Materials Applied in Aviation Structures and Modern Non-Destructive Testing Methods for Crack Detection

M. Kyoseva, N. Stoimenov

Abstract— **This article examines on the importance of aircraft structural integrity and stress resistance. Depending on the material in use and the location of different structural components which are exposed to load, different in strength and direction, also taking into account the operational conditions, environmental specifics, it is crucial to inspect and detect structural defects before any aircraft damage occurs. This work aims to present a new approach for inspections – Digital image technology, Infrared thermography, CT scanning, as a technology which are capable of improve the aircraft maintenance process as well as to shorten the inspection time and also to provide much safer working practices.**

I. INTRODUCTION

When an aircraft is manufactured it could be considered that its ageing start from that moment. Factors such as time (flight hours), exploitation (flight cycles), and manufacturing date are from great importance. During the life cycles of one model of a plane, if it is updated regularly its service exploitation experience it can lead to knowledge updates about its structural integrity, reduce and control the ageing process [1]. One method of aircraft fatigue testing can be performed by simulation. Nowadays, the simulations can inspect and predict possible areas of fatigue cracks. Those methods can optimize the structure of the plane and reduce production costs. Another benefit of the simulations is that the results can be used for maintenance and repairs. Detection of cracks during the life cycle of a plane are from great importance; if the cracks are not detected on time, they can lead to uncontrolled structural damage on the plane [2].

Industry 4.0, Industry 5.0 and the state-of-the-art technologies such as AI can optimize the whole process of designing, manufacturing and testing an aircraft [3].

Any event that occurs during flight and leads to serious injury, death, and aircraft damage is an aviation accident. In the history of aviation, there are at least four fundamental plane crashes that set the basic rules for aircraft construction.

The de Havilland Comet 1 Aircrafts experienced several accidents which has significant impact on evolvement of regulations, maintenance programs development and aviation safety standards. [34]. Aircraft G-ALYV experienced an aviation accident, resulting in an in-flight break-up, which was caused by a combination of severe thunderstorm and aircraft overcontrol from the pilots' side. The accident dated May 2, 1953, and was the first of three accidents that grounded the entire Comet 1 fleet. During the second incident (G-ALYP), dated January 10, 1954, shown in fig. 1, the plane crashed into the sea. The analysis shown that the main reason was in the early project level, where the process of design was not evaluated according to its overall structure. After the modification process, the plane model was returned in exploitation two months after the crash [4]. Another flight of the plane G-ALYY in April 8, 1954 when after take of from Rome, while reaching 35,000 feet, again occurs an in-flight break-up and the plane has fallen into the sea. And after this case, the planes were stopped from flighting and was considered that a stress concentrations occurs in the windows section of the plane.

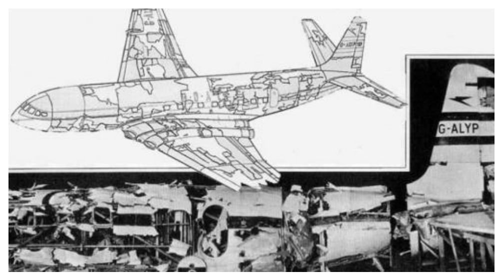


Figure 1. Incident with Comet 1 aircraft [45]

II. MATERIALS USED IN AVIATION

The materials used in the aviation manufacturing can be classified in few directions, such as nonmetals, ceramics, aluminum, as well as composites. Ceramic materials have the ability to withstand high temperatures, strength and thermal expansion, but their main disadvantage is that they cannot be used as structural materials due to their brittleness. The polymer composite materials are preferable for the aircraft manufacturers due to their excellent characteristics and the possibility of changing the material characteristics [56]. In aerospace engineering, the choice of material is as critical as the design of the aircraft.

A. Aluminum Alloys

Each aircraft aluminum grade has unique characteristics suited for different aerospace applications. The most common aircraft aluminum grades are shown in Table 1 [7, 8, 9, 10].

B. Composites

The most used materials in the aircraft manufacturing prosesses are the carbon, glass fibers, as well as aramid are shown in Table 2 [6, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20].

M. Kyoseva is with the Institute of Information and Communication Technologies at the Bulgarian Academy of Sciences (e-mail: Miglena.kyoseva@iict.bas.bg).

N. Stoimenov is with the Institute of Information and Communication Technologies at the Bulgarian Academy of Sciences (e-mail: nikistoimenow@gmail.com).

TABLE I. MOST COMMON AIRCRAFT ALUMINUM ALLOYS.

Al-ALLOY	PRIMERY ALLOY MATERIALS	CHARACTERISTICS	AIRCRAFT COMPONENTS
2024	Al-Cu	Good fatigue performance, fracture toughness, and slow propagation rate	Aircraft skin, structure, cowls. Used also for repair & restoration
3003	Al-Mn	Excellent corrosion-resistant and workability	Cowls & Baffle planting
5052	AL-Mg	High corrosion resistance	Fuel tanks
6061	Al-Silicone	High corrosion resistance and weldability	Structural tubing, hydraulic systems, and interior parts
7050	Al-Zn	Superior strength, corrosion resistance, fracture toughness	Critical wing and fuselage components
7055	Al-Zn-Mg-Cu	Superior stress corrosion	Wing lower skin
7075	Al-Zn-Mg-Cu	High-strength alloy	Used to strength aircraft structure, slat, flaps
7079	Al-Zn-Mg-Cu	Tempered to minimize residual heat treatment stress	Bulkhead, window frame, landing gears (B737-200 only)
7175	Al-Zn-Mg-Cu	Very tough, very high tensile strength alloy	Landing gear beam
7178	Al-Zn-Mg-Cu	The high compressive strength-to-weight ratio	Wing upper skin, spar, and beams

TABLE II. COMPOSITE MATERIALS USED IN AVIATION.

COMPOSITE	STRUCTURE TYPE	CHARACTERISTICS	AIRCRAFT COMPONENTS
Glare	Laminate	High strength & Stiffness, Firewall resistance, Corrosion Resistance	A380 Fuselage, Empennage Leading Edge
CFRP	Laminate	High Strength & Stiffness	Wing Upper Skin, Fuselage
CFRP	Sandwich	High strength, high bending Stiffness	Engine Fan Cowls, Elevator, Rudder
GFRP	Laminate	High strength to weight ratio, high fracture toughness, excellent corrosion & thermal resistance	Components from Vertical Stabilizer
QFRP	Sandwich	Exceptional strength-to-weight ratios & low electromagnetic interference	A380 Radome
Aramid	Laminate	Extremely light, High Strength, Thermal stability, high resistance to cutting	Engine Pylon
Aramid	Sandwich	Specific stiffness, cushioning, light-weight and high energy-absorbing efficiency	Cabin Floor, Landing Gear Doors
Graphite	N/A	High thermal & electrical conductivity	Brake units & Aircraft paints

C. Examples

Boeing 787 Dreamliner

The newly developed composite materials are applied, for example, in the Boeing 787 airplane, shown in figure 2. Composite materials can be used in larger fuselage components of the aircraft due to reduced weight structure, increased corrosion and fatigue resistance [21, 22].

Airbus A350-XWB

With a broad range and increased white body build-up, the Airbus A350 XWB, shown in figure 3, is the second most aircraft that employs more than 50% carbon composites in its manufacturing design [23, 24].

Airbus A380

GLARE (GLAss Reinforced Aluminium Laminate) is part of FMLs (Fiber Metal Laminate) [25] innovative material offers unparalleled durability, corrosion resistance, and fire resistance compared to conventional aluminum [26].

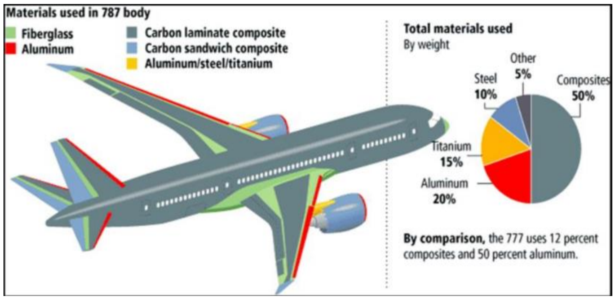


Figure 2. B787 structure material [15].

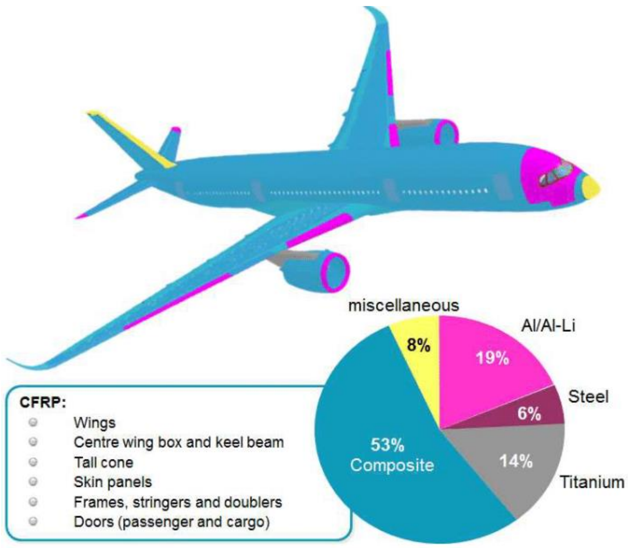


Figure 3. A350 structure material [12].

Figure 4. A380 structure material [25].

III. METHODS AND MEANS FOR CRACK DETECTION

Nowadays, there are three methods for crack detection, which are studied and developed over the years in the aviation industry – digital image technology, infrared thermography, and scanning electronic microscopy. All mentioned methods are in a test period and the investigations for non-destructive methods can be very effective, time-consuming, and much safer. After years of testing and validation of research, these methods can be applied in aircrafts maintenance.

A. Digital Image Technology

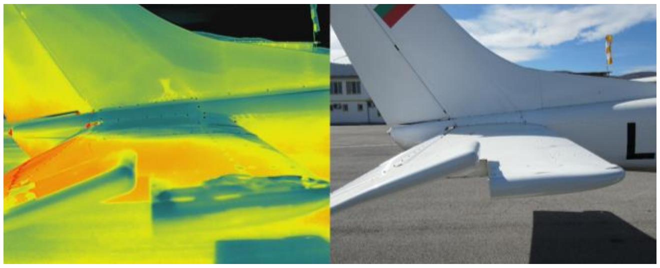
Nowadays, the non-contact and non-destructive methods are trending and the digital image processing technology is one of those methods. It can conduct an optical measurement experiment. The technology has a lot of advantages such as wide measurement range, automation possibilities including AI [3], as well as resistance to an aggressive external environment. The proposed method can facilitate the study of fatigue life. The usage of this method, including the usage of automated systems in the aircraft structural crack detection system, fatigue crack detection system are shown in Figure 5 [27, 28]. With the advent of drones, their constant improvement, and the availability of 20-megapixel images on the market allows their use for digital image technologies, which can contribute to faster examination of the analyzed object.

Figure 5. Digital Image [20].

B. Infrared Thermography

Infrared energy, emitted by all objects in nature, has been caught and measured by infrared cameras, aiming to detect the specific object's temperature emission. As the infrared(thermal) energy wave is too long, it is invisible for human eye, so human beings feel it as a heat emission. So, the hotter the object is, the shorter the energy wave it emits [29]. The aviation industry is facing several challenges in the realm of aircraft structure inspection and diagnosis. Current aircraft inspection methods still require full automation, which hinders the early detection and precise sizing of defects. Concerns have been expressed by researchers regarding the current aircraft inspection process. The issues highlighted include safety, maintenance costs, and reliability. The subsequent generation of aircraft inspection will be characterized by the integration of semi-autonomous and fully autonomous systems, which will incorporate robotic technologies with advanced Non-Destructive Testing (NDT) methods. The usage of Active Thermography (AT) is a great example of an NDT method that has been extensively utilized for the non-contact inspection of aircraft, to detect surface and near-surface defects, including delamination, debonding, corrosion, impact damage, and cracks [31].

An attempt at the implementation of non-destructive testing by using an infrared camera was used in Fig. 6. The figure shows a) an infrared image in which different materials are spotted and their different temperatures in sunlight are also noted. In fig. 6 b) is the digital image shot by the camera.



a) b)

Figure 6. Infrared thermography.

C. Scanning electron microscopy – CT scanning

The CT scanning method can investigate a wide scope of materials, such as metallic and non-metallic. Another feature of this method is the examination of the internal features of complicated detail geometry, localization of voids, cracks, measurements of wall thickness, etc. The aerospace quality control is under complex regulations that require testing, sample preparation for comparison, aiming to meet the needs of part production and certification standards. The CT scanning method has high data density and high-precision scans and can be applied to this industry [32].

The usage of CT scanning for the Kevlar material can be applied for determining the structure. Another application of CT is metal testing as well as composite investigations [33].

D. Comparative analysis of the methods.

An attempt has been made to compare the different methods, including the time required to perform the inspections, additional equipment/materials required, etc., which are presented in Table 3. The walkaround method, if it is necessary, includes General Vision Inspection, which is relevant to the postprocessing procedures of the other analyzed methods.

TABLE III. COMPARATIVE ANALYSIS OF THE INSPECTION METHODS.

	Walkaroun	UAV inspection	Thermography	CT scanning
Time frame	15min	5min	15min	30min
Postprocessing	GVI	5min	15min	40min
Additional tooling	Stairs/ Light/helmet	Not necessary	Not necessary	Not necessary
Safe for accomplishment	Securing of personnel	Not necessary	Securing if it is not UAV Thermography drone.	Not applicable
Capability	Direct monitoring over the structure for peeling paint, missing placards, any damage	Direct monitoring over the structure for peeling paint, missing placards, any damage	Direct monitoring over the structure for peeling paint, missing placards, any damage	Not applicable
Report	Checklist	Can include evidentiary material	Can include evidentiary material	Can include evidentiary material
Automation	Not applicable	Can be performed	Can be performed	Not applicable

IV. CLASSIFICATION OF AIRPLANE CRACKS

Depending on the loads that are applied to aircraft, structural components could be classified [34]:

1. Principle Structure Element (PSE) – it is an element which plays a major role in carrying the all types of loads applied to the structure, during the flight, ground operations and cycling load of pressurasation and it is strength is crucial for structural integrity;
2. Detail Design Point (DDP) – section of the structure whose cycle load durability and fatigue resistance is important to entire structure capability to withstand the periodic loading and its damage could lead to catastrophic consequences;
3. Single Load Path Structure – it is a structural element which is loaded by pressurisation -depressurisation cycles and its collapse will affect the entire structural integrity;
4. Multiple Load Path Structure - a group of structural elements which carries the load and failure of single element does not lead to damage to aircraft structure;
5. Fatigue Critical Structure (FCS) – part of the structure whose failure will lead to catastrophic consequences;
6. There are two basic concepts applied in aircraft structure at design stage [34]:

7. A fail-safe concept – “fail-safe” concept is based on principle that any single element failure (crack) would not compromise the structural integrity and does not lead to any catastrophic consequences;
8. Damage Tolerance – it is a structure’ s feature to resist the cycle pressure load in case an element is damaged (cracked) but the damage does not reduce the aircraft structural durability.

The aircraft structure is developed to a predefined operational period (utilization – flight hours, flight cycles and calendar) [34]:

1. Design Service Goal (DSG): It is an assessment of period (calculated in flight hours or cycles or both), carried out during design or certification stage, when the aircraft will be free of cracks;
2. Safe life – It is a term for calculated numbers of events (flight hour, flight cycles or both) during which the probability to occur and evolve any crack is very low;
3. Limit of Validity (LOV) – it is a calculated period (flight hour, flight cycles or both) of aircraft service, based on service experience, teardown inspections and analysis, during which no widespread fatigue damage is expected to occur. Several Examples are shown in Table 4 [21, 35].

Widespread fatigue damage (WFD) is a term to introduce an existence of several cracks at multiple structural details and they are wide enough to reduce the residual strength and compromise the aircraft structural integrity. WFD sources are [34]:

1. Multiple-site damage (MSD) – it is a widespread damage consists of several fatigue crack in single structural elements;
2. Multiple element damage (MED) – it is a source of widespread fatigue damage consists of several fatigue crack in adjacent structural elements;
3. Structural modification point (SMP) – it is a time when aircraft structural area has to be modified in order to avoid the WFD;
4. Inspection start point (ISP) – it is a time when inspections have to be initiated in order to reveal the crack MSD/MED.

TABLE IV. EXAMPLES OF LOV.

AIRCRAFT MODEL	LOV	
	CYCLES	HOURS
B717	110 000	110 000
B727-100/100C/200/200F	85 000	95 000
B737-300/400/500 (LN 1001-2565)	75 000	100 000
B737-300/400/500 (LN 2566-3132)	85 000	100 000
B737-600/700/700IGM/700C/800/900/900ER	100 000	150 000
B747-100/100B/100B/200B/200C/200F/300	35 000	135 000
B747-400/400D/400F	35 000	165 000
B757 ALL	75 000	150 000
B767-200/200SF/300	75 000	180 000
B767-300F/400ER	60 000	180 000
B777-200/300	60 000	180 000
A318	48 000	60 000
A319	48 000	60 000
A320–100	48 000	48 000
A320–200	48 000	60 000
A321	48 000	60 000
A330 non enhanced	40 000	60 000
A330 enhanced	33 000	100 000
A340-500/600	16 600	100 000

Several examples for MED and MSD are listed in Table 5 and shown in the figures below [36]:

TABLE V. MED & MSD EXAMPLES.

STRUCTURAL AREA	DAMAGE TYPE	FIGURE
Fuselage Frames	MED	Figure 7
Stringer to Frame attachments	MED	Figure 8
Window Surround Structure	MED/ MSD	Figure 9

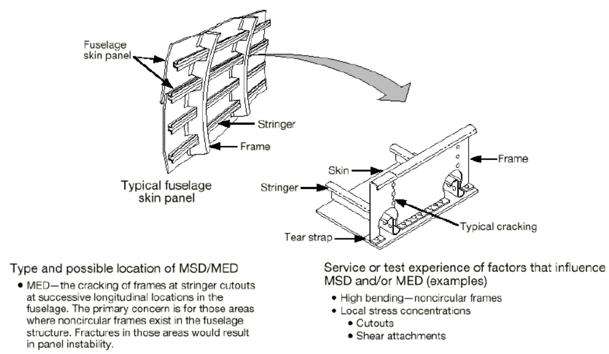


Figure 7. Fuselage Frames [35].

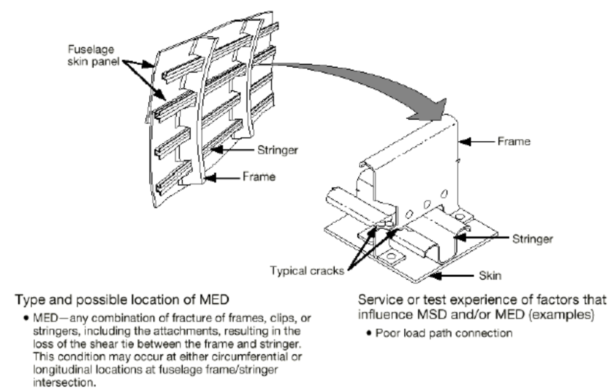


Figure 8. Stringer to Frame attachments [35].

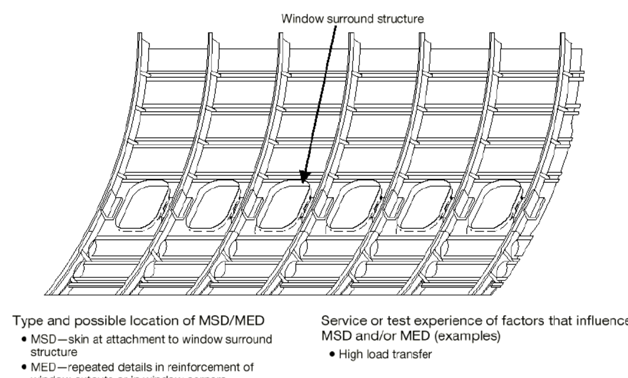


Figure 9. Window Surround Structure [35].

V. Conclusion

The use of different materials in aircraft construction leads to new requirements and tests for reliability, durability, and maintainability. With the development of technology, new methods for testing cracks in aircraft and their fuselage are introduced, which aim at faster and more accurate diagnostics. Non-destructive methods are one of these new types. They allow for a quick inspection and diagnosis of cracks in the aircraft fuselage, which, when localized, can be subjected to more thorough analysis and inspection. The analysis of the materials used in aviation shows that at present, there are 10 main types of aluminum alloys. In the future, the authors plan to try to use infrared thermography to locate defects in aircraft fuselage. The attempt with a thermal camera shows different heating of the individual components (metal and composite) of a small aircraft, which in the case of defects in riveted areas and assemblies made of different materials and/or the material itself should also give deviations in the temperature of the part and be easily localized.

ACKNOWLEDGMENT

The research was carried out as part of a Doctoral grant for supporting Ph.D. Students from the Bulgarian Academy of Sciences.

REFERENCES

[1] EASA Official Journal of the European Union - Regulation (EU) No 748/2012 - https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0699

[2] Zheng H., Detection of cracks in aircraft structures using digital image processing technology, Journal of Physics Conference Series 665(1):012023 DOI: 10.1088/1742-6596/2665/1/012023, 2023.

[3] Hasan A., Nasser A., Al-Araji A., Shafiq D., Al-Obaidi A., Al-Khazraji H., Humaidi A., Enhanced Product Defect Detection in Smart Manufacturing Using ConvNeXt-Stacked Autoencoder Architecture, Indonesian Journal of Science & Technology 10(2) (2025) 297-316, ISSN 2528-1410, E-ISSN 2527-8045, DOI: https://doi.org/10.17509/ijost.v10i2.82229

[3] FAA De Havilland DH-106 Comet 1 https://www.faa.gov/lessons_learned/transport_airplane/accidents/G-ALYV, last visited March 2026

[4] Feng Z., Keyia M., Zou T., Yang Y., Discussion on Airworthiness Requirement of Widespread, Procedia Engineering 80, DOI: 10.1016/j.proeng.2014.09.096, 2014

[5] Kushan M., Gurten S., Sofuolu M., Materials, Structures and Manufacturing for Aircraft, Chapter 3, Advanced Polymers in Aircraft Structures, Springer, 2022

[6] https://www.metalsupermarkets.com/history-of-aluminum-in-the-aerospace-industry/, last visited March 2026

[7] https://www.amspec-inc.com/aluminum-alloys-in-aircraft/, last visited March 2026

[8] http://www.b737.org.uk/production.htm#google_vignette, last visited March 2026

[9] https://www.aircraftmaterials.com/data/aluminium/3003.html, last visited March 2026

[10] Wanhill, R.J.H. GLARE®: A Versatile Fibre Metal Laminate (FML) Concept. In: Prasad, N., Wanhill, R. (eds) Aerospace Materials and Material Technologies . Indian Institute of Metals Series. Springer, Singapore, 2017. https://doi.org/10.1007/978-981-10-2134-3_

[11] Wanhill, R.J.H., Carbon Fibre Polymer Matrix Structural Composites. In: Prasad, N., Wanhill, R. (eds) Aerospace Materials and Material Technologies . Indian Institute of Metals Series. Springer, Singapore, 2017. https://doi.org/10.1007/978-981-10-2134-3_14

[12] Reddy S., Mondava R., Aero Space Applications of GFRP Composites: Review, R.V.R. & J.C.College of Engineering (Autonomous), Guntur, Andhra Pradesh, INDIA. pp.10-14, 2013

[13] https://www.aviationtag.com/en-en/blogs/blog/our-air-france-airbus-a380-edition?srsltid=AfmBOor8nlJ13v1MnLau5DWDw8SMmeyZmoqn75MEAu8WYqq8zwQVVhSO, last visited March 2026

[14] https://www.advanced-ceramic-composites.saint-gobain.com/news/using-quartz-fiber-aerospace-radomes, last visited March 2026

[15] Sabir,T., 2 - Fibers used for high-performance apparel, Editor(s): John McLoughlin, Tasneem Sabir, In Woodhead Publishing Series in Textiles, High-Performance Apparel, Woodhead Publishing, , Pages 7-32, ISBN 9780081009048, https://doi.org/10.1016/B978-0-08-100904-8.00002-X, 2018.

[16] Khusiafan F., Use of KEVLAR® 49 in Aircraft Components, Journal of Engineering Management Research, ISSN(Print): 1927-7318, Vol. 7, No 2, Publisher Published by Canadian Center of Science and Education, pp. 14-19, 2018

[17] Junfang Shan J., Xu S., Zhou L., Wang D., Liu Y., Zhang M., Wang P., Dynamic fracture of aramid paper honeycomb subjected to impact loading, Composite Structures, Volume 223, 2019, 110962, ISSN 0263-8223, https://doi.org/10.1016/j.compstruct.2019.110962, 2019.

[18] https://www.dupont.com/fabrics-fibers-and-nonwovens/kevlar-for-aerospace.html, last visited March 2026

[19] https://empoweringpumps.com/metcar-carbon-graphite-in-the-commercial-aircraft-industry/, last visited March 2026

[20] Chisholm S., Rufin A.,Chapman B., Benson Q., Forty Years of Structural Durability and Damage Tolerance at Boeing Commercial Airplanes, Boeing Technical Journal, 2016

[21] Kesarwani S., Polymer Composites in Aviation Sector, INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) Volume 06, Issue 06, 2017 http://dx.doi.org/10.17577/IJERTV6IS060291

[22] Patole R., Ambhore N., Agrawal D., Carbon Composites in Aerospace Application – A Comprehensive Review, Materials International, Vol. 5, Issue 4, 2023 Materials International 5(4):12

[23] Bachmann, J., Hidalgo, C. & Bricout, S. Environmental analysis of innovative sustainable composites with potential use in aviation sector—A life cycle assessment review. Sci. China Technol. Sci. 60, 1301–1317 (2017). https://doi.org/10.1007/s11431-016-9094-y

[24] Wanhill, R.J.H. GLARE®: A Versatile Fibre Metal Laminate (FML) Concept. In: Prasad, N., Wanhill, R. (eds) Aerospace Materials and Material Technologies . Indian Institute of Metals Series. Springer, Singapore, 2017. https://doi.org/10.1007/978-981-10-2134-3

[25] https://www.aviationtag.com/en-en/blogs/blog/our-air-france-airbus-a380-edition last visited March 2026

[27] Andrej Novák A., Sedláčková A., Bugaj M., Kandera B, Lusiak T., Use of Unmanned Aerial Vehicles in Aircraft Maintenance, Transportation Research Procedia, Volume 51, Pages 160-170, ISSN 2352-1465, 2020

[28] Stoimenov N., STUDY OF MOVEMENT AND INTERACTION OF DIFFERENT SHAPE BODIES, Dissertation thesis

[29] João Queirós J., Lopes H., Mourão L., dos Santos V., Inspection of Damage on Laminated Plates: Thermography vs Shearography, Procedia Structural Integrity, Volume 77, Pages 475-483, ISSN 2452-3216, 2026, https://doi.org/10.1016/j.prostr.2026.01.060.

[30] Bardis, K.; Avdelidis, N.P.; Ibarra-Castanedo, C.; Maldague, X.P.V.; Fernandes, H. Advanced Diagnostics of Aircraft Structures Using Automated Non-Invasive Imaging Techniques: A Comprehensive Review. *Appl. Sci.* **2025**, *15*, 3584. https://doi.org/10.3390/app15073584

[31] https://pes-scanning.com/benefits-of-ct-scanning-for-aerospace/ last visited March 2026

[32] Amir S., Sultan M., Jawaid M., Ariffin A., Mohd S., Salleh K., Ishak M., Shah A, 16 - Nondestructive testing method for Kevlar and natural fiber and their hybrid composites, Editor(s): Mohammad Jawaid, Mohamed Thariq, Naheed Saba, In Woodhead Publishing Series in Composites Science and Engineering, Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites, Woodhead Publishing, Pages 367-388, ISBN 9780081022900, 2019, https://doi.org/10.1016/B978-0-08-102290-0.00016-7.

[33] EASA Regulation CS-25 Large Aeroplanes

[34] FAA CFR-2011-title14-vol3-sec129-115 - Limit of Validity

[35] EASA AMC 20- Amendment 20