], Orowan E. [32] approach [53], Irwin G. R. [40] approach [53], and Westergaard's H.M. [41] stress analysis approach [53].

2.3. CRACK INITIATION AND PROPAGATION

Crack propagation laws have been investigated to answer composite laminate fatigue behavior and especially low cyclic fatigue. Usually, the fatigue life is distributed among crack initiation

and propagation stage, where initiation stage depends on the composite material point of origin and propagation stage affects throughout the composite x-section [53].

A major advancement to the theory of initiation of the composite crack was addressed by Ewing and Humphery approach, Forsyhe approach, Cottrel and Hall approach [53]. However, there is confusion about the crack characterization between initiation stage and birth of steady-crack propagation. Various researchers have detailed multiple techniques to numerically explain crack propagation mechanisms. The research work includes Thompson, N. [54] work, Head, A. K. [42] Law, Frost, E. and Dugdale, D. S. [35] law, McEvily, A. J. and Illg, W. [47] approach, Paris, P. C. [49] approach, Broek, D. and Schijve, J [29] approach, Forman R. G. [34] equation, Walker E. K. [56] method & Crichlow's W.J. approach [57]. These methodologies ascertain factors that account for stress intensity to relate with aircraft structural geometrical tediousness and have numerically correlated the calculated factors with crack propagation rate in the structural components.

2.4. DETECTABILITY OF IMPACT DAMAGES

The composite structure impact damage tolerance depends mainly on strength reduction from impact , achieving 50-75% of in-situ strength [25], [28]. It suggests that the impact energy has a direct relationship with structural damage and inverse relationship with residual strength. However, the detectability of the impact depends upon impact energy and there is a direct relationship between the two. Furthermore, the damage impact is first inspectable visually from the non-impacted side (interior of the wing-box, fuselage etc.) which is inaccessible, rather than the loading side [28]. Thus, the crack visibility from the loading side of composite laminate is generally considered, as illustrated in Figure 2.2.

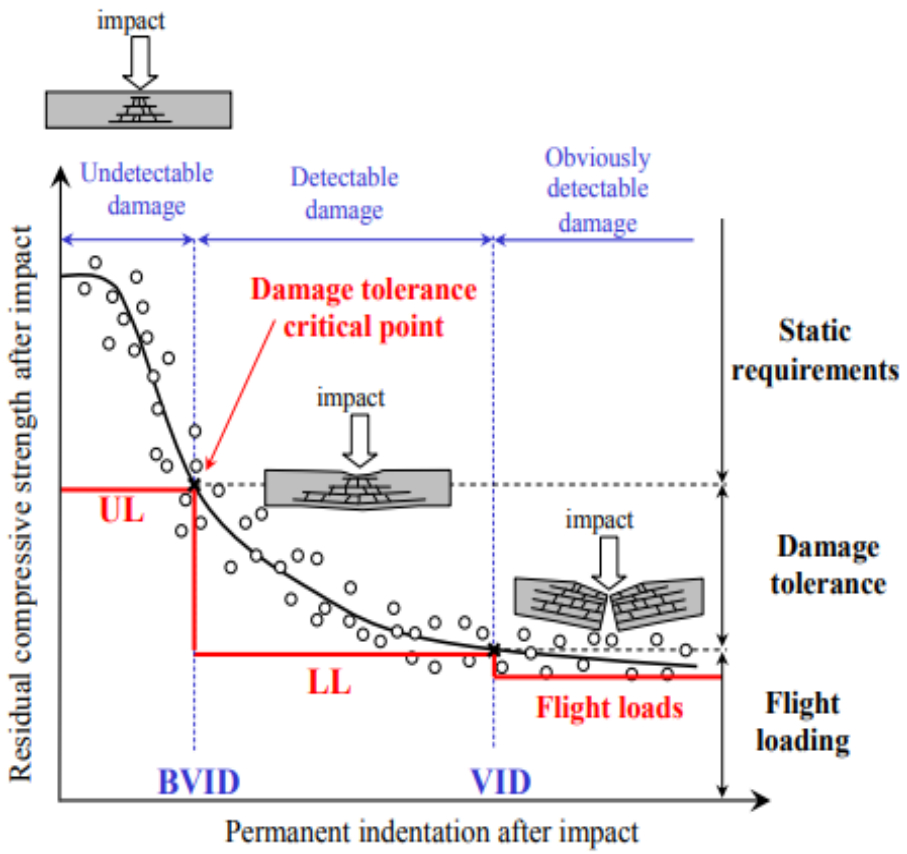


Figure 2.2: Residual strength after impact and detectability of impact [28]

Figure 2.2 graph defines the limits of damage load that a composite structural component of an aircraft can tolerate. It represents a curve for residual strength versus permanent indentation after impact. The impact damage tolerance can be characterized by compressive residual strength of the composite laminate [25], [24], [31], [28]. The delamination of composite structure from impact damage generates sub-laminates having lower thickness and reduced bending stiffness, resulting premature buckling (local) under compression.

The sizing areas of a composite structure (Figure 2.2) can be defined into three explicit areas:

A. The undetectable damage area is the area of static requirements where the composite structure bears the UL and static loads dictate the structural sorting.

B. The detectable damage area is the one to bear LL and once detected, should be repaired to cope with the UL. Meanwhile, the barely visible impact damage (BVID) area is the minimum damage that can be detected using explicit visual checkup of the composite structure. The BVID area decides the sizing of a composite structural component to damage tolerance as the impact damage (producing a permanent crack) equivalent to BVID should bear the UL throughout the structural useful life span [28].

C. The obviously detectable damage (ODD) area, also called visible impact damage (VID) area, is the one that copes with fatigue loads for operational flights and normal

operational capacity. It is the minimal damage area that can be identified with standard visual inspection. The ODD area must be replaced / repaired as early as detected. A general value of 2 mm indentation / crack is employed for describing the VID with 90% probability [50], [52].

2.5. IMPACT DAMAGE TOLERANT STRUCTURE DESIGN APPROACH

Figure 2.3 flowchart represents design methodology for acquiring impact damage tolerant structure. The flowchart can be used as a guideline to sustain impact damage tolerant design for composite aircraft. It is viable to composite structure damage impacts from high-explosives blast effects projectiles, fragmentation, small arms projectiles etc. The target is to predict structural capability of the impacted airframe and relate with composite structural efficiency requirements, usually expressed in load factors [27].

Structural requirements are analyzed from aircraft flight loads analysis and the physical environment influencing the aircraft deterioration. The next step is to evaluate primary structural components and calculate the operating stress loads inculcating levels corresponding to operating loads during projectile impact, cyclic and maximum loads after the impact. The impact loads and the environment institute composite structural strength requirements at impact, with the residual static strength demand and the cyclic loading of the impact damage structure. However, structural capability demands evaluation of the size and severity of the impact deterioration on the composite aircraft [27].

The factors influencing structural endurance involve damage size, type of exposed damaged structure and penetration effects. The inflicted damage on the composite structural part can be dominated by surrounding environment, loading conditions, and hybrid effects like hydrodynamic ram pressure from projectile flow through fuel cell liquid segment. Moreover, the damaged composed airframe may not be disconnected immediately from external impact load and will experience cycles of loading / unloading from maneuvers and gust during the flight path. The cycling loading alters the residual stiffness of the composite structure as the induced fatigue worsens the characteristics of the impact damage and net section of structural component shrinks. The stiffness deterioration can motivate instability in the aerodynamics of the structural component; Thus, the impacted airframe should have acceptable residual strength to undergo cyclic loading [27].

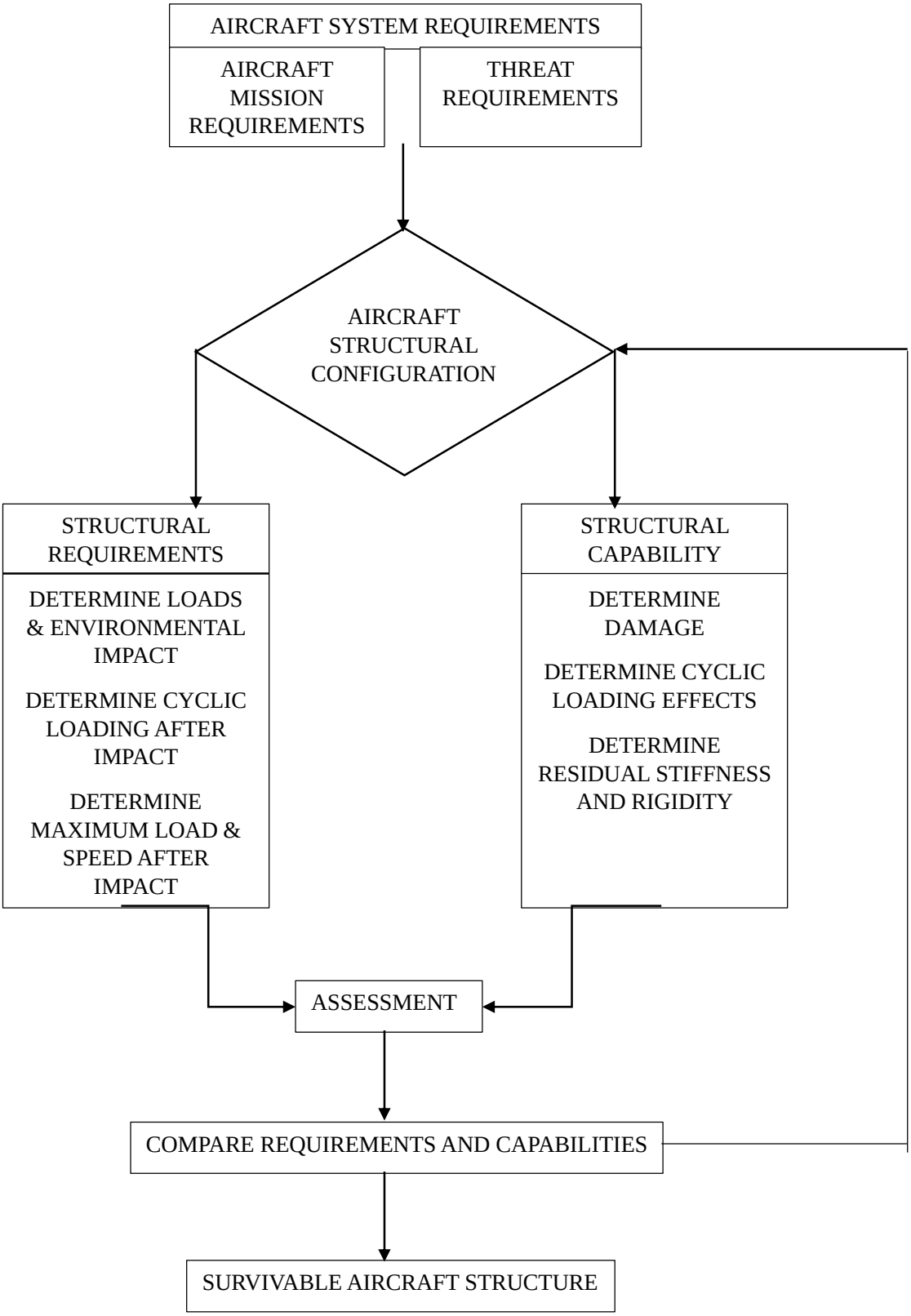


Figure 2.3 : Design strategy for achieving impact damage tolerant structure [27]

The impact damage tolerance assessment of the composite structure is represented as graph between residual strength versus time. Initially, the aircraft structure is designed at ultimate strength, but with the occurrence of impact damage and projectile penetration, there is an instantaneous strength loss. This strength reduction is the consequence of dynamic fallout, dynamic load redistribution and general forces that come in play from the projectile sudden impact with the composite structure [27].

2.6. ACCEPTABLE AND UNACCEPTABLE DAMAGES CRITERIA

Figure 2.4 shows the damage tolerance concept for composite structures unacceptable and acceptable damages using residual strength versus time graph. The inspection intervals (generally the detail provided by aircraft manufacturer) must be detailed to ensure reduced damage propagation earlier than aircraft damage detection. The shortest interval is the time between detectable damage and critical damage. The structural residual strength should be higher than the LL and inspection interval is kept minimal below UL. Initially, the residual strength remains uniform through time. With damage propagation, the residual strength reduces approaching the LL [28].

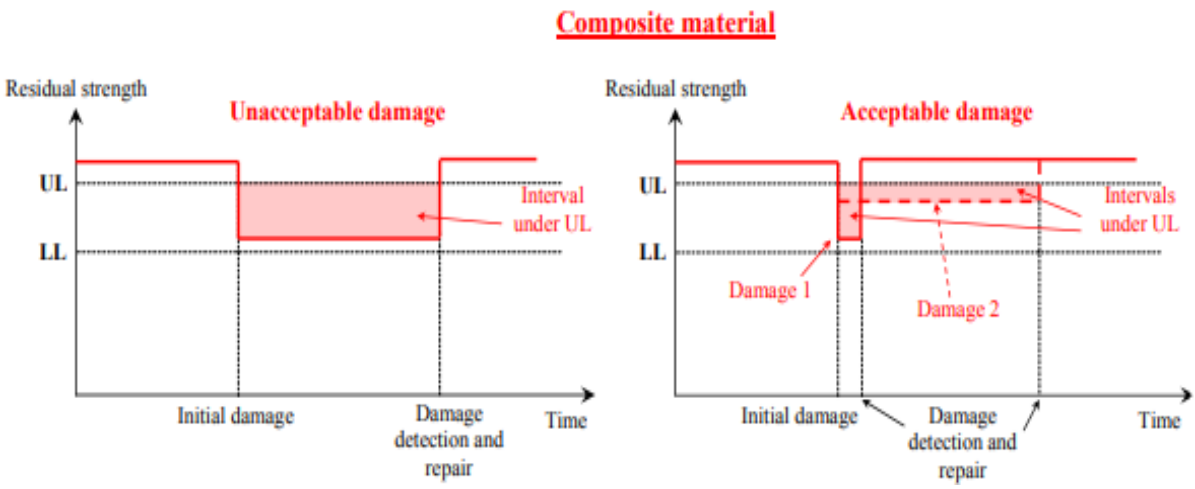


Figure 2.4: General principle of damage detection and repair in composite materials [28]

However, composite materials are unresponsive to fatigue damage [50]. Carbon fiber composites remain insensitive to fatigue loading cycles, while glass fiber composites show little tendency towards fatigue damage [26], [28]. Thus, the intensive load bearing primary and secondary composite structural components of an aircraft are usually based on carbon fiber composites and boron fiber composite.

Since the slow crack growth concepts are not viable with composite structures like metallic parts, it is hard to fix intervals of maintenance (Figure 2.4). However, composites are very sensitive to impact loading that can significantly deteriorate the residual strength below the UL.

The critical factors are the time interval below UL (Figure 2.4) and the disparity of the UL and residual strength [28]. .

The last part of the design analysis (Figure 2.3) is the fair comparison between the structural capabilities and its sustainable requirements. This is schematically visualized using strength versus time (capability) curve, which is set side by side with stress versus time (requirement) curve for a composite aircraft primary structural component. Usually, the projectile impact reduces the strength capability of composite laminates to some extent, but it sustains higher than the strength requirement [27].

2.7. SIZING FOR IMPACT DAMAGE TOLERANCE

Composite structures have complex sizing issues as the damage impact and detectability must be contemplated together. However, the damage impact on composite structures is not uni-dimensional and compressive stresses are accompanied with shearing stresses that impact the composite structural residual strength. Especially in the case of composite structural delamination from impact damage where shearing stresses contribute to the buckling and composite characteristic losses. However, shear tests are complex for practical purposes. The simple model used for shear / compression strain fracture criteria is illuminated in equation 2.1:

$$\sqrt{\left[\left(\frac{\varepsilon_l^{comp}}{\varepsilon_l^{res}}\right)^2 + \left(\frac{r_{lt}}{r_{lt}^{res}}\right)^2\right]} \leq 1 \tag{2.1}$$

Since the damage impact has no aftermath on the tensile strength of composite structure, the model consolidates ε_l^{comp} as the compressive strain, ε_l^{res} as longitudinal residual strain and r_{lt}^{res} as longitudinal shear strain. The characterization of residual strains after damage impact is extremely costly necessitating big data set of experiments and relative to impact energy, composite material, stacking sequence etc. [28].

The optimization of composite structural components to damage tolerance is tedious. The problem lies when establishing and optimizing the co-relation between the structural residual strength (depending on thickness) and detectability of the impact. If the thickness of the structure is increased to improve the structural capability to resist impact loads, the impact indentation becomes invisible, contradicting the composite strength to impact damage tolerance. Thus, the advanced numerical solution of the composite impact damage and compression after impact behavior of composite laminates is challenging and worldwide studies are being carried out to resolve the problem [39], [51], [55], [30]. The numerical modeling of composite laminates can assimilate residual strength and compression dents for

composite structures utilizing graphs with variables such as composite material, thickness, stacking sequence etc. Thus, the required impact damage tolerant composite structure can be designed. However, the reliability of the graphs is restricted to particular impact types and structures [28].

The first numerical models to assess structural crashworthiness were launched in 1989 [33] Since then, there are continuous improvements in the numerical modeling technology to attitudes such as specific energy absorptions, delamination techniques [36], force versus displacement graphs as assessed experimentally, and prompting mechanisms [46] to assess crash cytology. However, the numerical modeling competence to characterize initiation and development of a crushing mode is still narrow [44]

The numerical simulation is characterized by modeling scales options such as macro-scale models and micro-scale models. The macro-scale models [37], [58] cannot characterize impact damage mechanisms at sub-ply level. The micro scale models are restricted to small composite structures only as impact damage physical parameters are difficult to acquire and computation is temporally complex [44]. Between the two, the meso-scale approach can better characterize the impact damage mechanisms of composite structures [45].

Israr et al. [44] articulates a meso-scale numerical modeling strategy of carbon fiber reinforced plastic laminated plates ($0^0/90^0$) exposed to crushing mechanisms (low-velocity), integrating experimental tests dataset to the numerical model. The primary characteristic of the numerical model comprises of laminate ply meshing, characterization of ply splaying and delamination employing cohesive elements, macro-scale parts simulation, plies localized crushing characterization at their end nodes conceptualizing the free face crushing, and the characterization of intra contacts between plies, plies versus debris and plies versus impacted base. The Abaqus explicit mode simulation can analyze the impact force, failure systems and good correlation between experimental and numerically simulated results. The results illustrate that the localized crushing in the 0^0 plies during repartition of absorbed energies is the most potent mechanism as it is the majority stake holder out of the total energy release. Thus, the numerical modeling strategies are capable of performing crushing mechanisms simulation to composite laminates and are being employed to develop advanced composite structural components in the aviation sector.

THIS PAGE WAS INTENTIONALLY LEFT BLANK

3.1. INTRODUCTION

In the early development years of aviation to reap advantages of lightweight structural components, the non-structural parts (secondary structures) of the aircraft were tested with composite structures, mostly sandwich configurations. These non-structural composite parts do not disrupt the flight operations of the aircraft during failure simulations. The secondary composite structures initially included fiberglass floors, aircraft interiors, galleys, sidewalks, and baggage confinement area [60], but later replaced with boron epoxy and carbon fibers. With the advancement in composite technology, these structural components expanded to ailerons, flaps, rudders, and spoilers without compromising the aircraft structural integrity [61]. Once the secondary composite structures prove reliable, the aircraft industry authorizes primary structural parts built out of composites, involving wings, fuselage barrels, and stabilizers [61].

3.2. BOEING COMMERCIAL AIRCRAFT

The Boeing commercial aircraft are utilizing composites at increased proportions over time as shown in Figure 3.1. The Boeing 747 conducted its first flight in 1969 and utilized 1% composite materials in the manufacturing process. The aircraft utilized fiberglass and Nomex honeycomb structures in the leading and trailing edges of the wing surface. Over the course of time with improved understanding of composite materials, introduction of new manufacturing technologies and breakthrough in the testing and certification process, the proportion of composite materials have reached 50% in Boeing 787. The civil aircraft successfully tested with secondary composite components include Boeing 707, DC-9 etc. and primary structural parts in Boeing 737, Boeing 777 and Boeing 787. The details of the composite structural parts integrated with Boeing commercial aircraft series are depicted in Figure 3.1 as percentage of composite materials per gross structural weight of the aircraft; and the composite structural components are listed in Table 3.1.

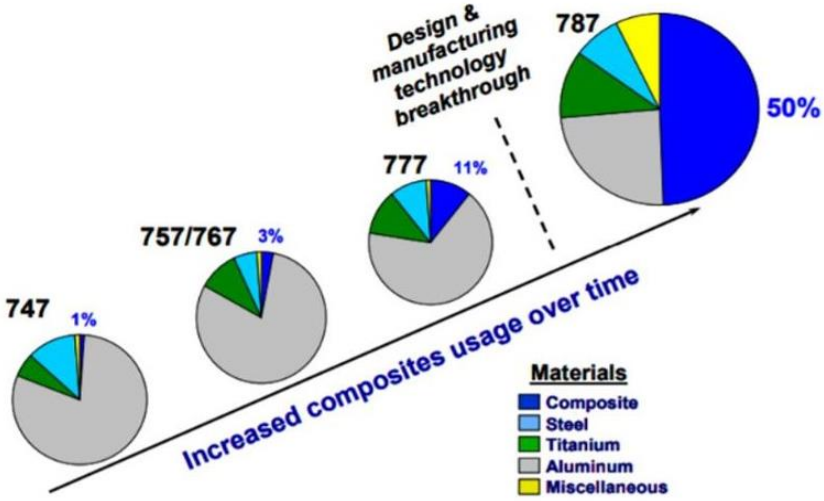


Figure 3.1: Increased composites usage over time in aircraft manufacturing [61]

The 787 (Dreamliner) has successfully implemented carbon composite fabrications in its primary / secondary structural components including carbon fiber epoxy laminate configured stabilizers, fuselage section, wing box, elevators, rudder, winglets etc. [61] as illustrated in Figure 3.2. The aircraft comprises of 50% composite materials, which is a breakthrough in the utilization of advanced composite structural components in the commercial aviation business.

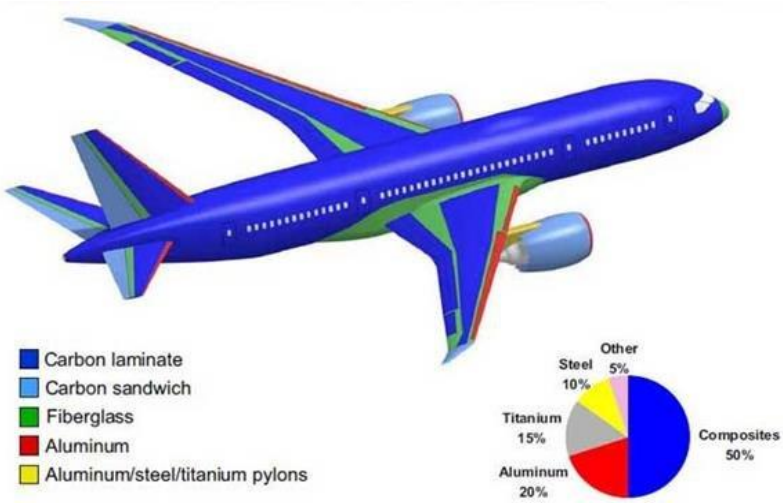


Figure 3.2: Boeing 787 configuration [61]

3.3. ATR COMMERCIAL AIRCRAFT

The ATR series aircraft build by French EADS and Italian Alenia Aeronautica have successfully implemented the idea of composite structural components in an aircraft. The ATR 42 utilized carbon / Nomex sandwich structure, carbon monolithic structure, Kevlar / Nomex sandwich, stiffened carbon plies and fiberglass / Nomex sandwich in mostly secondary structural components of the aircraft as shown in Figure 3.3. It led to the evolution of ATR 72 which is considered a breakthrough in the usage of Carbon composites, as it is the first civilian

aircraft to possess carbon composite wing box and composite sandwich secondary structures with carbon, glass and Kevlar skins as shown in Figure 3.4 [65], [59].

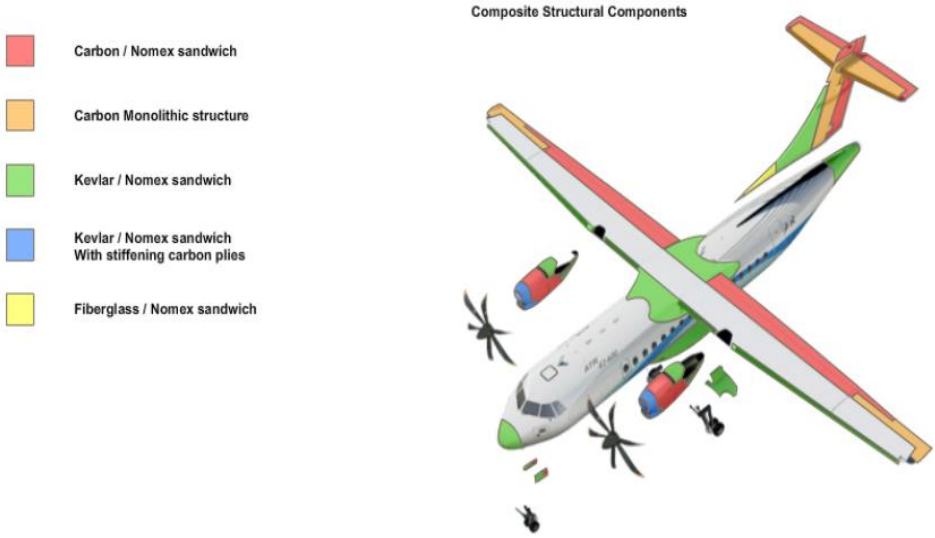


Figure 3.3: ATR 42 Composite Configuration [65]

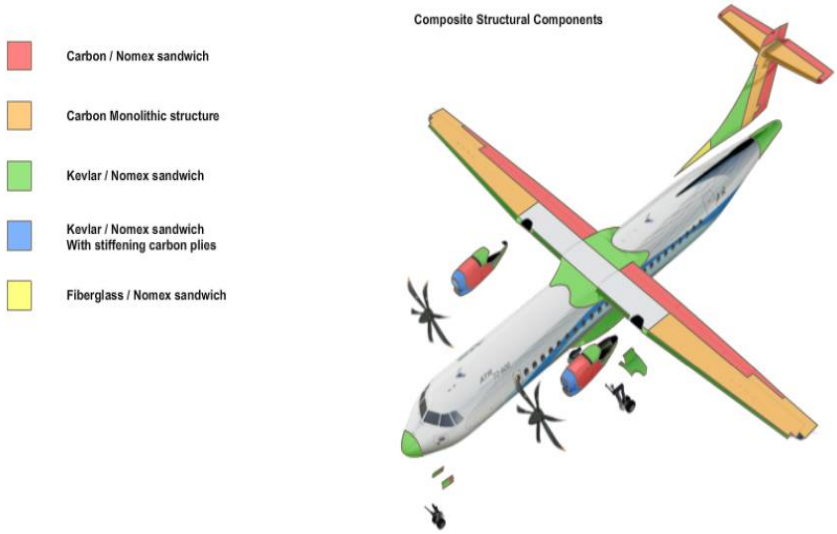


Figure 3.4: ATR 72 Composite Configuration [65]

3.4. AIRBUS COMMERCIAL AIRCRAFT

The Airbus A320, A330, A340 and A380 series aerovehicles have successfully implemented and revolutionized advanced composite structural components in secondary structural parts and increased usage in primary structures. The purpose is to enhance the reliability and integrity of the commercial aircraft and simultaneously reduce manufacturing, operations and maintenance expenditures. Since, the extraordinary mechanical properties of composite materials offer hundreds of applications in the commercial aviation business and deeply impact the futuristic trends of next generation aircraft. The A380 jumbo jet is considered one of the most advanced

aerovehicle in the aviation business for its pertaining to its cost-benefit ratio for inter-continental commercial transportation system. The aircraft comprises of carbon fiber reinforced polymer (CFRP) composite wing box. Almost 22% of the entire aircraft body consists of composite materials as shown in Figure 3.5, resulting in a weight reduction of up to 1.5 tonnes as compared to aluminum alloys [66].

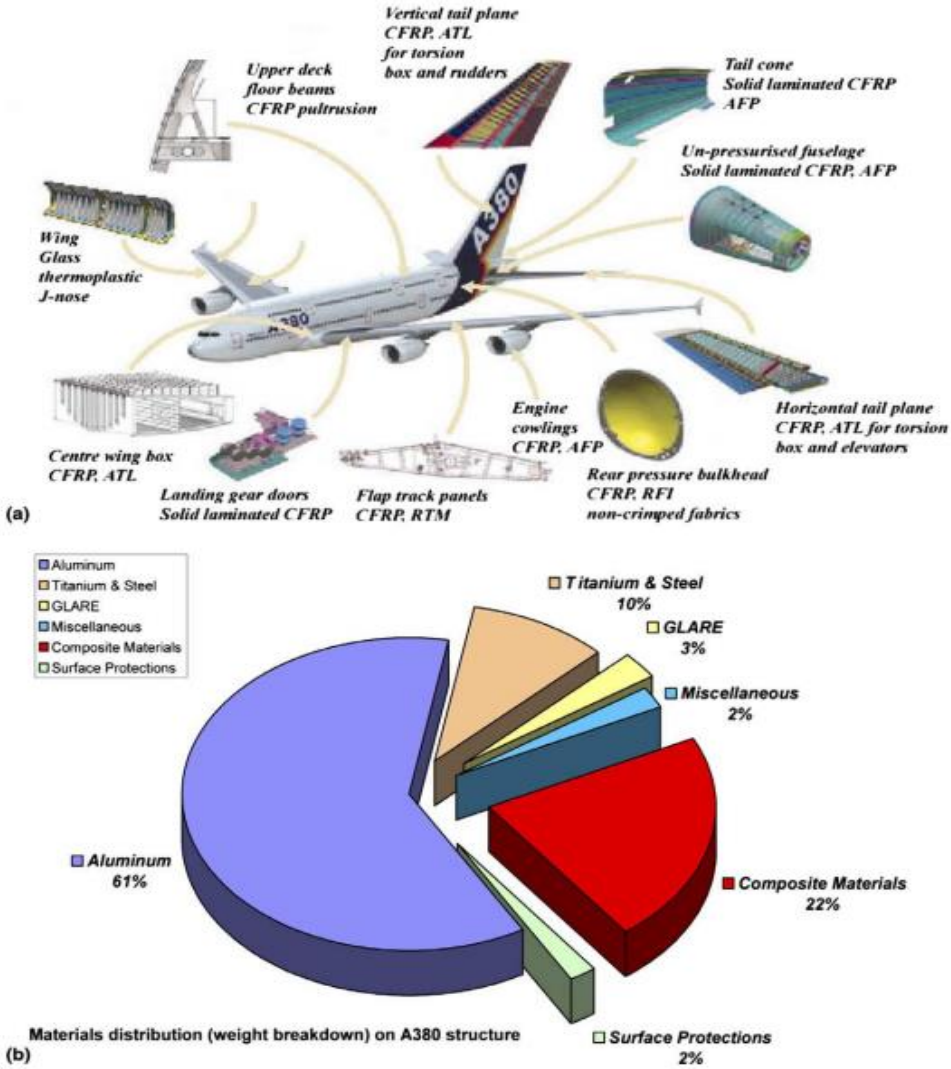


Figure 3.5: A380 composite structural configuration: (a) Thermoplastics and CFRP. (b) Weight percentage chart [66].

The advanced composite manufacturing techniques for A380 including resin film infusion, resin transfer moulding, automated fiber placement (AFP), and automated tape laying (ATL) have refashioned the composite structural components manufacturing process to be easy, reliable, cost and time efficient. The aircraft also incorporates GLARE composite material for enhancing corrosion and fire resistance, along with laser beam welding (LBW). GLARE composite material is a compound of aluminum foils alternating overlapping layers with unidirectional glassfiber placement [66]. The more advanced composite components with

enhanced composite structural applications are being conceptualized for B7E7 Dreamliner, increasing the economic competitiveness of the next generation aerial vehicles.

A brief table summary of composite structural components utilized in typical commercial aircraft is represented in Table 3.1.

Table 3.1: Composite built structural components in commercial aircrafts [66]

Commercial Aero-vehicles	Composite Structural Parts
Airbus 300	Pylon fairings, Wing cover panels, Radome
Airbus 310	Rudder, Pylon fairings, Apron, Fin leading, Spoiler
Airbus 320	Horizontal tail-plane, Stabilizer, Fin
Airbus 330	Pressure bulkhead, Flaps, Control lever, Empennage, Floor beam
Airbus 340	Cockpit furnishing, Flaps, Control lever, Empennage
Boeing 737	Elevator, Aileron, Rudder surface
Boeing 747	Nacelle parts, Winglet, Fairings
Boeing 757	Thrust reverser, Control surface, Block doors, Landing gear door
Boeing 767	Empennage, Horizontal stabilizer, Exterior surfaces
Boeing 777	Horizontal stabilizer, Rudder, Control surface, Fuselage side panel

3.5. ELIXIR AIRCRAFT

More recently, the development of Elixir light aircraft has been a big success for the aircraft carbon composite industry. Elixir is a two-seater commercial aircraft intended for private pilots and flying clubs. The aircraft has monoplane structural features (as shown in Figure 3.6) where the major parts are manufactured in one-shot and assembled efficiently with a smaller number of components. Moreover, the structural part reduction reduces the overall structural complexity, weight, and enhances the safety of the aircraft [59].

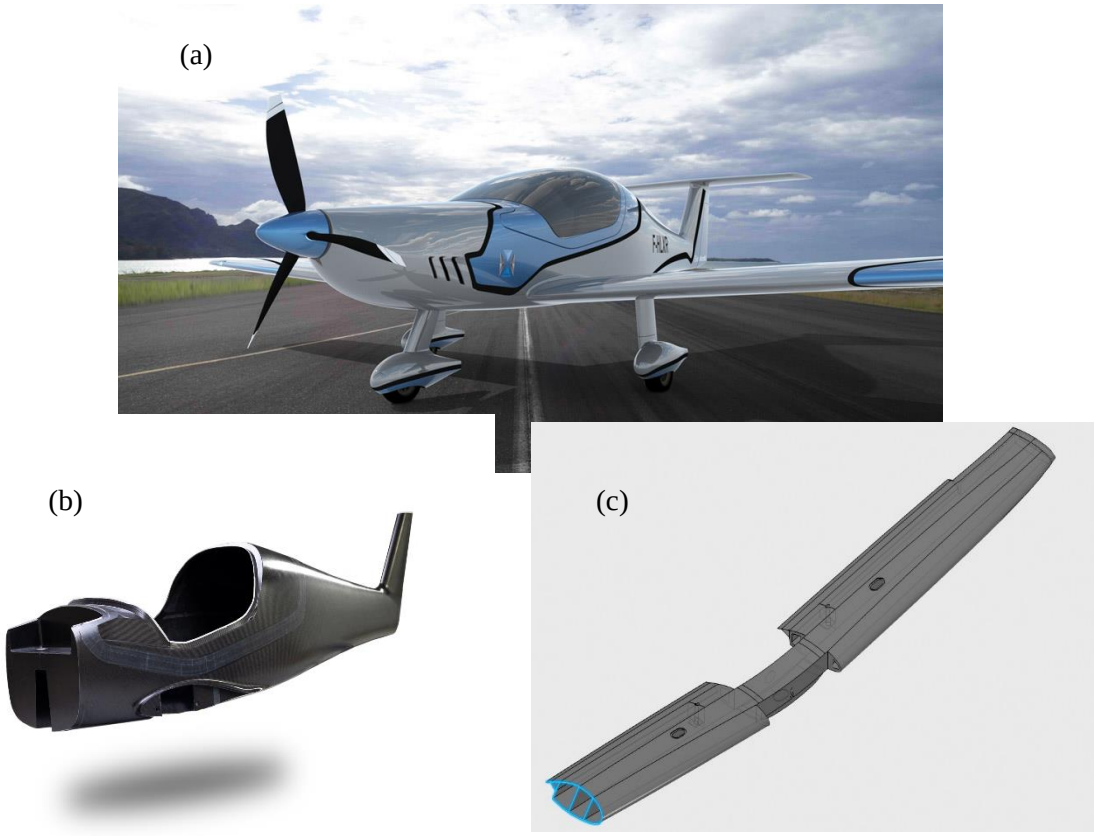


Figure 3.6: (a) The Elixir (b) One-shot fuselage (c) X-sec view of wing

3.6. COMMERCIAL HELICOPTERS

Helicopters have adopted composite rotor blades for nearly half a century. The composite helicopter blade has longer lifespan than the metallic blade and provides better economic option in the longer span-life of the aircraft. In the 1970s, the Ecureuil Helicopter proved its potency as viable civil application helicopter and accommodates composite rotors. The Eurocopter EC-155 Dauphin helicopter (since 1997) was evolved with 60% composite parts and with primary structure consisting of Nomex honeycomb structures [59]. It is depicted in Figure 3.7.

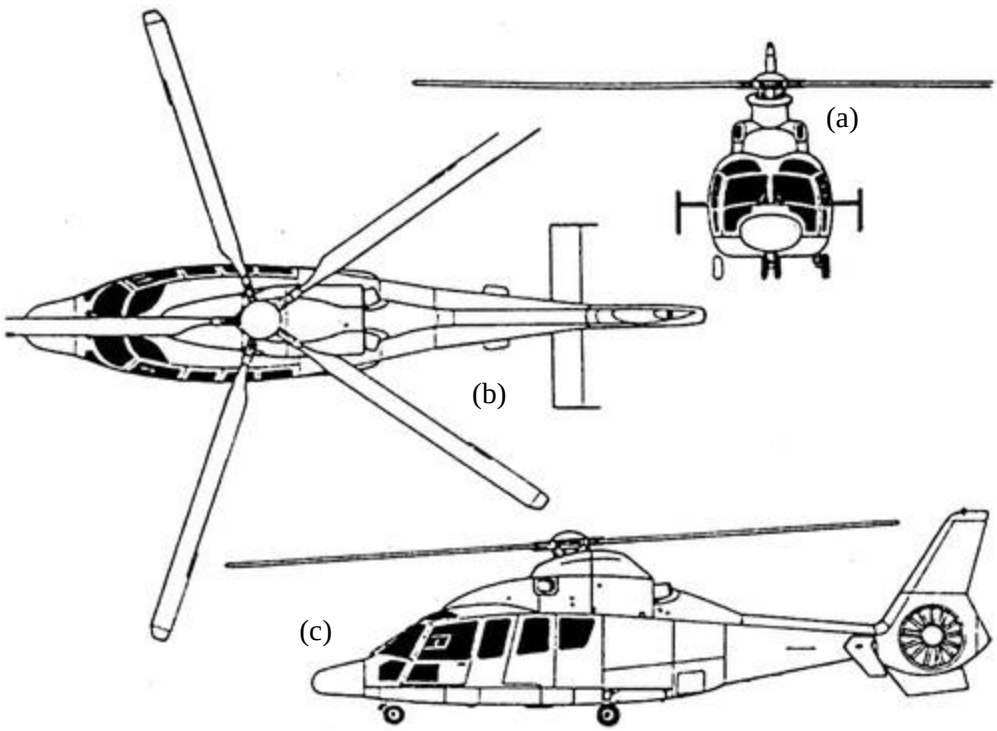


Figure 3.7: EC-155 Dauphin (a) Front view (b) Top view (c) Side view

Currently, the modern helicopter design encompasses an entire helicopter frame based on advanced composite materials, which reduces both dead weight and operating cost of the helicopter. The XE series helicopter (since 2004) manufactured by Composite-FX is an example of a single seat light weight composite helicopter, known as Mosquito. The helicopter possesses rotor head with bearing capacity of 4X centripetal force. The airframe is completely composite with E-glass in vinylester matrix and 62 lb. monocoque fuselage. It is easy to maintain, has low-cost operation per hour and the time between overhauls cost is $10 / hour @ 500 hours. In general, the evolution of composite parts in the helicopter industry has caused 15 to 55% weight loss and 30 to 80% cheap [62]. A typical XE series helicopter is depicted in Figure 3.8.

Figure 3.8: Mosquito Aviation XE series helicopter

3.7. SPACE AVIATION

The use of composites has found their way into the commercial spacecraft industry. The development and construction of Starship, a heavy lift launch vehicle used carbon composite structures to resist cryogenic temperatures for the starship prototype in 2018 [64]. However, the high cost of carbon composite material led to the change of structural materials for the Starship prototype to stainless steel, as it has low maintenance and manufacturing cost [63]. The SpaceX starship was finally launched in November 2022, having a length of 120 m, weighing 5 million kilograms, reusable and an estimated cost of 2 million dollars per launch (according to Elon Musk). In comparison, NASA launched SLS rocket in the same month of November 2022 with a height of 98 m, weighing 2.5 million kilograms and costing 4.1 billion dollars per launch. There significant cost difference is owing to the research and development in the evolution of hybrid composite materials for commercial space industry, that will be a game changer for the space travelers in future.

National Aeronautics and Space Administration (NASA), U.S.A. actualized the first utilization of composite structural components in the space aviation industry. Fiberglass honeycomb structure with phenolic epoxy resin structured the Apollo mission heat shield [67], as shown in Figure 3.9. Currently, NASA is working on Space Launch System (SLS) to explore deep space beyond the Earth orbital gravity. Interestingly, the SLS rocket structure comprises of sandwich structure in which core consists of honeycomb structure made of aluminum and carbon fiber face sheets veil the honeycomb core, to produce 8 meter diameter composite fairings and larger structural rocket parts. The automated fiber placement head enables precise carbon fiber patterns structuring of any size / shape. A cork layer on the exterior enhances structural heat resistance against the expected post-launch frictional heat. An additional layer of composite paint ensures moisture absorption resistance and heat reflection mechanism. The sandwich construction is shown in Figure 3.10.

Figure 3.9: Heat Shield of Apollo Mission Rocket [67]

Figure 3.10: Sandwich structure comprising of external cork layer, carbon fiber face sheets and aluminum honeycomb core [67]

The same material concept is being utilized for Atlas V launcher program and Vulcan program. Other space agencies like RUAG from Zurich, Switzerland have heavily invested on the composite manufacturing facilities for space aviation and the launch of next generation space program. The RUAG has a manufacturing facility in Alabama, U.S.A. where composite structures are being manufactured for Atlas V rocket and Vulcan program as shown in Figure

3.11. The facility delivers carbon fiber based composite structural components for Atlas rockets and development of Vulcan launcher program. The manufacturing process is explained in [67]. Thus, the evolution of next generation space programs primarily utilizes the advancements in the field of composite structures. Moreover, RUAG has started hot bonding technique for Vulcan program structural joints, getting rid of metallic fastener joints, resulting in reduced weight and enhanced payload capacity.

Figure 3.11: Composite Payload fairings (halves) production facility, RUAG Plant, Decatur, Alabama, U.S.A.

Hence, the adoption of composite material is the future of global space aviation industry that will allow the launch of large space telescopes, cargo missions and crewed missions to moon, mars and beyond.

4.1. PRE-FOURTH GENERATION AIRCRAFT

4.1.1. MORANE – SAULINER 406

The usage of composite structural parts in military aircrafts dates to the 1930s with the conception of wooden sandwich structural components. A French interceptor fighter jet 'Morane -Saulnier 406' used plymax wings in 1935, where the sandwich wing structure composed of okoume plywood core and aluminium face sheets. This type of sandwich composite structural configuration is useful for compression after impact qualities [68], [59]. The aircraft is depicted in Figure 4.1.

Figure 4.1: Morane - Saulnier 406 fighter aircraft.

4.1.2. Havilland Mosquito DH-98

The DH 98 also known as de Havilland Mosquito is a World War 2 bomber aircraft that operated with Allied powers. The plane's structural components are composed of configured wooden pieces, plywood and bonding glue reinforced with screws. Plywood box-spars, ribs and stringers composed the aircraft interior and exterior leading edges and flaps. The birch plywood skins on the top and bottom of the mainframe, reinforced with stringers increased the frame strength [69]. The fuselage was completed in one-shot to save cost while the aircraft is considered as a pioneer of modern composite based aviation industry [59]. The aircraft performed excellently during and post-World War 2 era with a top speed of 415 mph, range 1955 miles and ceiling height of 42000 ft. The aircraft remained in service with British and international air forces after the war and used as bomber / reconnaissance aircraft. It is shown in Figure 4.2.

(a) Fuselage (b) Operational bomber

Figure 4.2: de Havilland Mosquito DH98.

4.1.3. CONVAIR B-58

The Convair built B-58 bomber is a composite lightweight supersonic aircraft, tested in 1956 for USAF with the maximum cruising speed of Mach 2.4 and the structure comprises of 0.24 percent of the airframe gross weight. The bomber aircraft set new records of excellence at the time of its operations for the United States military and there are still 8 operational units with USAF. The B-58 wing-box consists of honeycomb core sandwich structure with fiberglass cloth, phenolic resins and 1 mm thick duralumin alloy top and bottom skins [70]. The sandwich structure was cured at 175 psi, 177^0c and 2 hours of period. This resulted in ultra-light, stiff and strong bomber aircraft capable of carrying nuclear and conventional warheads. It is depicted in Figure 4.3.

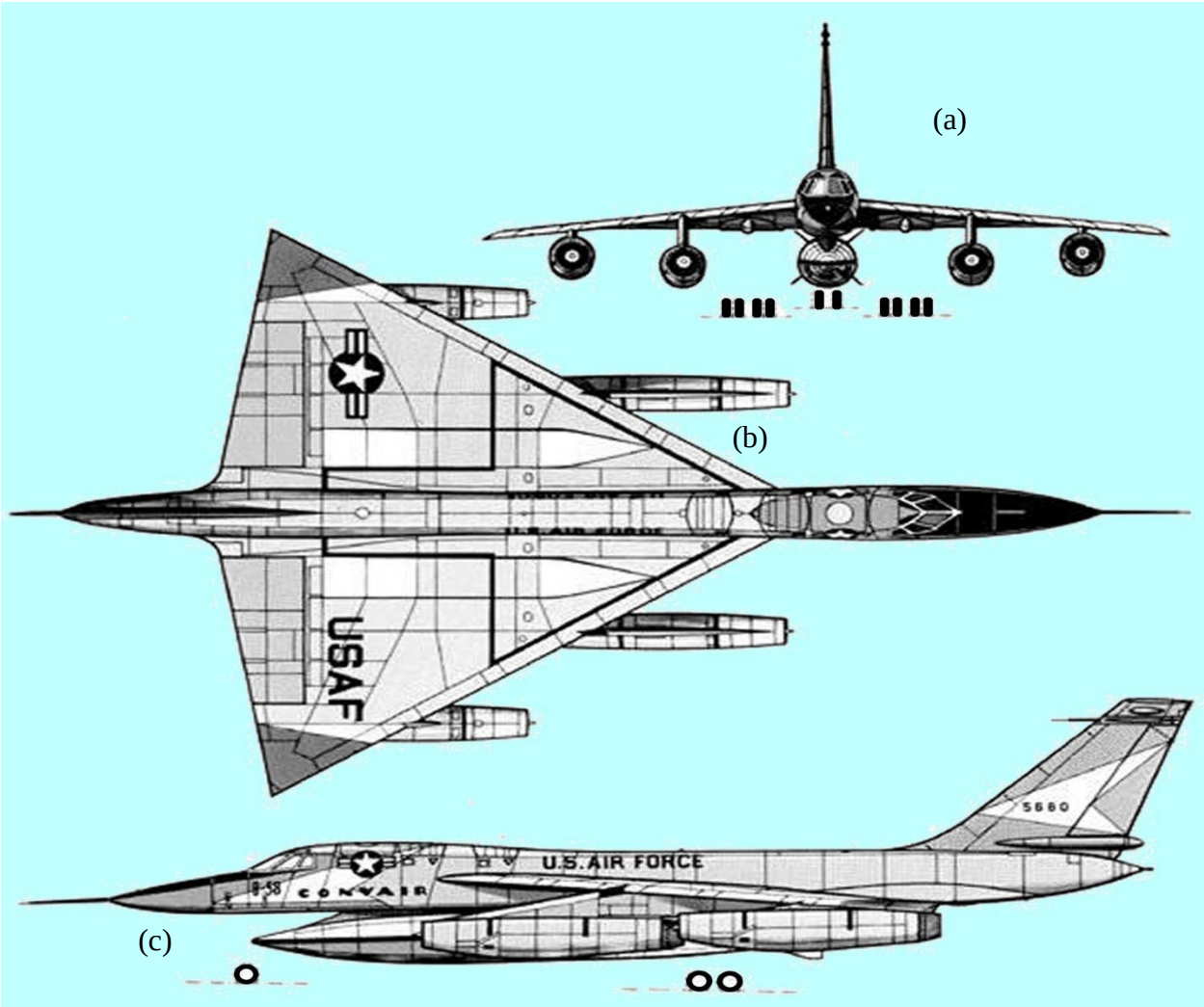


Figure 4.3: B-58 (a) front, (b) top and (c) side view.

4.1.4. VALKYRIE XB-70

The North American Aviation agency tested Valkyrie XB-70 fighter jet in 1964. The aircraft was intended as nuclear bomber that could carry up to 14 nukes. However, the introduction of SAM air defense systems with Soviet Union and shooting down of U-2 plane led to the cancellation of the program. The aircraft could attain supersonic speed of Mach 3 during flight test, ceiling height of 70000 ft and utilize composite honeycomb sandwich skin with stainless steel and titanium [71]. Only 2 protypes were produced for research purposes and the project led to the development of brazing alloys. The lessons learnt from Valkyrie program, depicted in figure 4.4 led to the development of Concorde supersonic aircraft program, the configuration and historical details of Concorde rudder are detailed in [72], along with Apollo and Saturn space vehicular missions [59].

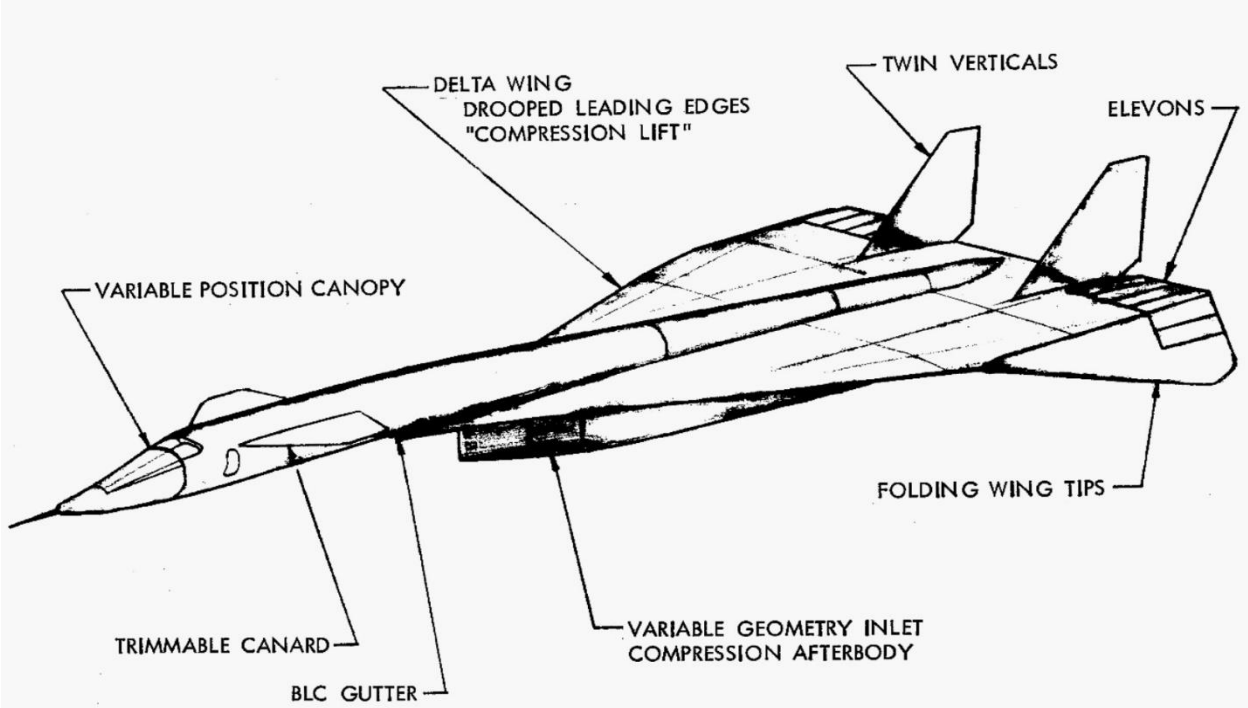


Figure 4.4: XB-70 Valkyrie Supersonic bomber configuration

4.1.5. F-14 TOMCAT

The Grumman F-14 Tomcat horizontal stabilizer consists of honeycomb core made up of aluminium with epoxy / boron skin as shown in figure 4.5. However, most of the aircraft is composed of aluminium while heavy loading structural parts like landing gear and wing-box are composed of steel and titanium [74].

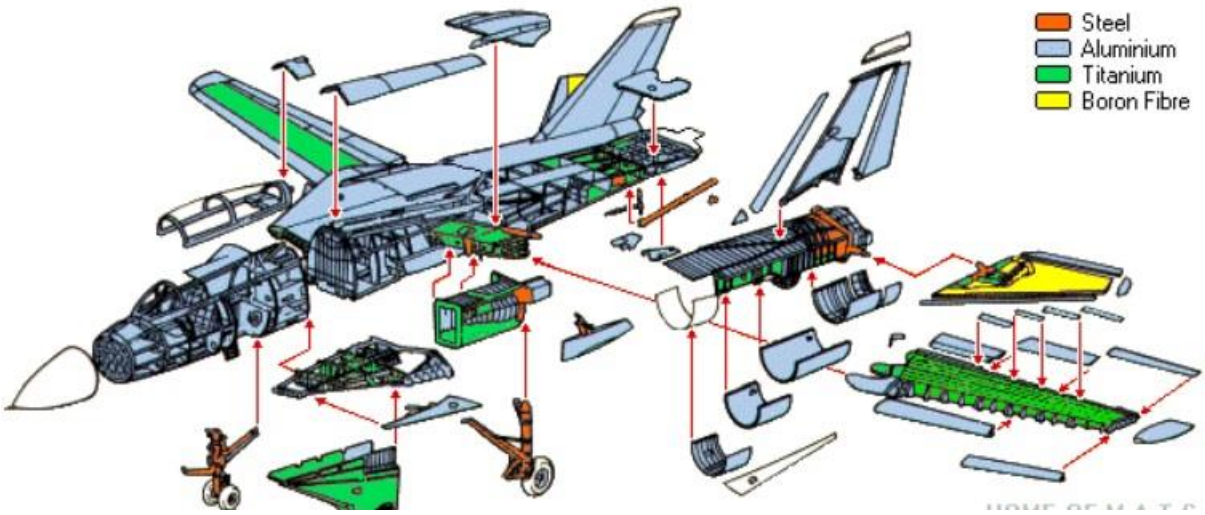


Figure 4.5: F-14 Tomcat configuration [74]

4.1.6. MIRAGE F-1

The Dassault Mirage F-1 fighter jet possesses carbon / boron sandwich structures on fin, rudder, elevons, main radio bay door, floating upper panel, engine door access and front gear door. The aircraft composite configuration is depicted in [59].

4.2. Fourth Generation ++ Modern Aircrafts

The modern military combat aircrafts that have utilized composite technology and are still in service in the modern-day world, are SR-71 Blackbird, General Dynamics F-16, McDonnell Douglas AV-8B Harrier II and F-15 Eagle, Boeing AH-64 Apache helicopter, Lockheed Martin F-22 Raptor and JSF F-35, Sukhoi SU-57 and many more. The need for composite structural parts in fourth and fifth generation fighter jets is owing to reduce the radial cross-section of the aircraft and achieve stealthy fighter aircrafts that can evade enemy air defense systems. Thus, all fourth generation ++ military aircraft are incorporating composite materials as fiberglass and plastics are transparent / less reflective and improve the aircraft stealth features. The details of composite structural parts utilized in the fourth generation ++ and fifth generation aircrafts are detailed in Table 4.1.

4.2.1. SR-71 BLACKBIRD

The SR-71 blackbird, manufactured by Lockheed Martin Corporation, U.S.A., mostly composes of titanium alloys. However, since the blackbird was designed to be stealthy, some of its structural side components were manufactured using composite materials like silicone asbestos, fiberglass, and phenyl silane. The composite honeycomb components were utilized for peripheral sections, vertical stabilizers, inlet spikes and chines, leading and trailing edges of the bird [73]. It was painted black to camouflage the enemy defenses and high heat emissivity. The blackbird configuration figure with composite structural components is detailed in [59].

A brief table summary of composite structural components utilized in typical military aircraft and fighter jets - fourth and fifth generation - is represented in Table 4.1.

Table 4.1: Composite built structural components in military aircrafts [66]

Military Air-vehicles	Composite Structural Parts
AH 64A	Stabilator, Lower leading-edge fairings
AV 8B	Aileron, Wing trailing edge, Flap, Wing skin,
C 17	Fairing, Tail cone, Winglet skins
F 15	Speed brake, Horizontal and vertical tail skin
F 16	Control surface, Horizontal and vertical tail skin,
F 22	Wing, Forward-fuselage frame, Fuselage, Empennage
F/A 18 E/F	Wing skin, Fuselage skin
Joint strike fighter (JSF-F35)	Engine access cover panel, Fuselage skin, Control surface, Upper wing skin tails, Inlet duct
Advanced jet fighter (AJF)	Tail stabilizer (Vertical)
Eurofighter aircraft (EFA)	Cured frames, Monocoque, Wetted area, Longerons

4.2.2. F-22 RAPTOR

The large-scale usage of composite materials in the military aviation sector aims to accomplish structural performance goals without compromising the integrity of the structure. The usage of composite materials as structural weight %age is plotted in Figure 4.6. The figure depicts that the world's most advanced fifth generation fighter jet F-22 Raptor, built by Lockhead Martin corporation, encompasses up to 38% composite materials. The fighter jet is designed as an air superiority fighter jet with 1st look, 1st shoot and 1st kill capability. According to Harris [76], the aircraft comprises of 24% composite thermoset materials, 1% composite thermoplastic materials, 16% aluminium alloys, 39% titanium alloys, 6% steel alloys and 14% hybrid materials. The aircraft fuselage is built with an amalgam of composite materials, aluminum and titanium. Monolithic bismaleimide / graphite formulate the wing skins, while wing control surfaces accommodate sandwich structure with non-metallic honeycomb core and co-cured composite skins. Both horizontal and vertical stabilizers utilize bismaleimide / graphite skins sandwich structure with aluminum honeycomb core structure and epoxy / graphite spars [76], The structural material breakdown of F-22 Raptor fighter jet is depicted in Figure 4.7, while the major design details are published in [75].

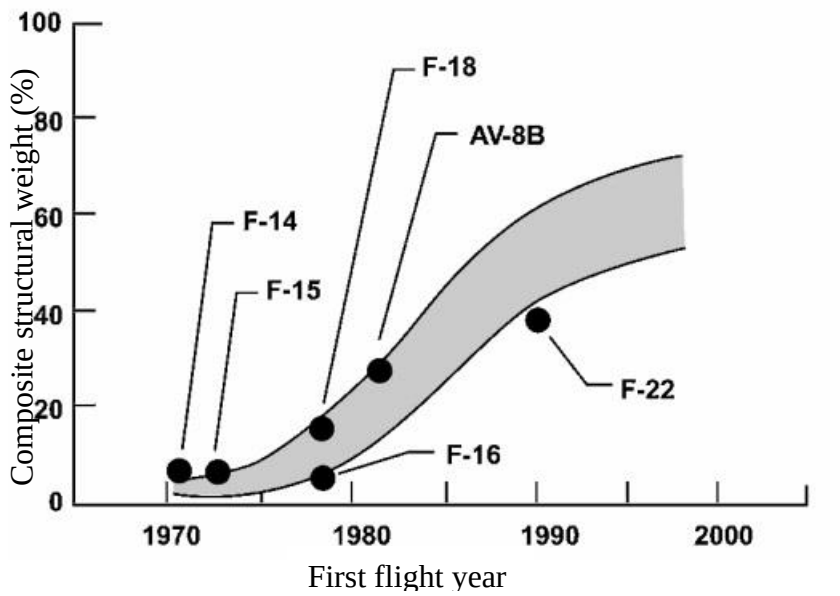


Figure 4.6: Composite structural components induction in fighter jets [76]

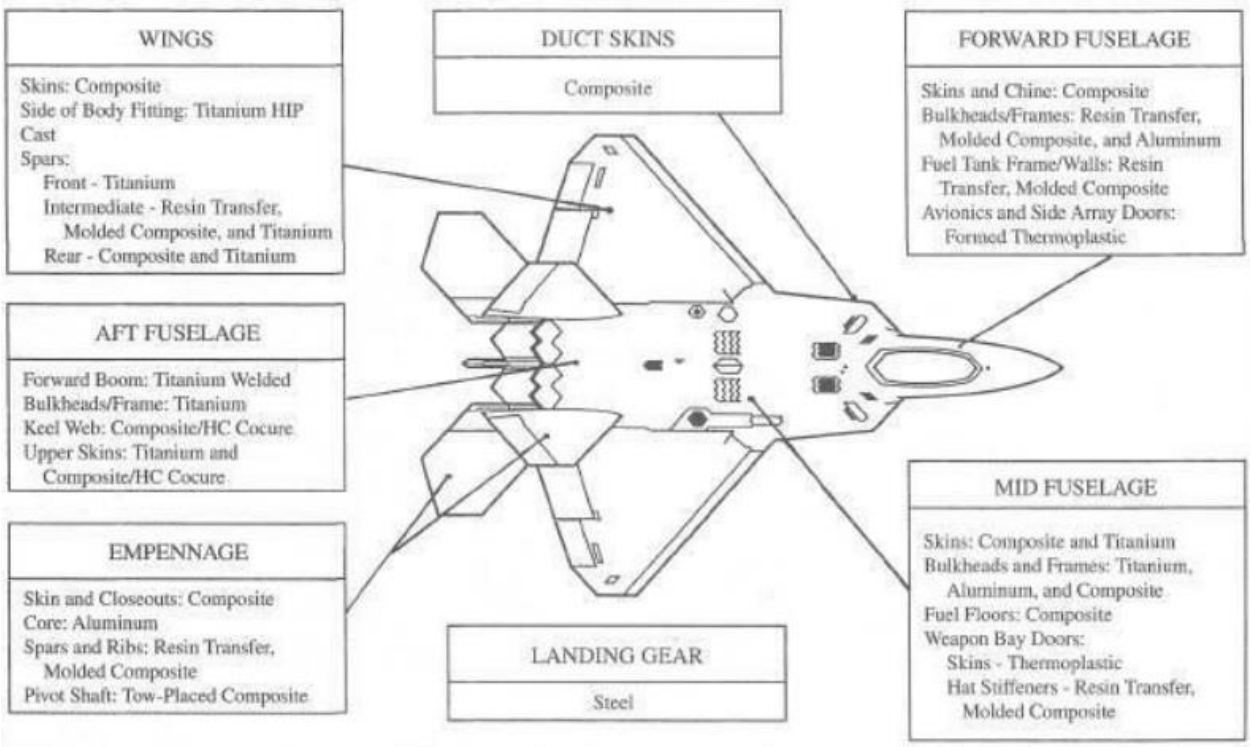


Figure 4.7: Structural material breakdown of F-22 Raptor fighter jet [75]

4.2.3. JOINT STRIKE FIGHTER F-35

The Joint Strike Fighter (JSF) F-35, also referred to as Lightening II, is the world's largest fighter procurement plan of the early 21st century. The Department of Defense, U.S.A. has ordered 2456 Lightening II aircrafts, while hundreds more have been ordered from the international program partners [77]. The JSF program is unique with three separate variants to boost air defense capabilities of all the branches of military, referred as Conventional Takeoff and Landing (CTOL) variant, Short Takeoff and Vertical Landing (STOVL) variant, and Carrier Variant (CV) as depicted in Figure 4.8.

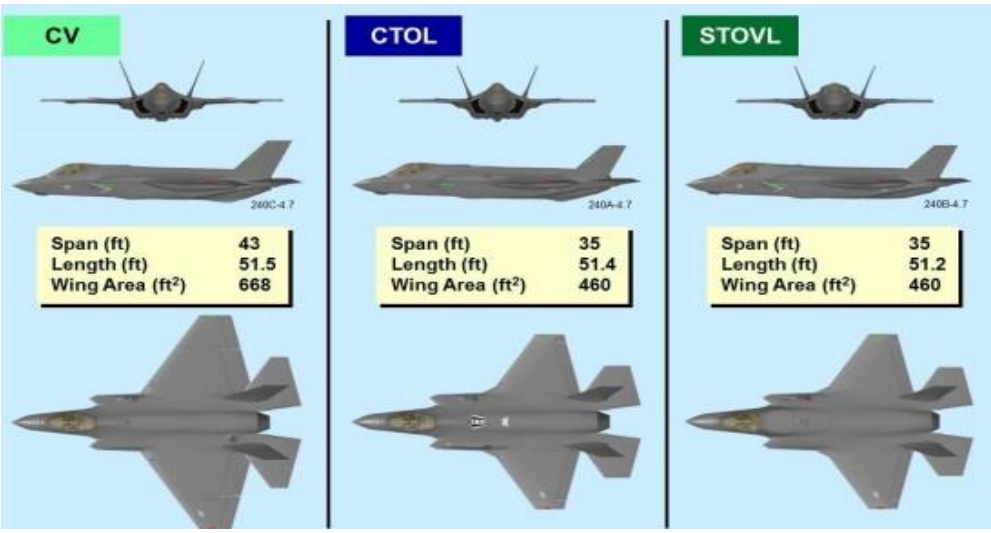


Figure 4.8: JSF F-35 Variants [78]

The JSF military program aims to produce multirole fighter platform having stealth and supersonic attributes and reduced lifecycle cost by 6 – 8 %. The program integrates advanced composite structural technologies into the aircraft manufacturing, to boost structural integrity; while keeping the aircraft light weight, minimizing the production and operational cost, and enhancing volumetric efficiencies [79].

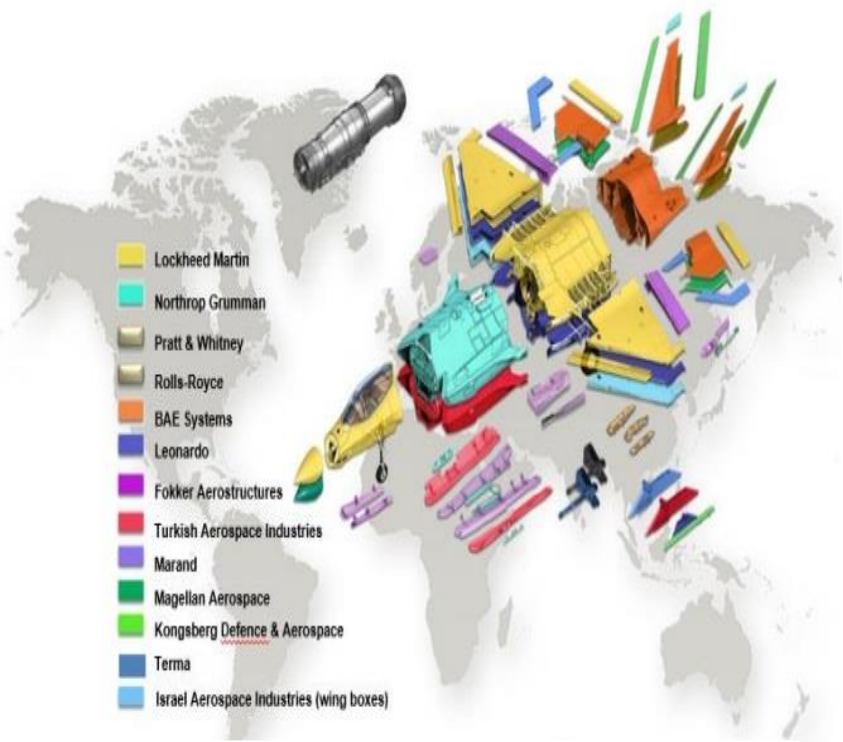


Figure 4.9: JSF international supply chain [79]

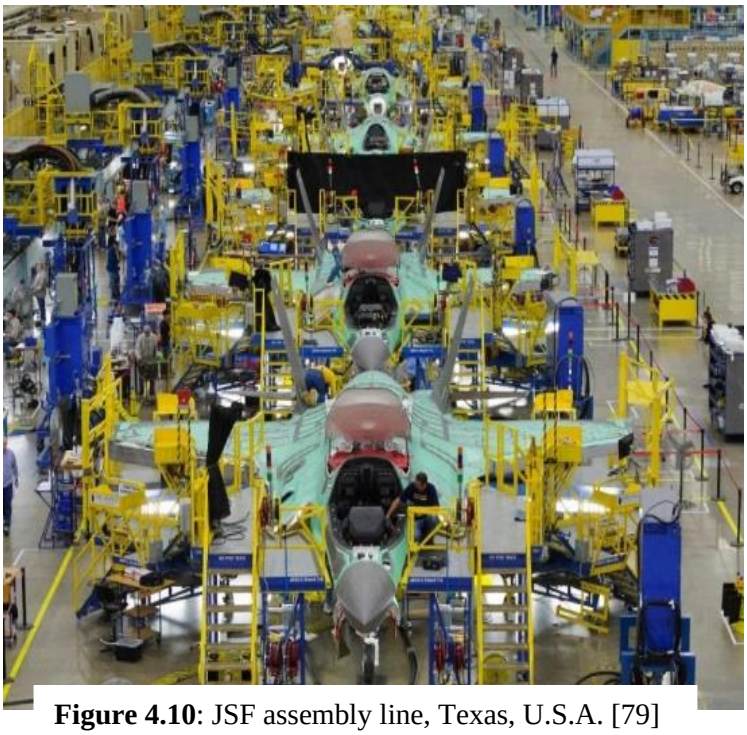


Figure 4.10: JSF assembly line, Texas, U.S.A. [79]

The composite structural components integrated into engine access cover panel, fuselage skin, control surface, upper wing skin tails, inlet duct wings, fuselage, and cockpit, constitute 35% of the gross structural weight of the aircraft. The composite materials involved are bismaleimide, carbon nanotube reinforced epoxy materials and composite epoxy materials comprising of woven glass fabric and non-woven glass core amalgamed in synthetic resin. Both the secondary and primary structural components of the aircraft consolidate composite materials to create lightweight frame wherever possible, without compromising the integrity and stealthiness. The JSF program international supply chain is depicted in Figure 4.9 and final assembly line is depicted in Figure 4.10.

The F-35 fighter jet processes a glass cockpit to improve combat situational awareness. Since the aircraft is designed for stealth, it encompasses radar absorbent materials to reduce radial cross-section (RCS) of the aircraft. Additionally, the aircraft is laced with electronic warfare suit characterizing RCS lower than metallic golf ball. The aircraft incorporates advanced propulsion systems and modern composite technologies as depicted in Figure 4.11.

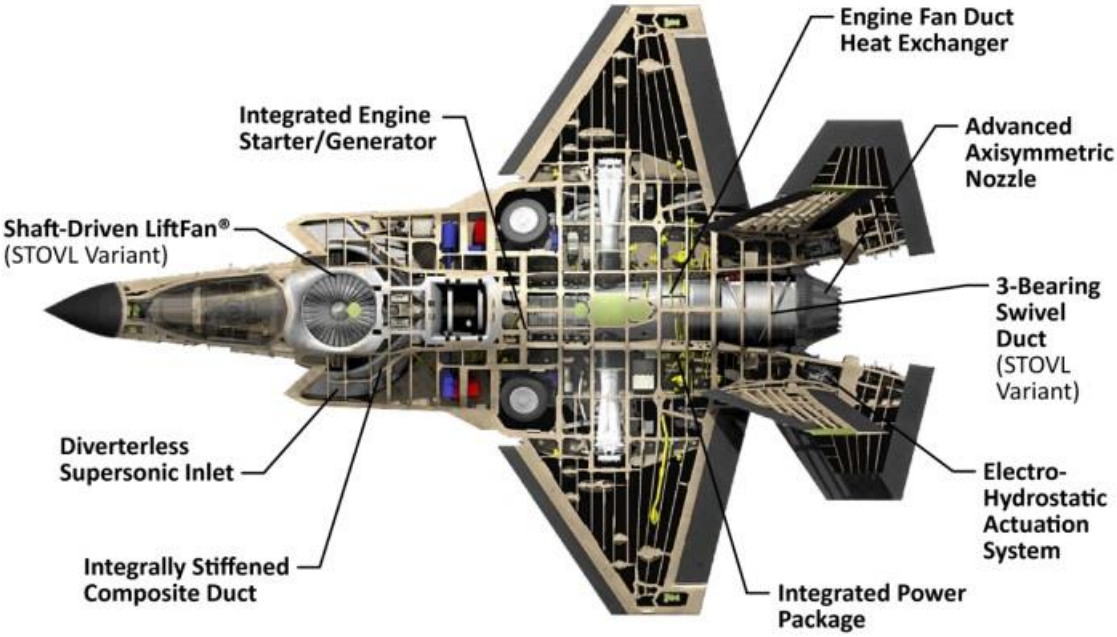


Figure 4.11: F-35 STOVL variant configuration depicting incorporation of advanced composite technologies and propulsion systems [80]

THIS PAGE WAS INTENTIONALLY LEFT BLANK

The composite repair works ensure a solid and sustainable joint for load / stress exchange in and out of the damaged patch. The repair works utilizing RIR, CFR, bolted and bonded repair, are intended to restore parent laminate strength by 80 – 100%. The structural stability requirements must also be met during repair procedures to restore local stiffness. The bonded repairs structural behavior depends upon the accurate repair application, adhesion, surface properties, curing etc. Meanwhile, the bolted repair work on composite structures relies on fastener-composite interaction and fastener mechanical properties to bear stress. The advanced automation processes can enable execution of repair works mechanically, ensuring effectiveness and sustainability in the repair cycle of the aircraft. The automation process is the future of composite repair technology.

The optimization of composite structural components to damage tolerance is tedious. The problem lies when establishing and optimizing the co-relation between the structural residual strength (depending on thickness) and detectability of the impact. If the thickness of the structure is increased to improve the structural capability to resist impact loads, the impact indentation becomes invisible, contradicting the composite strength to impact damage tolerance. Thus, the advanced numerical solution of the composite impact damage and compression after impact behavior of composite laminates is challenging and worldwide advanced studies are being carried out to tackle related challenges. The advanced numerical modeling of composite laminates is the future of achieving an optimized damage tolerant structural design. Moreover, the aviation industries are also developing advanced composite materials that can withstand acceptable amounts of impact loading without compromising the structural integrity of the aircraft.

The advantages of utilizing composite structures have outpaced typical metallic configurations of commercial civil aero-vehicles and the next generation civil aircraft accommodate up to 50% composite structural weight. The evolution of composite structures in commercial aircraft is owing to better fuel economy, lower noise pollution, reduced emissions, sustainable maintenance of aero-vehicles and efficient energy / cost saving. Carbon composite structures are currently incorporated in all new generation commercial aircraft making them lighter, high fatigue tolerant and reduced life cycle expenditure. Moreover, composite materials have revolutionized the space industry and work is under way to initiate crewed space missions to moon and mars with commercial space sector development. Thus, composite materials have a bright future in the coming decades, to be integrated in the next generation aircraft.

The military aircraft have integrated multiple advanced composite technologies that have significantly exceeded the state of the art for modern era combat aero vehicles. The advanced

composite technologies integrated into the primary structural airframes are going to help in the research and development of more advanced next generation sustainable military aircraft. This has enabled the advancement into 5th generation aircraft and beyond with exceptional combat effectiveness, creating a framework for long term growth and enhancing fighter jet capabilities beyond visual range. The constant innovation into composite technologies is enabling reduction in manufacturing costs with new manufacturing techniques and sustaining active-duty military aircraft worldwide.

Thus, it is concluded that the enhanced applications and better durability of composite structures in aeronautical applications is going to outpace conventional metals. However, the utilization of advanced manufacturing techniques are going to further revolutionize the composite structures market world-wide.

[1] E. Archer and A. McIlhagger, "Repair of damaged aerospace composite structures," in *Polymer Composites in the Aerospace Industry*, Elsevier, 2020, pp. 441–459.

[2] K. B.Armstrong, W. Cole, E. Chesmar, & F. Museux, "Care and repair of advanced composites," SAE international, 2020.

[3] A. A. Baker, "Repair of cracked or defective metallic aircraft components with advanced fibre composites—an overview of Australian work," Compos. Struct., vol. 2, no. 2, pp. 153–181, 1984.

[4] A. Baker, Bonded repair of aircraft structures, vol. 7. Springer Science & Business Media, 1988.

[5] A. Baker, "Bonded composite repair of fatigue-cracked primary aircraft structure," Compos. Struct., vol. 47, no. 1–4, pp. 431–443, 1999.

[6] A. A. Baker, R. J. Chester, G. R. Hugo, and T. C. Radtke, "Scarf repairs to highly strained graphite/epoxy structure," *Int. J. Adhes. Adhes.*, vol. 19, no. 2–3, pp. 161–171, 1999.

[7] N. Bhatnagar, N. Ramakrishnan, N. K. Naik, and R. Komanduri, "On the machining of fiber reinforced plastic (FRP) composite laminates," *Int. J. Mach. Tools Manuf.*, vol. 35, no. 5, pp. 701–716, 1995.

[8] W. Brostow and N. M. Glass, "Cure progress in epoxy systems: dependence on temperature and time," *Mater. Res. Innov.*, vol. 7, no. 3, pp. 125–132, 2003.

[9] M. A. Caminero, S. Pavlopoulou, M. Lopez-Pedrosa, B. G. Nicolaisson, C. Pinna, and C. Soutis, "Analysis of adhesively bonded repairs in composites: Damage detection and prognosis," *Compos. Struct.*, vol. 95, pp. 500–517, 2013.

[10] C. Dunsky, P. Tacheron, and M. Hashish, *Waterjet Techniques for Composite Material Jet Engine Component Repair. Phase 1*. 1996.

[11] G. B. Evans, "Bonded repair of aircraft structures. Edited by A. a. baker and R. jones Martinus nijhoff publishers, dordrecht. 1988. 214 pp. Illustrated. £59.00," *Aeronaut. J.*, vol. 92, no. 920, pp. 422–422, 1988.

[12] G. Fourche, "An overview of the basic aspects of polymer adhesion. Part I: Fundamentals," *Polym. Eng. Sci.*, vol. 35, no. 12, pp. 957–967, 1995.

[13] G. Gardiner, "Primary structure repair: the quest of quality," *High-Performance Composites*, vol. 19, pp. 48–54, 2011.

[14] D. Herzog, P. Jaeschke, O. Meier, and H. Haferkamp, "Investigations on the thermal effect caused by laser cutting with respect to static strength of CFRP," *Int. J. Mach. Tools Manuf.*, vol. 48, no. 12–13, pp. 1464–1473, 2008.

[15] K. B. Katnam, L. F. M. Da Silva, and T. M. Young, "Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities," *Prog. Aerosp. Sci.*, vol. 61, pp. 26–42, 2013.

[16] L. Crouzeix, "Repairing of aeronautical / mechanical structures," Lectures, February 2023

[17] V. Sabelkin, S. Mall, M. A. Hansen, R. M. Vandawaker, and M. Derriso, "Investigation into cracked aluminum plate repaired with bonded composite patch," *Compos. Struct.*, vol. 79, no. 1, pp. 55–66, 2007.

[18] D. K. Shanmugam, T. Nguyen, and J. Wang, "A study of delamination on graphite/epoxy composites in abrasive waterjet machining," *Compos. Part A Appl. Sci. Manuf.*, vol. 39, no. 6, pp. 923–929, 2008.

[19] G. R. Sherwin, Ed., *Non-autoclave processing of advanced composite repairs*, International journal of adhesion and adhesives, vol. 19(2–3), no. 155–159.1999.

[20] J. Y. Sheikh-Ahmad, *Machining of polymer composites*. New York, NY: Springer, 2011.

[21] X. Sourd, "Multi-scale analysis of the generated damage when machining pockets of 3D woven composite for repair applications using abrasive water jet process: Contamination analysis," *Composites Part A: Applied Science and Manufacturing*, vol. 139, 2020.

[22] C. Soutis and F. Z. Hu, "Design and performance of bonded patch repairs of composite structures," *Proceedings of the Institution of Mechanical Engineers*, vol. 211, no. 4, pp. 263–271, 1997.

[23] Westerman, E. A., & Roll, P. E., "U.S. Patent No. 4,987,700. Washington, DC: U.S. Patent and Trademark Office," 1991.

[24] "Standard test method for compressive residual strength properties of damaged polymer matrix composite plates," *American Society for Testing and Materials*, 2005.

[25] S. Abrate, "Frontmatter," in *Impact on Composite Structures*, Cambridge: Cambridge University Press, 1998, pp. i-iv.

[26] Alif, N., & Carlsson, L. A., *Failure mechanisms of woven carbon and glass composites*. ASTM special technical publication, 1285, 471-493, 1997.

[27] J. G. Avery, Design manual for impact damage tolerant aircraft structure. France: ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT NEUILLY-SUR-SEINE, 1981.

[28] C. Bouvet, Mechanics of aeronautical composite materials. John Wiley & Sons, 2017.

[29]. D. Broek and J. Schijve, The influence of the mean stress on the propagation of fatigue cracks in aluminum alloy sheet, vol. NLR-TN-M 2111. Nat. Aeronaut. Res. Inst., Amsterdam., 1963.

[30] C. Bouvet, B. Castanié, M. Bizeul, and J.-J. Barrau, "Low velocity impact modelling in laminate composite panels with discrete interface elements," Int. J. Solids Struct., vol. 46, no. 14–15, pp. 2809–2821, 2009.

[31] J. M. Berthelot, Matériaux composites. Comportement mécanique et analyse des structures, 4., 1999.

[32] M. I. T. Orowan and J. Wiiey, "Fundamentals of brittle behavior in metals," in Fatigue and Fracture Mechanics of Metals, New York, 1952.

[33] G. L. Farley, Energy-absorption capability of composite tubes and beams (Doctoral dissertation). 1989.

[34] R. G. Forman, V. E. Kearney, and R. Engle, "Numerical analysis of crack propagation in cyclic loaded structures," J. bas. Engng, 1967.

[35] N. E. Frost and D. S. Dugdale, "The propagation of fatigue cracks in sheet specimens," J. Mech. Phys. Solids, vol. 6, no. 2, pp. 92–110, 1958.

[36] D. C. Fleming, C. Morrow, C. W. Clarke, and C. E. Bird, "Finite element simulation of delamination with application to crashworthy design," *J. Am. Helicopter Soc.*, vol. 53, no. 3, p. 267, 2008.

[37] P. Feraboli, B. Wade, F. Deleo, M. Rassaian, M. Higgins, and A. Byar, "LS-DYNA MAT54 modeling of the axial crushing of a composite tape sinusoidal specimen," Compos. Part A Appl. Sci. Manuf., vol. 42, no. 11, pp. 1809–1825, 2011.

[38] A.A. Griffith, "VI. The phenomena of rupture and flow in solids." *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, vol. 221, no. 582, pp. 163-198, 1921, doi: 10.1098/rsta.1921.0006.

[39] E. V. González, P. Maimí, P. P. Camanho, A. Turon, and J. A. Mayugo, "Simulation of drop-weight impact and compression after impact tests on composite laminates," *Compos. Struct.*, vol. 94, no. 11, pp. 3364–3378, 2012.

[40] G. R. Irwin, Analysis of stresses and strains near the end of a crack transversing a plate. J. appl. Mech. 24: TransASME79,361-364 (1957).

[41] H.‘M. Westergaard, Bearing pressure and cracks. J. appl. Me&, Trans. ASME 61,49-53 (1939).

[42] A. Head, “XCVIII. The growth of fatigue cracks.” *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 44, no. 356, pp. 925-938, 1953, doi: 10.1080/14786440908521062.

[43] C. E. Inglis, “Stresses in a plate due to the presence of cracks and sharp corners,” *Trans Inst Naval Archit*, vol. 55, pp. 219–241, 1913.

[44] H. A. Israr, S. Rivallant, C. Bouvet, and J. J. Barrau, “Finite element simulation of 0/90 CFRP laminated plates subjected to crushing using a free-face-crushing concept,” Composites Part A: Applied Science and Manufacturing, vol. 62, pp. 16–25, 2014.

[45] P. Ladevéze and G. Lubineau, “On a damage mesomodel for laminates: micro-meso relationships, possibilities and limits,” Composites Science and Technology, no. 15, pp. 2149–2158, 2001.

[46] C. J. McGregor, R. Vaziri, A. Poursartip, and X. Xiao, “Simulation of progressive damage development in braided composite tubes under axial compression,” Compos. Part A Appl. Sci. Manuf., vol. 38, no. 11, pp. 2247–2259, 2007.

[47] A. J. McEvily, and W. Illg, “The rate of fatigue-crack propagation for two aluminum alloys under completely reversed loading.” *Wear*, vol. 3, no. 2, p. 154, 1958, doi: 10.1016/0043-1648(60)90062-4.

[48] B. Palmberg, A. F. Blom, and S. Eggwertz, “Probabilistic damage tolerance analysis of aircraft structures. Probabilistic fracture mechanics and reliability,” pp. 47–130, 1987.

[49] P. Paris and G. Sih, “Stress Analysis of Cracks.” *Fracture Toughness Testing and its Applications*, 1965, doi: 10.1520/stp26584s.

[50] J. Rouchon, “Fatigue and damage tolerance aspects for composite aircraft structures,” in *Proceedings of ICAF symposium*, Delft, 1995.

[51] W. Tan, B. G. Falzon, L. N. S. Chiu, and M. Price, “Predicting low velocity impact damage and Compression-After-Impact (CAI) behaviour of composite laminates,” Compos. Part A Appl. Sci. Manuf., vol. 71, pp. 212–226, 2015.

[52] A. Tropis, M. Thomas, J. L. Bounie, and P. Lafon, “Certification of the composite outer wing of the ATR72,” *Proc. Inst. Mech. Eng. G J. Aerosp. Eng.*, vol. 209, no. 4, pp. 327–339, 1995.

[53] P. M. Toor, “A review of some damage tolerance design approaches for aircraft structures.” *Engineering Fracture Mechanics*, vol. 5, no. 4, pp. 837-880, 1973, doi: 10.1016/0013-7944(73)90054-4.

[54] N. Thompson and N. Wadsworth, “Metal fatigue.” *Advances in Physics*, vol. 7, no. 25, pp. 72-169, 1958, doi: 10.1080/00018735800101177.

[55] M. R. Wisnom, “The role of delamination in failure of fibre-reinforced composites,” *Philos. Trans. A Math. Phys. Eng. Sci.*, vol. 370, no. 1965, pp. 1850–1870, 2012.

[56] E. K. Walker, “The correlation of crack growth data at various range ratios,” Lockheed Report, 1967.

[57] W. J. Crichlow, “The material-structure interface,” in Proc. AZAA/ASME Tenth Structures, Structural, Dynamics and Material ConJ, New 0rlea11s, 1969.

[58] X. Xiao, C. McGregor, R. Vaziri, and A. Poursartip, “Progress in braided composite tube crush simulation,” Int. J. Impact Eng., vol. 36, no. 5, pp. 711–719, 2009.

[59] B. Castanie, C. Bouvet, and M. Ginot, “Review of composite sandwich structure in aeronautic applications,” *Composites Part C: Open Access*, vol. 1, no. 100004, p. 100004, 2020.

[60] R. Seemann and D. Krause, “Numerical modelling of partially potted inserts in honeycomb sandwich panels under pull-out loading,” *Compos. Struct.*, vol. 203, pp. 101–109, 2018.

[61] W. G. Roeseler, “Composite structures: the first 100 years,” in *16th International Conference on Composite Materials. Japan Society for Composite Materials*, Kyoto, Japan, 2007.

[62] J. Cinquin, “Les composites en aérospatiale,” *Systèmes aéronautiques et spatiaux*, 2002.

[63] K. Chang, *SpaceX Unveils Silvery Vision to Mars: “It’s an I.C.B.M. That Lands”". The New York Times. Archived from the original on*. 2019.

[64] S. Spacex, *Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia*. 2023.

[65] ATR Training Centre. ‘’ATA 00 general familiarization,’’ 2011

[66] L. Ye, Y. Lu, Z. Su, and G. Meng, “Functionalized composite structures for new generation airframes: a review,” *Compos. Sci. Technol.*, vol. 65, no. 9, pp. 1436–1446, 2005.

[67] *Compositesworld.com*. [Online]. Available: https://www.compositesworld.com/articles/composites-in-space(2), [Accessed: 04-Sep-2023].

[68] J. Susainathan, F. Eyma, E. De Luycker, A. Cantarel, and B. Castanie, “Manufacturing and quasi-static bending behavior of wood-based sandwich structures,” Compos. Struct., vol. 182, pp. 487–504, 2017.

[69] https://www.airforce.gov.au/sites/default/files/minisite/static/7522/RAAFmuseum/exhibitions/restoration/dh_98.htm, accessed 25 April 2020

[70] L. M. Smith and C. W. Rogers, “Bonded Bomber - B-58,” in *SAE Technical Paper Series*, 1962.

[71] J. C. Joanides, S. C. Mellin, and L. M. Lackman, “Mach 3 wing structures stiffened skin versus sandwich,” in SAE Technical Paper Series, 1961.

[72] J. Hamer, “Honeycomb structure and its application to the Concorde rudder,” *Composites*, vol. 2, no. 4, pp. 242–245, 1971.

[73] P. Merlin, “Design and development of the blackbird: Challenges and lessons learned,” in *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition*, 2009.

[74] “HOME OF M.A.T.S. - The most comprehensive Grumman F-14 Reference Work - by Torsten Anft!,” Anft.net. [Online]. Available: http://www.anft.net/f-14/f14-detail-material.htm. [Accessed: 04-Sep-2023].

[75] S. Pace, “F-22 Raptor: America's next lethal war machine,” McGraw Hill, 1999

[76] C. E. Harris, H. James, and M. J. Starnes, “Design and manufacturing of aerospace composite structures, state-of-the-art assessment,” *Journal of aircraft*, vol. 39, pp. 545–560, 2002

[77] J. Gertler, “F-35 joint strike fighter (jsf) program,” *Congressional Research Service*, vol. 16, 2012.

[78] M. A. Counts, B. Kiger, J. Hoffschwelle, A. Houtman, and G. Henderson, “F-35 Air Vehicle Configuration Development,” in *2018 Aviation Technology, Integration, and Operations Conference*, 2018.

[79] D.A. Kinard, "F-35 digital thread and advanced manufacturing," in *2018 Aviation Technology, Integration, and Operations Conference*, 2018.

[80] C. Wiegand, “F-35 air vehicle technology overview,” in *2018 Aviation Technology, Integration, and Operations Conference*, 2018.