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The Application of Advanced Composites for the Construction of Commercial Transport Aircraft

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The Application of Advanced Composites for the Construction of Commercial Transport Aircraft

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Abstract

This individual Capstone project examined and evaluated current industry methods of testing, certification, and maintenance of advanced composite materials for the construction of commercial transport aircraft and the FAA regulations governing their use. The project critically compared and contrasted existing FAA standards and regulations governing the testing, certification, and maintenance of advanced composites for commercial transport aircraft structural applications with current industry practices to determine whether there were any areas of conflict between the two in order to accept or reject that current testing, certification, and maintenance procedures for advanced composites used in primary and secondary commercial transport aircraft structures are standardized throughout the aerospace industry and sufficiently capable of detecting damage or component failure. This was accomplished by performing a qualitative and quantitative analysis utilizing meta-analysis to contrast and compare past and current aerospace composite materials studies with non-destructive inspection (NDI) testing and structural health monitoring (SHM) data to determine statistical significance that supported or refuted the hypothesis of comprehensive process improvement throughout the industry. The results of the analysis showed that the hypothesis was accepted for testing and certification, but overwhelmingly rejected for current maintenance and repair. In addition, industry concerns were examined to determine whether limitations exist that would preclude the future use of advanced composites in structural applications based on current FAA standards and regulations. This project determined how current industry practices and FAA methodologies for the testing, certification, and maintenance of advanced composites in commercial transport aircraft structural applications may need to be modified in order to capture and address future industry use.

Keywords: advanced composites, testing, certification, maintenance, damage detection

Proposal

(Approved by ERAU Worldwide Aeronautics Department on April 6th, 2013)

The Application of Advanced Composites for the Construction of Commercial Transport Aircraft

Structural Composite Materials Integration

The use of composite materials by the aerospace industry has increased over the past several decades for the construction of commercial transport aircraft that now includes the use of advanced composites in primary and secondary structures such as wings and fuselage components. This increased use also brings with it the requirement for new validation tests, certification processes, and standardized repair procedures that will differ significantly from traditional metallic aircraft structure testing, certification, and repair. This recent expanded use of advanced composites by aerospace manufacturers warrants further discussion into current and future testing, certification, and repair procedures for primary and secondary structures advanced composite parts and assemblies used in the construction of commercial transport aircraft.

The integration of composite materials for use in aerospace applications originated from the desire to replace conventional metallic structures with a light-weight, higher strength alternative. Advanced composites are used by the aerospace industry and in other high-performance applications where high-strength and stiffness are required. Advanced composites are composite materials that start with high-strength and high extensional stiffness fibers such as carbon, boron, and aramid (Kevlar™) that are imbedded within a homogenous resin matrix of epoxy, bismaleimide, or polyimide which then becomes a composite of the two separate materials that forms a single material (laminate) with high strength and stiffness properties. The strength and stiffness characteristics that are created by lightweight composite materials have allowed them to replace traditional heavier metallic structures in order to yield a higher strength-to-weight ratio for aerospace applications. Early structural use of advanced composites by aerospace manufacturers included parts and assemblies such as doors and panels, engine nacelles, control surfaces, and nose radomes. Due to the high-strength and stiffness properties of advanced composites, the use has been expanded to include aircraft structural load-bearing parts and assemblies primary structures such as wings and fuselage components. With the demonstrated advantages of advanced composites in the aerospace industry such as increased strength-to-weight and stiffness, and increased fatigue life and static life, there are also industry concerns such as damage detection, standardized maintenance procedures and structural health monitoring.

Damage Vulnerability

According to the U.S. Navy's description of typical damage that occurs to advanced composite materials, most damage is not readily detectable. Non-visible sub-surface damage can exist due to the brittle characteristics of advanced composites that make it prone to impact damage. Impact forces that occur on the surface of composite materials can rupture the matrix which will cause matrix cracking, delamination between fiber plies, and broken fibers. Because the full extent of the damage is impossible to detect by visual inspection alone, non-destructive inspection (NDI) such as ultrasonic testing must be performed to evaluate and assess the damaged area. As well as NDI testing, structural health monitoring such as piezoelectric *SMART Layers*™ and in-flight load monitoring are also critical for the detection of sub-surface material failure that may be occurring due to other factors such as fatigue or material softening from liquid intrusion or high heat. The relevance of NDI testing and structural health monitoring of advanced composite components suggests a need for further discussion into the current techniques used for damage and failure detection of composite materials in the aerospace industry with respect to maintenance and repair for commercial transport aircraft applications.

Statement of the Project

Are current testing, certification, and maintenance procedures for advanced composites used in primary and secondary commercial transport aircraft structures standardized throughout the aerospace industry and sufficiently capable of detecting damage or component failure? This proposed research project will examine current industry methods of testing, certification, and maintenance of advanced composite materials for the construction of commercial transport aircraft and the FAA regulations governing their use to determine whether the continued use of advanced composites is sustainable within the industry under the current regulations by completing a mixed-method qualitative and quantitative analysis. The scope will be to critically compare and contrast existing FAA standards and regulations governing the testing, certification, and maintenance of advanced composites for commercial aircraft structural applications with current industry practices to determine whether there are any areas of conflict between the two, and examine industry concerns to determine whether limitations exist that would preclude the future use of advanced composites in structural applications based on current FAA standards and regulations by utilizing meta-analysis with ANOVA. The goal of this project will be to determine how the current FAA standards and regulations governing the testing, certification, and maintenance of advanced composites in commercial transport aircraft structural applications may need to be modified in order to capture and address future industry use. Conclusions and recommendations will be made based on data that shows comprehensive process improvement throughout the aerospace industry and government regulatory agencies.

Program Outcomes (POs)

PO (1)

Students will be able to apply the fundamentals of air transportation as part of a global, multimodal transportation system, including the technological, social, environmental, and political aspects of the system to examine, compare, analyze and recommend conclusions.

This research project will examine current testing, certification, and maintenance of advanced composites for commercial transport aircraft applications in the aerospace industry and analyze the impact of its use on air transportation. The ***multimodal transportation system*** aspect will be addressed by examining and comparing current structural validation testing used by industry manufacturers with the certification requirements established by the FAA for the use of advanced composites in primary and secondary commercial transport aircraft structures in order to show how this has impacted the overall air transportation industry. The ***technological*** aspect will be addressed by examining the integration of advanced composites for the construction of commercial transport aircraft and how this integration has benefited and challenged the aerospace industry with the development and manufacturing of innovative and more efficient aircraft that have significant differences over traditional commercial transport aircraft. The ***social*** aspect will be addressed by examining and contrasting the confidence that airline passengers have towards commercial transport aircraft that are constructed mostly from advanced composites such as the new Boeing 787 *Dreamliner* with traditional commercial aircraft that utilize metallic construction. The ***environmental*** aspect will be addressed by examining the impact of composite commercial transport aircraft on the environment such as fuel conservation, noise abatement, and improvements in manufacturing efficiency. The ***political*** aspect will be addressed by critically examining the government regulatory methodology to determine composite materials testing and certification requirement criteria for both primary and secondary commercial transport aircraft structures and the proactive improvement approaches implemented by the FAA such as the establishment of funded research for the *Joint Advanced Materials & Structures Center of Excellence* (JAMS). Conclusions and recommendations will be made for possible process improvements and the continued use of advanced composites in the aerospace industry based on the research presented.

PO (2)

The student will be able to identify and apply appropriate statistical analysis, to include techniques in data collection, review, critique, interpretation and inference in the aviation and aerospace industry.

This research project will utilize a meta-analysis to contrast and compare past and current aerospace composite materials studies (> 5) from the *Joint Advanced Materials & Structures Center of Excellence* (JAMS) with *Composites Materials Handbook* (CMH-17) non-destructive inspection (NDI) testing (disbond/delamination and damage tolerance) and structural health monitoring (SHM fatigue and reliability) data to determine statistical significance that supports or refutes comprehensive process improvement throughout the industry in order to answer the research question. Utilizing ANOVA, the effectiveness of NDI testing and structural health monitoring of advanced composite structures will be analyzed to examine whether there is a statistically significant difference ($p = .05$) between damage and failure detection and standardized testing, certification, and maintenance/repair procedures currently being utilized throughout the aerospace industry. Data interpretation and inferences for aerospace composite materials studies with NDI testing and structural health monitoring of composite materials in the aerospace industry will be made based on the results of the meta-analysis and ANOVA.

PO (3)

The student will be able (across all subjects) to use the fundamentals of human factors in all aspects of the aviation and aerospace industry, including unsafe acts, attitudes, errors, human behavior, and human limitations as they relate to the aviators adaption to the aviation environment to reach conclusions.

The fundamentals of ***human factors*** will be examined based on the critical nature of component failure and the relation to performing composite repair correctly. The aspect of ***unsafe acts*** will be addressed by examining how component failure can be directly related to how the repair is performed and how this is especially critical if the composite part or component is used in a load-bearing area of the aircraft which could cause catastrophic failure if the component fails due to improper repair. The ***attitudes*** aspect will be addressed by examining and comparing past and current composite repair artisan *best practice* methods that may be unique to manufacturers and airline maintenance with the prescribed industry standard methods of composite repair. The ***human limitations*** and ***error*** aspects will be addressed by examining multiple composite repair techniques and procedures to show how composite repair artisan training and experience will impact the quality and correctness (free of defects and errors) for the type of repair being performed. Additionally, this research project will critically examine non-standard repairs and maintenance performed on damaged composite components by addressing how the ***human behavior*** aspect in the aerospace industry can cause malpractice within the organizational (airline) and intermediate (manufacturer and repair facility) levels of composite maintenance and repair.

PO (4)

The student will be able to develop and/or apply current aviation and industry related research methods, including problem identification, hypothesis formulation, and interpretation of findings to present as solutions in the investigation of an aviation/aerospace related topic.

This research project will present a qualitative and quantitative study that will be used to identify and examine current industry concerns and problems regarding the use of advanced composites in commercial transport aircraft applications with the ***hypothesis*** that industry-wide comprehensive process improvement should be implemented and maintained for the promulgation of improved structural validation testing, certification, and standardized repair procedures. Meta-analysis in-conjunction with ANOVA data interpretation will be used to formulate proposals that address current testing, certification, and standardized repair with recommendations and changes for aerospace industry manufacturers and the FAA to determine whether current industry practices and FAA regulations support the continued use of advanced composites in primary and secondary structures for the construction of commercial transport aircraft.

PO (5)

The student will investigate, compare, contrast, analyze, and form conclusions to current aviation, aerospace, and industry-related topics in aeronautics, including advanced aerodynamics, advanced aircraft performance, simulation systems, crew resource management, advanced meteorology, rotorcraft operations, and advanced aircraft/spacecraft systems.

This research project will compare and contrast the standards and regulations currently implemented by the FAA governing the use of advanced composites for commercial transport aircraft structural applications with current industry practices to determine whether they are congruent. The topic of ***advanced aerodynamics*** will be addressed by examining the performance benefits of advanced composites integration for the construction of commercial transport aircraft with respect to design innovation that will show how the use of composite materials has increased the aerodynamic flight performance characteristics. The topic of ***simulation systems*** will be addressed by examining the industry methods currently used to predict fatigue life and failure mode for advanced composites used in aerospace structural applications. The topic of ***advanced meteorology*** will be addressed by examining the industry concern of lightning strike protection for commercial aircraft that utilize composite materials in place of traditional metallic structures. The topic of ***advanced aircraft/spacecraft systems***[1] will be addressed by further examining current commercial transport aircraft design and manufacturing industry concerns and determining whether any limitations exist that would preclude the future use of advanced composites in structural applications based on current FAA regulations and industry practices and if the continued use of advanced composites for the construction of commercial transport aircraft is sustainable within the industry. Additionally, the topic of ***crew resource management*** (CRM) will also be addressed by examining and comparing the maintenance training of composite materials repair artisans at the organizational (airline) and intermediate (manufacturer and repair facility) levels with the prescribed composite industry repair procedures, methods, and techniques to show how aerospace industry-wide CRM for composite materials repair will need to be implemented and standardized in order to maintain effective and safe repairs for commercial transport aircraft.

Note. Refer to Table A1 in the Capstone Project Guide (Appendix A) for *Program Outcome* correlation. The topics of ***advanced aircraft performance*** and ***rotorcraft operations*** will not be addressed because they were not included in the student's Aeronautics specialization curriculum.
[1] The topic of ***advanced aircraft/spacecraft systems*** will be sufficiently addressed with the student's applicable Aeronautics specialization curriculum core topic of ***aircraft and spacecraft development*** from the 2008-2010 Worldwide Catalog.

The Application of Advanced Composites for the Construction of Commercial Transport Aircraft

Project Introduction

With the manufacturing of new composite transport aircraft such as the Boeing 787 *Dreamliner* and Airbus A350 *XWB*, multi-national regulatory agencies (FAA and EASA) have addressed the industry concerns of using carbon fiber reinforced polymers (advanced composites) for primary and secondary aircraft structures (wings, fuselage, and empennage). This has been accomplished here in the United States through the formation of the *Joint Advanced Materials & Structures Center of Excellence* (JAMS) in 2003 by the FAA for the Air Transportation Centers of Excellence under the FAA Research, Engineering and Development Authorization Act of 1990. After the first JAMS Technical Review Meeting was conducted in 2005, annual coordination meetings have been taking place in-conjunction with the following composite materials standardization organizations: CMH-17 (Composite Materials Handbook) and ASTM International Committee D30 on Composite Materials. These organizations along with the JAMS partnership research universities (University of Washington and Wichita State University), combined with over 200 industry members from all over the world, converge in an open forum environment for the sole purpose of presenting studies and data in order to advance the field of polymer matrix composites in the aerospace industry. This type of collaboration is necessary (and critical) not only for updating composite materials standards, but it also allows for new research and data to be presented that can be used by manufacturers and the FAA. As aerospace manufactures increase the use and integration of advanced composites for Part 25 aircraft, increased industry collaboration will also be required for its continued and safe use.

Literature Review

The Impact of Composite Aircraft on Air Transportation

Validation Testing

In order to receive FAA certification, all aircraft manufacturers must prove (through validation testing) that their aircraft meet the structural criteria as prescribed in Part 25 regulations. Under the Code of Federal Regulations (CFR) for the Airworthiness Standards of Part 25 (Transport Category Airplanes), subpart (a) under § 25.307 (Proof of Structure) states:

> Compliance with the strength and deformation requirements of this subpart must be shown for each critical loading condition. Structural analysis may be used only if the structure conforms to that for which experience has shown this method to be reliable. The Administrator may require ultimate load tests in cases where limit load tests may be inadequate (Government Printing Office [GPO], 1990, Subpart C – Structure § 25.307).

This requirement revealed the need for new validation testing of primary structural composite components used for the construction of transport aircraft based on the fact that this type of structural analysis had not yet been accomplished or proven reliable as in the case of Boeing's new 787 *Dreamliner*. From a *multimodal transportation system* perspective, this regulatory requirement impacts the air transportation industry (commercial transport aircraft manufacturers) by creating a new demand for structural analysis that must be proven reliable to regulatory administrators before aircraft certification can be considered. The burden of proof for new structural analysis rests solely with the manufacturer in order to keep up with the performance demands of the industry which will also include high uncertainty and risk (Wells & Wensveen, 2004).

For 787 *Dreamliner* structural validation testing, Boeing contracted NSE Composites to develop damage tolerance analysis methods for the wings and fuselage structures. NSE was able to combine large-scale wing and fuselage tests from Boeing with finite element models in order to predict the necessary strength curves required for the performance envelope of the aircraft (NSE Composites [NSE], "n.d.", Aerospace Projects). NSE used the strength curve modeling to develop engineering guidelines for the sizing of 787 structural components. In order to prove and validate that the design was sufficiently damage tolerant, testing was performed on structural stringers with large notches/damage to show that the aircraft can still fly safely even if damage occurs to primary structural components such as the wings or fuselage (NSE, "n.d.", Aerospace Projects). This method of damage tolerance analysis developed by NSE was the initial structural validation needed for Boeing to show regulatory administrators that the 787's design was sufficient to meet Part 25 structural requirements.

FAA Certification Requirements

Recognizing that CFR Part 25 did not address the use of composite materials for the construction of transport aircraft, the FAA released AC 20-107A (Composite Aircraft Structure) in April of 1984 which has been superseded with the release of AC 20-107B in September of 2009, and Change 1 release in August of 2010. This is the most current FAA certification requirements publication for the airworthiness standards of composite aircraft structures. However, as AC 20-107B was published as a means to provide guidance for the use of composite materials in-conjunction with CFR Part 25 regulations, its purpose is exactly that (for guidance only) and as AC 20-107B states: "is not mandatory or regulatory in nature" (Federal Aviation Administration [FAA], 2009, p. 1). What this means is that while Part 25 was first established for traditional transport aircraft structures and was void of any composite structure regulations, it is still the governing publication for certification requirements. AC 20-107B was published for composite aircraft structure guidance to be used in-conjunction with the regulations published in Part 25. According to Dr. Melanie Violette of the FAA, final (adherence to) and compliance with all applicable regulations and guidance governing the use of composite materials for the construction of transport aircraft is the responsibility of the manufacturer and will dictate the certification process (M. G. Violette, personal communication, April 9, 2013). With respect to the *multimodal transportation system* and air transportation industry, this philosophy supports the FAA's responsibility for the safety of civil aviation by maintaining and enforcing regulations and minimum standards for the manufacturing and certification of composite structure transport aircraft (Wells & Rodrigues, 2004, p. 2).

Structural Integration

Early uses of composite materials for the construction of commercial transport aircraft included secondary and ancillary structures such as doors, engine nacelles, control surfaces, and nose radomes starting with the Boeing 747 in 1970 (Stickler, 2002). Typical composite use/type for early applications included light-weight sandwich construction that consisted of thin face sheets with a honeycomb core that was prone to water intrusion (Stickler, 2002). Boeing and Airbus began using advanced composites in structural applications in the 1990's with the 777 and A320; Boeing's 777 entire empennage assembly is constructed with advanced composites. Figure 1 shows the progression of composite material integration by aircraft model and percentage of use in relation to structural weight (Stickler, 2002, figure 1). With Boeing's recent integration of advanced composites in primary structures construction (wings and fuselage) for the 787 *Dreamliner*, the industry's first full structural integration for a commercial transport aircraft has now been achieved and is shown in Figure B1 (Appendix B) by the breakdown in materials used for the 787's construction ("Boeing 787," 2006, p. 18-19).

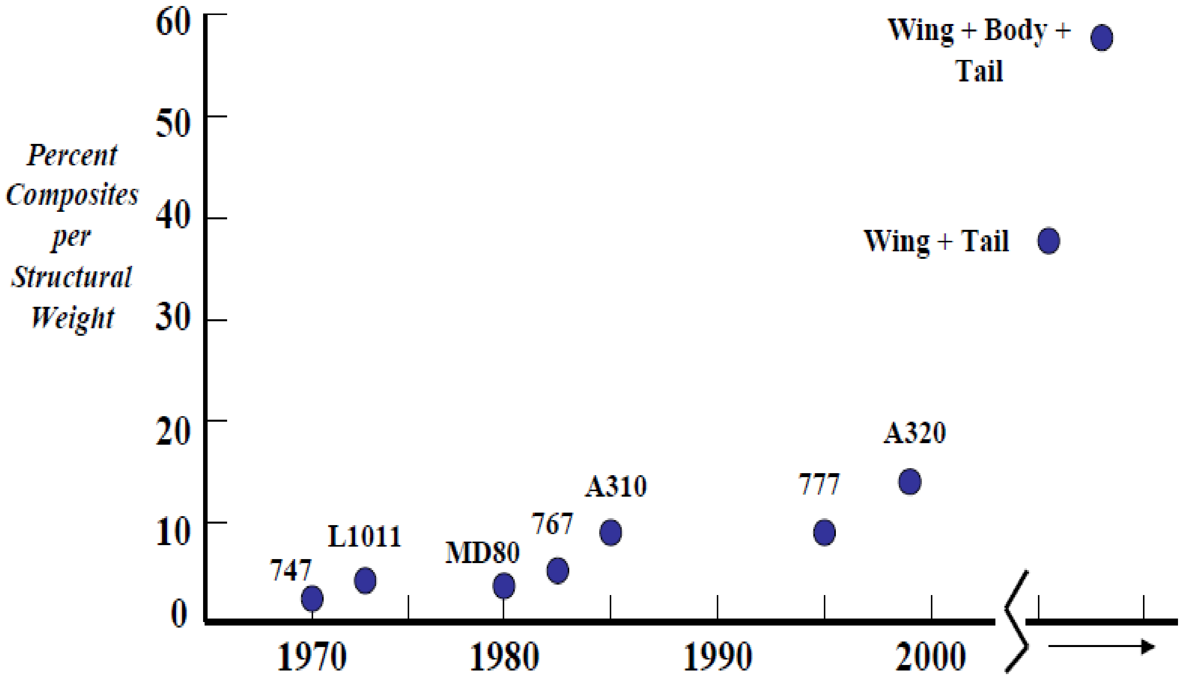

Figure 1. Timeline progression of integration showing aircraft model and percent of composite materials used in relation to total structural weight. Reproduced from "Introduction – Composites use in Commercial Transport Aircraft," by P. B. Stickler, 2002, *Composite Materials for Commercial Transport – Issues and Future Research Direction, Figure 1*, p. 2.

Dr. Patrick B. Stickler's research study conducted in 2002 suggested that further integration and increased use of advanced composites for the construction of commercial transport aircraft will occur based on the future need (and requirement) to increase manufacturing efficiency and lower operating costs for the airlines in order to sustain the industry (Stickler, 2002). This was proven with the development of the Boeing 787 *Dreamliner* starting in 2003, and then finally entering service in 2011. With respect to the *technological* aspect, this advancement by Boeing in the structural integration of advanced composites for transport aircraft has yielded performance and production benefits for both industries (airline and aerospace) such as increased fuel efficiency due to the reduction of airframe weight, and the utilization of bonded joints in the manufacturing process (reducing the number of mechanical fasteners) which lowers the assembly cost. Enabling this technology has also created challenges such as focusing on new research and development efforts that create low-cost products, automated processes, new analysis methods, and the establishment of certification requirements in order to utilize advanced composites for the construction of transport aircraft (Stickler, 2002). To derive maximum benefit from advanced composite technology as its use increases within the aerospace industry will require continued research and critical analysis of milestone structural integration that exists and is being actively applied with aircraft such as the 787 by developing (and sharing) *best practice* methods throughout the industry.

Passenger Confidence

Will people feel safe flying on a commercial transport aircraft that is constructed with composite materials? This is certainly a question that Boeing had to consider in 2003 when development of the 787 began. If queried, the general population would not know the difference between a traditionally constructed aircraft (mostly aluminum) such as the 737 versus the 787 (mostly composite) until the material and construction differences are explained in detail. Hypothetically, if both aircraft were placed side-by-side at an airport, airline passengers would make a typical comparison based on both aircraft being relatively the same shape and form without much consideration given to the materials that they are constructed from. Are they concerned with or do they really care about the materials used? The most likely response (if asked) would be “no” based on the aforementioned hypothetical scenario. Their biggest concern will be safety. When contrasting the 787 with a traditionally constructed commercial transport aircraft, the Boeing 737 is the most widely used commercial aircraft in the world that has a proven safety record. This proven reliability instills a sense of security and confidence that makes passengers feel safe (Wells & Rodrigues, 2004).

Unfortunately, building passenger confidence in the first composite aircraft is on hold due to the present grounding of all Boeing 787s for lithium-ion battery modification and re-certification at the time this paper was written. With respect to the *social* aspect, even though the 787 battery issue has caused a lengthy and costly grounding period for Boeing, immediate passenger concern will be the safe return-to-flight of all 787s which will be accomplished through rigorous testing and re-certification to prove that this aircraft is once again safe and reliable (Wells & Rodrigues, 2004). After the 787 is re-certified by the FAA and given the green light to resume service, passenger concern (or social impact) regarding the confidence in composite construction will be negligible (non-existent) unless a problem arises that is specific to a composite component on the 787 found by Boeing or an operator (Garland, Wise, & Hopkin, 1999). Future research of this topic after sustained in-service time of the Boeing 787 would reveal an accurate representation of the social impact of composite commercial transport aircraft.

Environmental Impact

As previously mentioned, one of the primary advantages of increasing the use of composite materials for the construction of commercial transport aircraft is the parallel increase in aircraft performance due to the overall weight savings that are intrinsic to composites. Another intrinsic benefit previously mentioned is the increase in the manufacturing efficiency by reducing the overall part and fastener count through the use of secondary bonding (co-curing and co-bonding) techniques (Stickler, 2002) that exemplifies the *lean manufacturing* process which creates less waist in order to decrease manufacturing costs while simultaneously reducing environmental impact (U.S. Environmental Protection Agency [EPA], 2000).

By reducing the weight of an aircraft, less fuel burn is required during all phases of flight (takeoff, cruise, and landing) which immediately decreases the aircraft's CO_2 and noise footprint on the environment due to the use of reduced engine power (Fielding, 1999). For every barrel of crude oil that is refined, jet fuel (kerosene) is the third largest (by volume) refined output (approximately 4.2 gallons) per barrel (42 U.S. gallons) with gasoline as the highest (19.3 gallons) and diesel/home fuel oil being the second highest at 9.8 gallons ("Oil: petroleum products," "n.d."). With jet fuel being the third highest output of crude oil refinement, it is no surprise that the airline industry is the largest consumer of jet fuel which equates to approximately 30% of a typical airline's operating cost according to *Airlines for America* ("High airline costs," 2012). With respect to the *environmental* aspect, the immediate desire and need to decrease fuel operating costs with the use of more efficient composite aircraft in order to sustain the airline industry will have an immediate impact on the environment by reducing its dependency on fossil fuels which will lower emissions to help sustain the environment.

Regulatory Methodology

Dr. Stickler's research on the growth and increased use of composite materials in the aerospace industry conducted in 2002 states:

> The approach for composite and metallic materials involves analysis supported by coupon thru component level test evidence. Analysis approaches and structural testing is performed in compliance with FAA/JAA regulations. The "analysis supported by test evidence" approach is accomplished by establishing material allowables, performing element level tests on structural details such as joints, subcomponent, and full-scale component level tests on wings, fuselage barrel sections and horizontal and vertical stabilizers (Stickler, 2002, p. 2).

This methodology supports current FAA guidance for the certification of composite aircraft (as previously discussed) and was first used and evidentiary in Boeing’s approach with early composite certification for the 777 that included static and fatigue full-scale testing of the horizontal and vertical stabilizers which are constructed with advanced composites (Stickler, 2002).

The FAA realized the need for continued improvement and development of the certification process for composite materials used in the aerospace industry based on increased use by aerospace manufacturers for the construction of Part 25 commercial transport aircraft by forming the *Joint Advanced Materials & Structures Center of Excellence* (JAMS) in 2003 for the Air Transportation Centers of Excellence under the Federal Aviation Administration Research, Engineering and Development Authorization Act of 1990 ("FAA Creates Center of Excellence," n.d.). The center’s primary focus is on “the safety and certification of existing and emerging applications of composites and advanced materials in commercial transport aircraft.” ("FAA Creates Center of Excellence," n.d., About Us).

In September of 2011, the U.S. Government Accountability Office published its own independent report on the safety of composite commercial transport aircraft in order to review FAA and EASA certification processes based on the safety concerns associated with transport aircraft constructed primarily with composite materials in structural areas (wings and fuselage) for the Boeing 787, which is the first large commercial transport aircraft to undergo this certification process (U.S. Government Accountability Office [GAO], 2011). The findings of this report will be discussed later, and presented in the meta-analytic review section of this project. With respect to the *political* aspect, this GAO report is a prime example of government oversight for the purpose of checks and balances within its own (and joint) administrations in order to verify that the process of certification and all applicable standards of regulation have been adhered to.

The Human Factors Associated with Composite Repair and Maintenance

Component Failure

According to Mr. Kenneth Cooper[2] and Mr. Timothy Moore of the U.S. Navy's Fleet Readiness Center Southwest Advanced Composite Repair School at Naval Air Station North Island, California, advanced composite component failure due to substandard repair is probable and likely to occur based on lack of experience and the complexity of the repair procedures (K. Cooper, personal communication, December 3, 2012). All repair procedures for advanced composite components used in structural and high-load applications are extremely complex and difficult to master. Special care and extreme attention-to-detail must be maintained throughout the entire repair process in order to comply with the strict guidelines and procedures as prescribed in the applicable *structural repair manual* (SRM). If not followed correctly, significant change in part stiffness could cause excessive part deflection, improper function, and dynamic instability which could lead to structural failure (Naval Air Systems Command [NAVAIR], 2011).

With respect to *unsafe acts*, regardless of either intentionally or unknowingly performing improper composite repair, the resulting effects will increase the probability of components returned to service that are insufficiently capable of handling their designed load tolerances which could lead to structural or catastrophic failure (NAVAIR, 2011).

[2] *Mr. Kenneth Cooper is a Master Composite Materials Repair Artisan and Advanced Composites Work Leader/Training Instructor, and Mr. Timothy Moore is the Training Specialist/Master Composite Materials Repair Artisan at FRCSW, NAS North Island, CA.*

Composite Repair Methods

According to Dr. Lamia Salah of the National Institute for Aviation Research at Wichita State University, current composite repair at the depot level (airline maintenance) is deficient in the areas of composite repair technician training and quality control (Salah, 2013). Dr. Salah's research and findings will be presented in the meta-analytic review section of this project. While Dr. Salah's research of airline composite maintenance practices revealed severe deficiencies in the areas of training and quality control, *original equipment manufacturer* (OEM) in-house practices by Boeing are currently being reviewed for training standardization according to Ms. Holly Thomas of the Boeing Company (H. Thomas, personal communication, April 9, 2013). Based on these observations, the *attitudes* aspect of human factors regarding the repair and maintenance methods for composite materials may indeed have a very strong impact on the quality of repairs being carried out on all levels (Hawkins, 1993). With the advent of composite commercial transport aircraft, in-service damage will occur and will need to be effectively repaired. As previously discussed, due to the critical nature of composite repair, it is imperative that the repair methods used (at every level) are standardized throughout the industry. Based on Dr. Salah's research, this concern validates the need for further research of this topic in order to actively engage all applicable industry professionals for the development of standardized repair and maintenance methods/procedures for composite materials used in the aerospace industry.

Artisan Training and Experience

As previously mentioned, the SRM procedures for repairing advanced composites are extremely difficult and require extensive training and practice in order to become proficient with the many complex repair procedures. Some of the common types of advanced composite field repairs that are taught by the U.S. Navy include bonded repairs such as standard wet layups, double vacuum debulk (DVD) wet layup, delamination/disbond repair, pre-cured patch repair, and substructure (honeycomb) repairs (NAVAIR, 2011). Refer to Figures 2-5 for an illustration of the DVD advanced composite repair method. With respect to the *human limitations* aspect, it cannot be overstated that mastery and proficiency of these repair methods and procedures will be critical in order for the repair to be correct and free of defects. Without proper training, experience, and proficiency, the probability of *error* will be much greater (Garland, Wise, & Hopkin, 1999).

Figure 2

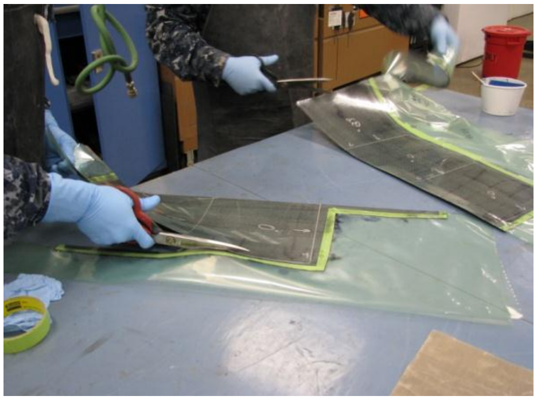

Figure 3

Figure 4

Figure 5

Figures 2-5. Illustration of the U.S. Navy's 9-ply artisan certification panel using the double vacuum debulk (DVD) wet layup repair procedure that all technicians have to perform in order to become certified to perform DVD repairs for their type/model aircraft. The DVD process is an extremely labor-intense and complex evolution that involves starting with dry woven carbon-fiber fabric ply preparation/fiber orientation, and then laying up each ply in the correct orientation after resin impregnation (*Figures 2-3*). The 9-ply laminate is then placed on a double vacuum bench for heat curing (*Figures 4-5*). The DVD method was developed by the U.S. Navy (NAWC Warminster) to produce superior repairs in order to eliminate porosity (small voids) that cause strength degradation (NAVAIR, 2011). Photos provided by K. Cooper, U.S. Navy.

The U.S. Navy has multiple levels of repair artisan training with proficiency standards in order to become a qualified composite repair technician. After the technician receives artisan training, proficiency must be maintained through practical repair experience. If proficiency (by making frequent repairs) is not maintained, the artisan's skills will diminish over time and repeat proficiency training may be required depending on the time lapse between repairs. This information suggests that the U.S. Navy's standard of training and certification for composite repair could be used as a model program for standardization throughout the aerospace industry.

Non-Standard Repairs and Maintenance Malpractice

For the purpose of discussion, it is assumed that *aircraft maintenance technicians* (AMTs) would not intentionally or maliciously perform composite repair incorrectly based on the potential results of that *human behavior*; possible catastrophic failure with loss of life (Garland et al., 1999). Based on the previous statement, then any (or all) defective composite repairs can be attributed to either maintenance malpractice or the environmental condition at the time of repair (Salah, 2013). When considering the malpractice factors for improper/non-standard or substandard composite repair (excluding intentional acts), SRM procedural violations due to unfamiliarity (lack of proper training), or non-use of SRM procedures stand out as the cause of malpractice.

As previously discussed, performing bonded repairs on advanced composites used in structural applications is complex and also time-consuming; if performed incorrectly, the likelihood of structural failure is high. Conditions for field repairs may not always be adequate for airline maintenance technicians that are performing composite repairs. Constraints such as short aircraft turnaround time would cause inadequate time allotted for a complex repair procedure, and the environment in which the repair is being performed (moisture/high humidity) have been identified as causal factors for defective/substandard repairs (Salah, 2013). Also, field repairs made by airline maintenance technicians are not performed with the same systems used at the OEM level such as autoclave processes that provide the optimal (heat and pressure) conditions for part production (Salah, 2013). However, it has been shown in Dr. Salah's research that maintenance technician training and experience directly affects the quality and structural integrity of a bonded repair (Salah, 2013) which validates the impact of the *human behavior* aspect with respect to improper/non-standard or defective/substandard composite repairs that are performed at all levels (airline, intermediate repair facilities, and OEM).

Aeronautics Discussion

Performance and Design Innovation

Boeing has indeed challenged the boundaries of the commercial transport aircraft industry with the development and manufacturing of the 787 *Dreamliner*, which is the first commercial transport aircraft in the industry that uses composite materials for its primary structures (wings and fuselage). By being the first commercial aircraft manufacturer to make the transition from traditional metallic construction to composite materials for primary structures, Boeing is demonstrating *Blue Ocean*[3] innovation (Tidd & Bessant, 2009, p. 171).

Monolithic and sandwich structures.

The two most common types of advanced composite structures used in primary and secondary structural aircraft applications are monolithic *carbon fiber reinforced polymer* (CFRP) and sandwich construction. Monolithic construction typically consists of multi-ply CFRP laminate panels that are used for a variety of aircraft parts and components such as panels, structural parts, and entire fuselage sections (Boeing 787) as illustrated and explained further in Figures B4-B7 (Appendix B). Advanced composite sandwich construction typically consists of a honeycomb core made from aluminum that is covered with two (top and bottom) carbon fiber face sheets bonded to the core with an adhesive in order to create a high-strength and light-weight structure that is used for control surfaces, wings, and the empennage where greater structural loading occurs. As previously mentioned, honeycomb sandwich construction was one of the very first applications of composite materials by the aerospace industry, and has been used for several decades. Typical honeycomb sandwich construction is illustrated in Figure 6.

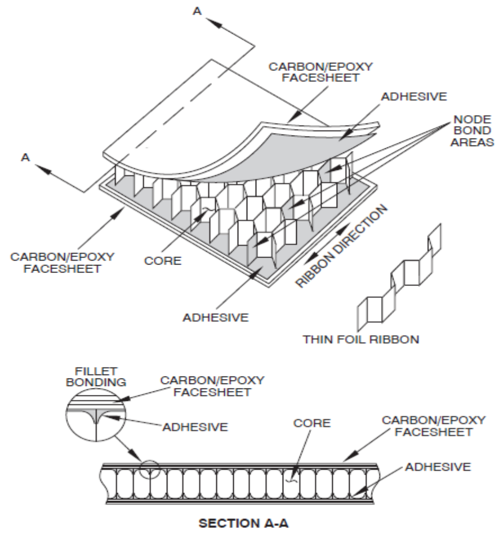

Figure 6. Illustration of typical aluminum honeycomb sandwich construction. The strength of the core material is determined by its hexagonal cell size, material type, and foil thickness (NAVAIR, 2011, p. 5-8). Reproduced from “Honeycomb Core Repair Sections,” by Naval Air Systems Command, 2011, *General Composite Repair*, *Change 1,* p. 5-9, Figure 5-2.

Performance benefits through improved design characteristics.

The immediate performance benefit gained from using composite materials for the construction of commercial transport aircraft (or any aircraft) is the reduction in airframe weight due to the light-weight characteristics of composites which increases the overall efficiency of the aircraft. The 787 nets close to 20% weight savings with the use of composite materials when compared to a traditional metallic airframe of roughly the same size ("Boeing 787," 2006). This increase in efficiency will translate into fuel savings; one of the key performance benefits that the operators (airlines) will desire in order to lower their operating costs. Another major benefit of using composite materials is the relative ease in creating unlimited design configurations that contain complex shapes and curves which is more difficult, time-consuming, and costly with traditional metallic aircraft construction (Stickler, 2002). This can be seen by the elegant features of the Boeing 787 *Dreamliner* as illustrated in Figures B2 and B3 (Appendix B), paying close attention to the shape of the wings, the curves for the blended wing tips and vertical stabilizer, and the smooth transition of the nose and cockpit. This is due in part to the autoclave manufacturing process associated with composite materials that allow parts and components to be molded into almost any shape which yield high strength and stiffness for aerospace applications. With respect to the topic of *advanced aerodynamics*, the use of composite materials for the manufacturing of transport aircraft that utilize complex shapes and curves in their design will create a more efficient streamlined aircraft design. This streamlined design (through the use of complex shapes and curves) will also increase the aircraft’s aerodynamic efficiency by increasing the laminar characteristics (decreasing turbulent airflow) which will lower the drag coefficient (c_d) due to the unlimited shape possibilities of composite materials that effectively create a streamlined design (Anderson, 2008). This increase in aerodynamic efficiency combined with the weight savings gained through the use of composite materials decreases the aircraft fuel burn rate, making the Boeing 787 20% more fuel efficient when compared to a traditional commercial aircraft of the same size (The Boeing Company, n.d.).

[3] *Blue Ocean innovation represents all potential markets which currently do not exist and must be created.* (Tidd & Bessant, 2009, p. 171)

Fatigue Life and Failure Mode

Another intrinsic characteristic and benefit of composite materials is improved fatigue performance over metallic structures which will increase airframe service life and reduce maintenance costs (Stickler, 2002, p. 2). However, the poor out-of-plane load transfer characteristics of composite materials have proven to be challenging for engineers to predict and accurately model failure mode. Due to the complex nature of the failure modes associated with composite materials, extensive *non-destructive inspection* (NDI)[4] testing is required to detect the flaw growth within a composite component (Seneviratne, 2008). In Mr. Waruna Seneviratne's research for the *National Institute for Aviation Research* (NIAR), it was found that even though the loading and failure modes for composite commercial transport aircraft structures are significantly different, current certification programs use the load-life factors generated by the U.S. Navy's F/A-18 program (Seneviratne, 2008, p. 2) based on the fact that these are the only known load-life factors for composite materials structural applications. Mr. Seneviratne's primary research objective suggested a probabilistic approach to synthesize life factor, load factor, and damage in composite structures to determine fatigue life (Seneviratne, 2008, p. 3).

Modeling and simulation systems.

Some of the modeling and *simulation systems* used to predict fatigue and failure mode in composite materials include: *double cantilever beam* (DCB), *four points end notched flexure*

(4ENF), *3D plane strain modeling*, and *finite element analysis* (FEA). The most common and robust FEA simulation system currently being used in the aerospace industry for composite materials is *SIMULIA Abaqus* developed by Dassault. *Abaqus* performs virtual tests with realistic simulation which helps reduce product development time and costs while improving reliability (Dassault Systemes, n.d.). According to Dr. Ernest L. Roetman[5], robust simulation modeling in-conjunction with new research and approaches to theoretical problem-solving will be required for the development of new *non-destructive testing* (NDT) computational methods that address the dynamic problems of *anisotropic*[6] materials in order to effectively create new analysis tools for the prediction of composite materials fatigue and failure mode (E. L. Roetman, personal communication, April 16, 2013).

[4] *The NDI method most commonly used to detect damage in aerospace composite components is pulse-echo ultrasonic (UT) scanning.* (Buckley, 2006)

[5] *Dr. Ernest L. Roetman is an Adjunct Professor for ERAU Worldwide and is recognized as one of the leading professionals in the field of non-destructive testing for composite materials.*

[6] *Anisotropic properties (dependent/differs based on direction) are common to composite materials due to the multi-directional fiber construction which exhibits different or varying properties depending on the axis or plane.* (NDT Education Resource Center, n.d.)

Lightning Strike Protection

Lightning is a discharge of electricity (giant spark) that is typically associated with a thunderstorm that can occur inside a cloud, from cloud to cloud, from a cloud to the air, or from a cloud to the ground (Ahrens, 2009, p. 389). The destructive nature of the electrical current and heat associated with a lightning strike (around 54,000°F) posses a significant threat to composite materials used in aerospace applications due to their poor electrical conductivity characteristics and susceptibility to weaken when exposed to high heat. Traditionally constructed aircraft with metallic (aluminum) airframes are excellent conductors of electricity which will allow the electrical discharge of a lightning strike to flow through and exit as if it were a piece of wire; the metallic airframe is simply completing the electrical circuit (Severson, 2012). The following is true for a metallic aircraft provided that the entire airframe is electrically bonded:

> As long as the electrical circuit is not interrupted (does not encounter resistance), the lightning strike will be able to flow through the external skin of the aircraft without causing any damage. Poorly fastened joints or gaps could cause arcing and burning when the electrical current from the lightning strike tries to continue its path by jumping to the closest piece of metal (Severson, 2012, p. 8).

To clarify and emphasize this point, if electrical bonding is maintained throughout the metallic airframe and metallic aircraft skin, the aircraft should be sufficiently protected from a lightning strike and simply act as a large electrical circuit. The same holds true for a composite aircraft with some differences. The FAA's AC 20-107B, *Composite Aircraft Structure*, under part 11 (Additional Considerations), subpart (c) Lightning Protection states:

> Lightning protection design features are needed for composite aircraft structures. Current carbon fiber composites are approximately 1,000 times less electrically conductive than standard aluminum materials, and composite resins and adhesives are traditionally non-conductive. Glass and aramid fiber composites are non-conductive. A lightning strike to composite structures can result in structural failure or large area damage, and it can induce high lightning current and voltage on metal hydraulic tubes, fuel system tubes, and electrical wiring if proper conductive lightning protection is not provided (FAA, 2009, para. (c), p. 26).

As AC 20-107B recognizes, composite materials (fibers, resins, and adhesives) are non-conductive and must be given conductive properties in order to be adequately protected and to protect critical aircraft systems (hydraulic, fuel, and electrical) from the potential catastrophic damage caused by lightning strikes. This is accomplished by adding a wire mesh layer to the external ply of a composite laminate in order to make the entire panel or component electrically conductive as illustrated in Figure 7 (Dexmet Corporation, 2007). When properly bonded with other composite components and panels that have been made conductive with wire mesh, the same conductive qualities (and protection) inherent to metallic components can now be achieved with composite structures (Severson, 2012). This is especially important for aircraft such as the Boeing 787 that use advanced composites for the entire skin of the fuselage, wings and empennage.

Lightning strike protection (LSP) for composite materials used by the aerospace industry was a valid and known concern early on (several decades ago), and has been properly addressed by the FAA with the applicable LSP *Aircraft Circulars* (ACs) as prescribed in AC 20-107B for certification guidance with respect to LSP and how to mitigate the specific risks for composite structures (FAA, 2009).

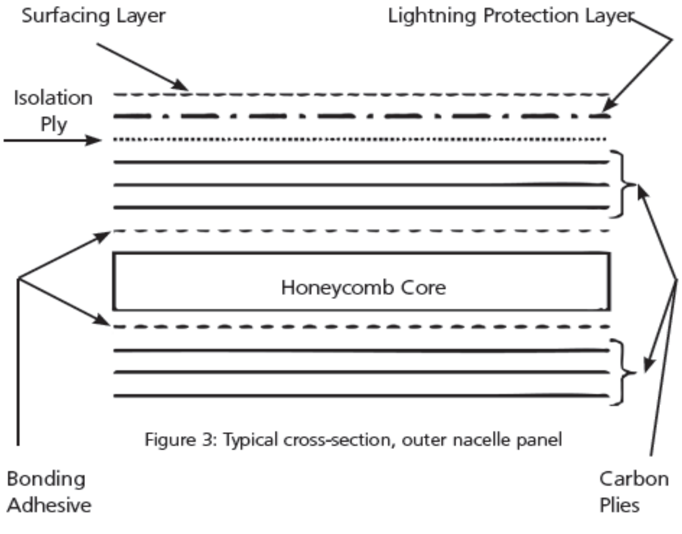

Figure 7. Illustration of protective wire mesh imbedded within typical honeycomb construction. Reproduced from “Lightning Strike Testing Results on Honeycomb Panels Protected with a Series of Dexmet Microgrid® Products,” by the Dexmet Corporation, 2007, *Lightning Strike Protection for Carbon Fiber Aircraft, Figure 3,* p. 2.

Industry Concerns

Validation testing and load data.

When discussing the topic of *aircraft and spacecraft development*, any newly developed aircraft will have system validation concerns that are identified and must be addressed (proven reliable) through proper testing (Fielding, 1999). With respect to the first large-scale application of composite materials for primary structures (fuselage and wings) for a commercial transport aircraft, structures validation (for certification) must be performed through *coupon testing*.[7] However, since there is no pre-existing load data for such an aircraft, actual in-service load data collection may be required in order to correct possible deficiencies that could not be produced during developmental simulation due to a lack of proven data for *load enhancement factor* (LEF)[8] computation (FAA, 2009). In-service *structural health monitoring* (SHM) for large-scale composite transport aircraft will be vital for the collection of working load data in order to accurately compute LEF for future applications (Stickler, 2002).

The utilization of structural health monitoring (SHM) for load monitoring.

Structural health monitoring (SHM) has been used in the aerospace industry for several decades through many different techniques that include simple strain gauges affixed to load-bearing structures, to more advanced devices such as piezoelectric actuators/sensors called *SMART Layers™* that can be surface-mounted or embedded within the structure (Lin, Qing, Kumar, & Beard, 2005) similar to a wire mesh layer as previously discussed for lightning strike protection. Current piezoelectric devices such as *SMART Layers™* and the *SMART Suitcase™* that have been developed by Acellent Technologies, Inc. are extremely sensitive and robust systems of load measurement that have been proven reliable in several aerospace applications (Acellent Technologies, Inc., n.d.). The current applications of this technology for composite structures are: sub-surface damage detection (delaminations), hot-spot monitoring and crack detection, impact detection, and in-flight load monitoring (Acellent Technologies, Inc., n.d.). All of these are critical concerns for large composite structures that have been identified throughout the industry for composite transport aircraft applications. Advancements in SHM and *non-destructive testing* (NDT) technology will also be required in order to keep up with industry use by developing new and more efficient/accurate methods of monitoring and testing that will provide the empirical data needed for future applications (Stickler, 2002). One such advancement for SHM that is currently being researched by Mr. Peter Osterc[9] proposes the use of *phased array beam-steering*[10] for guided wave structural health monitoring by developing a new beam-forming algorithm that is specific to composite materials (Osterc, Kim, & Yoo, 2012). This type of research is indicative of observed advancement needs that address developmental process improvements directed towards existing material concerns for the continued use of advanced composites in the aerospace industry.

FAA methodology and GAO safety concerns.

As previously discussed, the FAA has been taking a very proactive approach in collaborating with industry leaders to address the concerns with the expanded use of composite materials in the aerospace industry by sponsoring research organizations such as the *Joint Advanced Materials & Structures Center for Excellence* (JAMS), and the *Commercial Aircraft Composite Repair Committee* (CACRC) which is responsible for the development of improved maintenance, inspection, and repair of commercial aircraft composite structures and components (GAO, 2011, p. 34). The 2011 GAO report *Status of FAA's Actions to Oversee the Safety of Composite Airplanes* stated the following regarding safety concerns specific to composite repair and maintenance:

> On the basis of expert interviews and a review of literature, GAO identified four key safety-related concerns with the repair and maintenance of composites in commercial airplanes – (1) limited information on the behavior of airplane composite structures, (2) technical issues related to the unique properties of composite materials, (3) standardization of repair materials and techniques, and (4) training and awareness. None of the experts believed these concerns posed extraordinary safety risks or were insurmountable. FAA is taking action to help address these concerns identified by GAO related to the repair and maintenance of composite airplane structures. However, until these composite airplanes enter service, it is unclear if these actions will be sufficient (GAO, 2011, para. What GAO Found).

Based on this information and recent research presented by Dr. Lamia Salah (CACRC Committee Member), it is apparent that the industry concern of commercial aircraft composite maintenance and repair is sufficiently valid and must be addressed, but also suggests that it is too early for assessment of this concern based on the lack of in-service time of composite aircraft.

Composite materials fire safety concern.

Fire safety for large composite commercial transport aircraft such as Boeing’s 787 has been a valid concern since its initial development with respect to crashworthiness and passenger safety due to the flammability of the components used for composite materials (fiber, resins, and adhesives). Most composite materials in their raw form are vulnerable (can weaken) when exposed to high-heat and are less fire resistant than traditional metallic structures if a protective coating is not used (Ohlemiller & Shields, 1998). The FAA was aware of this safety hazard with the early use of composite materials for air transport applications and implemented extensive guidelines under AC 20-170B *Composite Aircraft Structure* that addresses the mitigation required for proper fire protection which initially states under part 11 (Additional Considerations) subsection (b) Fire Protection, Flammability and Thermal Issues:

> **(1)** Fire and exposure to temperatures that exceed maximum operating conditions require special considerations for composite airframe structure. (Refer to note below) Requirements for flammability and fire protection of aircraft structure attempt to minimize the hazard to occupants in the event that flammable materials, fluids, or vapors ignite. ***The regulations associated with each aircraft product type (i.e., transport, small airplane, rotorcraft) should be used accordingly.*** Compliance may be shown by tests or analysis supported by test evidence. A composite design, including repair and alterations, should not decrease the existing level of safety relative to metallic structure. In addition, maintenance procedures should be available to evaluate the structural integrity of any composite aircraft structures exposed to fire and temperatures above the maximum operating conditions substantiated during design (FAA, 2009, para. (b), p. 24).
>
> > **Note:** Aircraft cabin interiors and baggage compartments have been areas of flammability concerns in protecting passenger safety. This revision of the AC does not address composite materials used in aircraft interiors and baggage compartments. Please consult other guidance material for acceptable means of compliance with flammability rules for interiors.

Boeing 787 special conditions.

In the previously discussed GAO report that addresses composite aircraft safety concerns, the FAA required Boeing to conduct fire tests as delineated in AC 20-170B for the certification of the fuselage and wings as outlined in Table 1. This special condition testing was performed in-part by Boeing Aircraft Rescue and Firefighting (ARFF) professionals in June of 2012 with conclusive results that showed the 787’s combustion hazard was similar to that of a metallic structured aircraft, and that the toxicity levels of the 787’s skin panels were also similar to that of a metallic structure aircraft (The Boeing Company, 2012). It was also shown in Boeing's flame tests that "composite fuselage structures do not sustain combustion and do not aid in the spread of fire" (The Boeing Company, 2012, p. 5) which is in compliance with the FAA's special condition test "to show that the 787 composite fuselage is resistant to flame propagation." (GAO, 2011, table 1) Overall, the tests showed that composite structures did not exhibit any flame propagation characteristics, and that they actually had slower burn-through times than aluminum structures with lower radiant heat transfer (The Boeing Company, 2012, p. 5).

Table 1

FAA Special Conditions for the Boeing 787 (Fire Testing for the Fuselage and Wings)

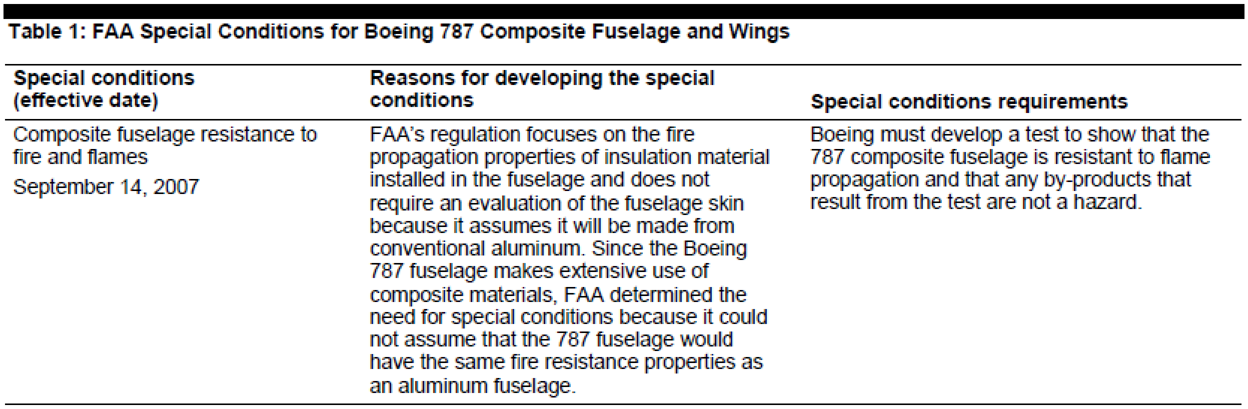

Table 1: FAA Special Conditions for Boeing 787 Composite Fuselage and Wings

Special conditions (effective date)	**Reasons for developing the special conditions**	**Special conditions requirements**
Composite fuselage resistance to fire and flames September 14, 2007	FAA's regulation focuses on the fire propagation properties of insulation material installed in the fuselage and does not require an evaluation of the fuselage skin because it assumes it will be made from conventional aluminum. Since the Boeing 787 fuselage makes extensive use of composite materials, FAA determined the need for special conditions because it could not assume that the 787 fuselage would have the same fire resistance properties as an aluminum fuselage.	Boeing must develop a test to show that the 787 composite fuselage is resistant to flame propagation and that any by-products that result from the test are not a hazard.

Note. Reproduced from "FAA Established Special Conditions for Boeing to Demonstrate That the 787's Composite Airframe Meets Existing Safety Levels," by U.S. Government Accountability Office, 2011, *GAO Report, GAO-11-849,* Table 1, p. 16.

In summary, the industry concerns that have been discussed are unique aircraft developmental processes that needed to be addressed by Boeing and its industry partners for the development and construction of the first composite commercial transport aircraft, and will need to be continued throughout the entire life cycle of the 787 in order to effectively improve design characteristics for the enabling of future composite materials technology. However, current research has identified that composite maintenance and repair is an observed limitation that exists within the industry which may cause future safety concerns regarding the continued use of advanced composites for commercial transport aircraft. With respect to the sustainability of advanced composites used for structural applications within the aerospace industry for Part 25 aircraft, continued in-service time will be required to fully assess the adequacy of current actions and to allow for the identification and correction of unexpected deficiencies that may occur.

[7] *Composite coupon testing is a small test specimen (e.g., usually a flat laminate) for evaluation of basic lamina or laminate properties or properties of generic structural features (e.g., bonded or mechanically fastened joints).* (FAA, 2009, Appendix 2)

[8] *Load (or Life) Enhancement Factor (LEF) is an additional load factor and/or test duration applied to structural repeated load tests, relative to the intended design load and life values, used to account for material variability. It is used to develop the required level of confidence in data.* (FAA, 2009, Appendix 2)

[9] *Mr. Peter Osterc is a Graduate Student at Embry-Riddle Aeronautical University's Department of Aerospace Engineering, Daytona Beach, Florida.*

[10] *Electronic beam-steering is a method of non-destructive evaluation (NDE) developed and used for metals.* (NDT Education Resource Center, n.d.)

Maintenance and Repair Standardization

When discussing and applying the topic of *crew resource management* (CRM) for composite repair standardization, teamwork and organizational factors will dictate how standard operating procedures (SOPs) are formed which will directly impact the safe maintenance of composite transport aircraft (Kanki, Helmreich, & Anca, 2010). As previously discussed, composite repair and maintenance was found to be a valid safety concern in the GAO report that addressed composite aircraft safety. Both the GAO report and Dr. Lamia's research show that there is an immediate need for standardization of composite repair throughout the aerospace industry with specific concentration at the airline level on training and quality control. Dr. Lamia has identified that even though the published *structural repair manual* (SRM) procedures for specific composite repairs applicable to the type/model aircraft are being utilized (and have been developed) based on current industry standards and best practice methods, variances in repair techniques exist between each depot (airline) facility due to a lack of training and experience (Salah, 2013).

Mitigating composite material repair variance and technician training deficiency at all levels (OEM, airline, and intermediate) is the mission of the *Commercial Aircraft Composite Repair Committee* (CACRC) in order to “reduce the cost of maintaining composite structures through standardization of materials, technique, and training.” (Commercial Aircraft Composite Repair Committee [CACRC], n.d., Mission Statement) To date, the CACRC’s repair technique task group has published eight documents with another six (pending) for the standardization of common composite repairs such as wet layup and vacuum bagging.

OEM level training development and standardized repairs.

As previously mentioned, Boeing is actively pursuing composite repair training standardization for all of its manufacturing facilities (commercial and military) which is currently in the developmental stage according to Ms. Holly Thomas of the Boeing Company (H. Thomas, personal communication, April 9, 2013). According to Ms. Kirsten Bossenbroek of the Boeing Company, Boeing’s approach to composite repair standardization for the 787 was the development and implementation of a *quick composite repair* (QCR) kit that is used to perform *pre-cured patch* repairs (see note) in less than one hour with a cure time of 30 minutes, making this process/type of composite repair (when applicable) highly beneficial to the airlines for short maintenance turnarounds in order to reduce aircraft down time. The QCR kit has been distributed to all 787 operators along with proper training for its use in accordance with the applicable SRM composite repair procedures for pre-cured patch use (K. Bossenbroek, personal communication, April 29, 2013).

Note. The utilization of a pre-cured patch repair (while common) may not apply to all composite repair situations and will depend on the type/severity of damage. With ALL composite damage, thorough inspection (NDI) must be performed for complete damage assessment (NAVAIR, 2011).

Implementation of organizational crew resource management (CRM).

The concept of CRM can be applied to the problem of composite maintenance and repair standardization by addressing factors such as organizational cultures and subcultures which are directly related to the type/style of leadership and mid-level managers (Kanki et al., 2010). Depending on how well any organization recognizes and deals with these organizational cultures and subcultures is a direct reflection of that organization's measure of health with respect to its safety culture, and the first step to creating a working safety culture is to develop and refine an organization's *standard operating procedures* (SOPs) (Kanki et al., 2010, p. 71).

By taking the basic approach of CRM which is to focus on attitudes, behavior, and performance, SOP's can be developed for composite maintenance and repair by creating a philosophy that states how the organization will conduct their composite maintenance and repair in a safe and efficient manner that is in compliance with all published procedures and regulations (Kanki et al., 2010). As composite maintenance and repair will become more common-place for airline maintenance departments with the arrival of composite commercial transport aircraft such as the Boeing 787 *Dreamliner* and the Airbus A350 *XWB*, a CRM based approach to composite maintenance and repair standardization can be adopted (and may be needed) in order to create a working environment that effectively addresses the challenges associated with the safe repair of advanced composites used in structural applications; in-part due to the complexity of composite repair procedures and the skill that is required to perform them correctly. This methodology in-conjunction with the CACRC will prove to be successful for composite repair standardization.

Methodology

Overview

The qualitative meta-analysis performed in this project is divided into three independent categories (validation testing, certification, and maintenance/repair) for the purpose of grouping each study used to the applicable category for isolated comparison of each group in order to validate the ***hypothesis*** that industry-wide comprehensive process improvement should be implemented and maintained for the promulgation of improved structural validation testing, certification, and standardized repair procedures. The quantitative statistical analysis performed in this project is accomplished by analyzing the data from specific studies in order to accept or reject the hypothesis and to answer this project's research question: are ***current testing, certification, and maintenance procedures for advanced composites*** used in primary and secondary commercial transport aircraft structures ***standardized throughout the aerospace industry and sufficiently capable of detecting damage or component failure***? This type of organizational analysis has been chosen based on the number/type of studies used in order to effectively extract the information presented in each study for correlation.

Meta-Analytic Review

The studies used for the meta-analysis are identified and listed by category in Table 2. Summaries of the studies with findings are presented in this section of the project for reader familiarization and are ***quoted directly*** for accuracy. Composite materials study selection was accomplished by recognizing each study's applicability to current problems/concerns and needed research/data that has been identified by regulatory agencies, standards organizations, and through industry collaboration. The project findings for each study with respect to their overall impact and effectiveness for each category will be presented in the results section of this paper.

Table 2

Composite Materials Studies Listed by Category used for the Meta-Analysis

---

Validation Testing

1. *Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures Under Repeated Loading* (J. Tomblin, W. Seneviratne)
2. ***Durability of Adhesively Bonded Joints for Aircraft Structures*** (D. Adams, K. DeVries, and C. Child)
3. *Damage Tolerance Test Method Development for Sandwich Composites* (D. Adams, B. Kuramoto)
4. *In-service Inspection Guidelines for Composite Aerospace Structures* (J. Heida, D. Platenkamp), [Study 4-1]
   NDT Inspection of Composites for In-Service Defects (T. Marshall)[a], [Study 4-2]
5. *Boeing Composite Airframe Damage Tolerance and Service Experience* (A. Fawcett, G. Oakes)
6. *Impact Damage Formation on Composite Aircraft Structures* (H. Kim)
7. ***Structural Health Monitoring for Advanced Composite Structures*** (I. Herszberg, et al.)

Certification Standards

1. *Status of FAA's Actions to Oversee the Safety of Composite Airplanes* (Government Accountability Office)
2. *FAA Composite Safety and Certification Initiatives* (L. Ilcewicz)
3. *Simplifying Certification of Discontinuous Composite Material Forms for Primary Aircraft Structures* (M. Tuttle, et al.)

Maintenance and Repair

1. ***CACRC Depot Bonded Repair Investigation – Round Robin Testing (2013 Technical Review)*** (J. Tomblin, L. Salah)
2. *CACRC Depot Bonded Repair Investigation – Round Robin Testing (2012 Technical Review)* (J. Tomblin, L. Salah)
3. *Effect of Repair Procedures Applied to Composite Airframe Structures* (J. Tomblin, L. Salah, and C. Yang), Laminate and sandwich structures. [Study 3-1]
   Effect of Repair Procedures Applied to Composite Airframe Structures (J. Tomblin, L. Salah, and C. Yang), Laminate scarf joints. [Study 3-2]

Note. Studies also used for quantitative statistical analysis (ANOVA and linear regression) are in boldface.

[a] This study is used for the test data in-conjunction with (and also contained in) *In-service Inspection Guidelines for Composite Aerospace Structures* (J. Heida, D. Platenkamp).

Qualitative Analysis Criterion

Meta-analysis hypothesis validation criterion has been established and simplified for each category. The criterion is used to specifically evaluate each study (diagnostically) in order to show hypothesis validation for the purpose of answering this project's research question. The specific criterion (arguments) for each category used to evaluate each study are as follows:

Validation Testing – does the study critically investigate (with credible research) to conclusively prove that the testing methodology presented is needed for standardization within the industry and/or regulatory agencies and has the potential for implementation?

Certification Standards – does the study critically investigate (with credible research) to conclusively prove that the certification methodology presented is effective at improving and standardizing certification processes for the industry and/or regulatory agencies?

Maintenance and Repair – does the study critically investigate (with credible research) to conclusively prove that the maintenance and repair methodology presented will effectively create standardization for the industry?

Validation Testing (VT) Studies

VT Study (1).

Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures Under Repeated Loading (J. Tomblin, W. Seneviratne)

Summary and findings of the study.

The purpose of this study was to "produce a guideline FAA document, which demonstrates a "best practice" procedure for full-scale testing protocols for composite airframe structures with examples." (Tomblin & Seneviratne, 2008, Presentation p. 2) The primary objective was to "develop a probabilistic approach to synthesize life factor, load factor and damage in composite structure to determine fatigue life of a damage tolerant aircraft" by performing the following:

> Demonstrating acceptable means of compliance for fatigue, damage tolerance and static strength substantiation of composite airframe structures. Evaluating existing analysis methods and building-block database needs as applied to practical problems crucial to composite airframe structural substantiation. Investigating realistic service damage scenarios and the inspection & repair procedures suitable for field practice (Tomblin & Seneviratne, 2008, p. 3).

The secondary objectives stated for this study are as follows:

> Extend the current certification approach to explore extremely improbable high energy impact threats, i.e. damages that reduce residual strength of aircraft to limit load capability by investigating realistic service damage scenarios and establishing inspection & repair procedures suitable for field practice. And to also incorporate certain design changes into full-scale substantiation without the burden of additional time-consuming and costly tests (Tomblin & Seneviratne, 2008, p. 3).

The findings of this study revealed the following:

> The future need for training and reliable NDI and health monitoring techniques for damage characterization during full-scale testing and service, as well as focusing further studies on extremely improbable high energy impact threats and their impact on the residual strength of the composite structure and inspection intervals (Tomblin & Seneviratne, 2008, p. 30).

VT Study (2).

Durability of Adhesively Bonded Joints for Aircraft Structures (D. Adams, K. DeVries, and C. Child)

Summary and findings of the study.

The purpose and objective of this study was to “revisit and revise the Metal Wedge Crack Durability Test ASTM D3762 in order to consider a reliable method for investigating adhesive bond durability.” The current test “provides minimal guidance regarding acceptable metal bonded joints with concerns regarding strength reduction over time due to hydration.” (Adams, DeVries, & Child, 2011, Presentation p. 3) After the researchers of this study conducted their literature review and discussions with industry stakeholders, current wedge test potential issues were identified as the following:

> Several aspects of the ASTM D3762 wedge test were identified for experimental investigation, including methods of specimen manufacturing, testing procedures, accounting for the failure mode produced (cohesion vs. adhesion), environmental conditions during testing, and the need for an improved acceptance criterion. Those aspects associated with specimen manufacturing and the initial test procedure have been investigated first. Two issues associated with the wedge specimen manufacturing that were investigated are controlling the bondline thickness and proper machining of the specimens from the test panel. Additionally, three issues associated with the initial testing procedures were also investigated concurrently: the method of wedge insertion, measurement of the initial crack length, and the specimen orientation during testing (Adams et al., 2011, Abstract).

The findings of this study revealed the following:

> Testing was performed using 2024-T3 aluminum specimens bonded using AF 163-2K adhesive. Test results showed that the method of wedge insertion does affect the initial crack length, especially for the "weak" bonded specimens. Not only were the initial crack lengths affected by the method of wedge insertion, but the crack growth and resulting crack length from five days in ambient air were also affected. While crack growth and length during environmental exposure varied with surface preparation, specimen orientation caused no recurring trend in any of the three surface preparation methods tested to date. Expected benefits to aviation include an improved adhesive bond durability test method for use in assessing the reliability of adhesively bonded aircraft structures as well as an FAA Technical Center report to provide additional guidance for aviation industry users (Adams et al., 2011, Abstract).

VT Study (3).

Damage Tolerance Test Method Development for Sandwich Composites (D. Adams, B. Kuramoto)

Summary and findings of the study.

The purpose and objective of this study was to "investigate candidate damage tolerance test methodologies for sandwich composites and to propose specific methodologies for standardization." (Adams & Kuramoto, 2012, Abstract) The researchers identified three candidate test configurations with the following methodologies:

> The first methodology utilizes an end loaded compression after impact (CAI) test configuration. Second, a four-point flexure test methodology has been identified for evaluating post-impact performance when the damaged facesheet is loaded in

> compression. Additionally, a third candidate test method has been developed by the marine composites community. This test method, based upon ASTM D6416, supports the damaged sandwich composite panel on the edges and a distributed load is applied by a bladder until failure. This test methodology is believed to also be of interest for aircraft applications such as fuselages were pressure loadings are present. A secondary focus of this investigation is to provide a comparison of residual strength of sandwich composites obtained using all three of the proposed test methodologies. Initial efforts have focused on performing a preliminary evaluation of the three candidate damage tolerance test methodologies using sandwich composites composed of G11 glass/epoxy facesheets and Nomex honeycomb cores. The three methodologies will be examined for their limits of applicability and recommended procedures. Additionally, guidance will be established for interpreting test results and selecting the most appropriate test method for a particular application (Adams & Kuramoto, 2012, Abstract).

The summary of this study stated the following:

> An initial evaluation of the three identified damage tolerance test methodologies is underway. Impact damage is to be idealized as a circular hole in the upper facesheet to minimize the variability in test results due to variations in damage states. These tests will provide an initial comparison of residual strength among the three candidate test methodologies as well as provide an initial assessment of each test methodology. Expected benefits to aviation from this research project include the development of standardized test methodologies for use in assessing the damage tolerance of sandwich composites used in aircraft structures (Adams & Kuramoto, 2012, p. 12).

VT Study (4-1).

In-service Inspection Guidelines for Composite Aerospace Structures (J. Heida, D. Platenkamp)

Summary and findings of the study.

The purpose and objective of this study was to review "the damage tolerance design approach for composites and conclude with general guidelines for the in-service inspection of composite aerospace structures." (Heida & Platenkamp, 2012, para. 1) This was performed through the evaluation of *carbon fiber reinforced polymer* (CFRP) test specimens that are "representative for primary composite aerospace structures, including relevant damage types such as impact damage, delaminations and disbonds." (Heida & Platenkamp, 2012, Abstract) The following NDI methods were evaluated based on critical aspect:

> A range of NDI methods were evaluated such as visual inspection, vibration analysis, phased array ultrasonic inspection, shearography and thermography inspection. Important aspects of the evaluation were the capability for defect detection and characterization, portability of equipment, field of view, couplant requirements, speed of inspection, and level of training required and the cost of equipment (Heida & Platenkamp, 2012, Abstract).

The findings of this study revealed the following:

> Damage tolerance requirements for composite aerospace structures should be interpreted so that as long as damage occurring in-service cannot be detected visually, it should not be structurally significant in the sense that is does not affect the safety during the aircraft life. In terms of load capability this implies that the damage should never reduce the structural strength below ultimate load (UL) capability. Only detectable damage may cause structural degradation below UL (but never below LL, limit load – the maximum

> load per fleet lifetime) and should be timely detected by visual inspection or more advanced NDI methods. The inspection interval should be related to the probability of damage occurrence, depending e.g. on the structure type. In the period before detection, any damage should not show significant growth. After detection, the damage should be repaired to restore UL capability or the component should be replaced. Recommended NDI methods are automated tap test for detecting relevant impact damage, and ultrasonic conventional or, preferably, phased array inspection for the detection and characterization (size, depth) of relevant impact damage, delaminations and disbonds. Shearography and thermography are considered to be less applicable because of their poor to moderate defect characterization capabilities, when compared to ultrasonic inspection. But, thermography and shearography may be optional, non-contact techniques (especially thermography) for specific inspection configurations such as curved panels and repaired structures, and for the inspection of specific defect types such as water ingress in honeycomb structures (Heida & Platenkamp, 2012, para. 5).

VT Study (4-2).

NDT Inspection of Composites for In-Service Defects[11] (T. Marshall)

Summary and findings of the study.

The purpose and objective of the *aerospace applications* section of this study conducted by Sonatest, Ltd was to show the effectiveness of NDI (C-Scan) for the detection of in-service BVID (barely visible impact damage) on four separate common advanced composite structures used in aerospace structural applications using the prescribed impact test protocol under AR-03/74 *Bonded Repair of Composite Aircraft Structures*. “Mixed monolithic and sandwich panels with manufactured defects and controlled energy impacts were tested with the *RapidScan*™

system." (Marshall, n.d., Presentation p. 26) The findings of the C-Scan evaluation revealed the following:

> Measurements can be "drawn" onto scan for sizing. The sizes and areas of defects can be evaluated. Statistical data can assist with the evaluation. Depths of defects are easily measured. Evaluation results are easily reported. The evaluation can determine volume of material to repair (Marshall, n.d., Presentation p. 33).

[11] *The data from this study was used for ANOVA (2) and will be examined in the next section.*

VT Study (5).

Boeing Composite Airframe Damage Tolerance and Service Experience (A. Fawcett, G. Oakes)

Summary and findings of the study.

The purpose and objective of this study was to evaluate "Boeing's design criteria for damage tolerant CFRP primary structures and their relationship to maintainability as well as CFRP structures service experience." (Fawcett & Oakes, n.d., Outline) The criteria requirements for *barely visible impact damage* (BVID) and *visual impact damage* (VID) are identified as well as sample damage tolerance for impact by type and location. In-service aircraft (737 and 777) composite structures are evaluated. The findings of this study revealed the following:

> In-service experience with primary composite structure has been excellent. Visual based inspection program validated. In-service NDT techniques validated. Damage occurrences are at or below those for equivalent metal structure. Repair techniques have proven to be effective and efficiently applied (Fawcett & Oakes, n.d., Summary).

VT Study (6).

Impact Damage Formation on Composite Aircraft Structures (H. Kim)

Summary and findings of the study.

The purpose and objective of this study was to investigate the “impact of composite structures from sources that involve wide area contact due to the tendency to produce internal damage with little or no exterior visibility.” (Kim, 2012, Abstract) This was accomplished with the following specific objectives and approach:

> Characterize blunt impact threats and locations where damage can occur. Understand BID formation and visual detectability. Determine key failure modes, phenomena and parameters by evaluating how failure is affected by bluntness/contact-area, ID & predict failure thresholds (useful for design), and what conditions relate to development of significant internal damage with minimal or no exterior visual detectability. Develop analysis & testing methodologies, and establish new modeling capabilities validated by tests. The approach uses experiments that are impact representative structure/specimens wide area high energy blunt impact – e.g., from ground service equipment, high velocity hail ice impacts – in-flight and ground-hail conditions, internal stiffeners low velocity impacts – non-deforming impactor, large radius effects. Modeling – nonlinear FEA, analytical, and to communicate results to industry, collaboration on relevant problems/projects via workshops and meetings (Kim, 2012, Presentation p. 4).

The findings of this study revealed the following:

> Low velocity large radius metal tip impact conclusions: The failure thresholds increase with both panel thickness and tip radius. The primary forms of damage are surface denting and delamination, followed by back wall fiber breakage with increasing energy.

> Impacts often create a visible surface dent which is more pronounced with the smaller impact tips than the blunt ones. Dent formation does not necessarily indicate internal damage. Internal damage can be present without a surface dent and surface dents can be present without internal damage. Dents measured immediately after the impact event will be deeper than when measured at another point in the future. The dent relaxes, decreasing in depth as well as visibility. Large radius metal tips: Deeper understanding of material behavior subject to impacts, particularly how increased radius affects damage formation and visual detectability. Establish correlation between the onset of damage and the radius of the impactor. Determine the relationship between visible damage and internal damage. Material level test described by failure threshold force results are applicable to other conditions and specimen configurations (Kim, 2012, p. 53-55).

VT Study (7).

Structural Health Monitoring for Advanced Composite Structures (Herszberg, et al.)

Summary and findings of the study.

The purpose and objective of this study "focuses SHM application to aircraft as a means of highlighting the issues that face SHM in composite structures, including those in the maritime, oil and gas, civil infrastructure and other industries." (Herszberg, Bannister, Li, Thomson, & White, n.d., Abstract) This is accomplished by "addressing issues involved in the design, certification, manufacture and through life support of such structures as well as identifying the critical areas of development to enable the implementation of SHM in future composite aircraft structures." (Herszberg et al., n.d., Abstract). The findings of this study revealed the following:

> Within the aircraft industry the benefits of SHM relate to the opportunity for reduced maintenance costs through an adoption of condition based maintenance, together with

> reduced aircraft weight and improved performance through more optimized aircraft design. In order to achieve these goals, research and development is needed in the following areas: Development of validated post-buckling design and analysis tools to accurately predict the behavior of thinner, more efficient structures. Material models that accurately predict damage evolution at high strain levels and under increased through-thickness stresses, with the possible need to incorporate composite fatigue analysis. Validated diagnostic systems that can identify the size and location of damage within the composite structure to the required accuracy. Validated prognosis methodologies to predict the structural integrity of the damaged structure. Robust techniques for sensor embedding and connection. Power and data handling equipment compatible with aircraft on-board systems. Validation of SHM system durability under aircraft service conditions, including repair or replacement procedures for damaged sensors. Through dialogue with the airworthiness authorities, SHM has the potential to be accepted within the aircraft industry. However, addressing the issues raised in this paper needs to be a focus for future work within the composites and SHM research community if the acceptance of this technology and its potential benefits are ever to be realized (Herszberg et al., n.d., para. 7).

Certification Standards (CS) Studies

CS Study (1).

Status of FAA's Actions to Oversee the Safety of Composite Airplanes (Government Accountability Office)

Summary and findings of the study.

The purpose and objective of this GAO report was to "review FAA's and EASA's certification processes and FAA's oversight of the composite airplanes once they enter service." (GAO, 2011, Highlights) The GAO objectively "examined how FAA and EASA assessed the use of composite materials in the Boeing 787 fuselage and wings, and the extent to which FAA has addressed safety-related concerns associated with the repair and maintenance of composite airplanes." (GAO, 2011, Highlights) This was accomplished by "reviewing certification documentation, conducting a literature search, discussing repair and maintenance issues with experts, and interviews with FAA and EASA officials and Boeing representatives." (GAO, 2011, Highlights) The findings of the GAO report revealed the following:

> GAO found that FAA followed its certification process in assessing the Boeing 787 airplane's composite fuselage and wings (see fig.) against applicable FAA airworthiness standards. FAA applied five special conditions when it found that its airworthiness standards were not adequate to ensure that the composite structures would comply with existing safety levels. These special conditions require Boeing to take additional steps to demonstrate the 787's structures meet current performance standards. FAA also granted Boeing an equivalent level of safety finding when the manufacturer determined it could meet the standard but prove it differently from the method specified in that standard. On the basis of a review of FAA's special condition requirements, Boeing submissions, and discussions with FAA and Boeing officials, GAO found that FAA followed its process by

> documenting the technical issues related to the design of the composite fuselage and wings, determining the special conditions and equivalent level of safety finding, obtaining public comments on draft special conditions, and monitoring Boeing's compliance with those conditions (GAO, 2011, What GAO Found).

The following safety concerns were identified in the GAO report:

> On the basis of expert interviews and a review of literature, GAO identified four key safety-related concerns with the repair and maintenance of composites in commercial airplanes – (1) limited information on the behavior of airplane composite structures, (2) technical issues related to the unique properties of composite materials, (3) standardization of repair materials and techniques, and (4) training and awareness. None of the experts believed these concerns posed extraordinary safety risks or were insurmountable. FAA is taking action to help address these concerns identified by GAO related to the repair and maintenance of composite airplane structures. However, until these composite airplanes enter service, it is unclear if these actions will be sufficient (GAO, 2011, What GAO Found).

CS Study (2).

FAA Composite Safety and Certification Initiatives (L. Ilcewicz)

Summary and findings of the study.

The purpose and objective of this study was to identify and explain composite safety and certification initiatives that included: background, expanding the FAA composite team, industry interface, the role of research, and how research projects are identified and prioritized (Ilcewicz, 2010). This study focused on the methodology of the FAA with respect to initiative progress and relevance to the *Joint Advanced Materials & Structures Center of Excellence* (JAMS), as well as future plans and review of progress that concentrates on technical issues addressing safety issues and training initiatives (Ilcewicz, 2010). The findings of the study identified the following:

> Challenges for JAMS - *Need More Industry, FAA & other Govt. Agency Involvement.* Help JAMS identify key R&D areas, realizing the need for a safety & certification emphasis: outline existing industry problems and near-term applications, participate in FAA Safety Awareness Course developments, cost sharing partners should have proactive involvement in project from start to finish. Actively participate in ongoing projects: provide advice/guidance to the PI and researchers, interface with additional FAA personnel directing the project, help convert results to practice (deliverables to support industry and FAA needs). Review JAMS detailed project descriptions, references and presentations: provide feedback and suggestions for improvement (Ilcewicz, 2010, Presentation p. 29).

CS Study (3).

Simplifying Certification of Discontinuous Composite Material Forms for Primary Aircraft Structures (M. Tuttle, et al.)

Summary and findings of the study.

The purpose and objective of this study was to evaluate “discontinuous fiber composite (DFC) parts produced using compression molding that are being implemented in complex structural geometries in new generation commercial aircraft.” (Tuttle, Shifman, Boursier, & Head, 2013, Abstract) This study identified that “structural analysis of DFC parts is a challenge since DFC materials do not behave like traditional composites or isotropic materials.” (Tuttle et al., 2013, Abstract) The objectives of the study were accomplished by “presenting some initial results related to the behavior of HexMC®, a proprietary DFC system produced by the Hexcel

Corporation." (Tuttle et al., 2013, Abstract) "Flat HexMC test panels were produced using compression molding and used to study the effects of material flow on material behavior." (Tuttle et al., 2013, Abstract) The findings of the study revealed the following:

> This paper has focused on tensile tests performed using HexMC coupon specimens that had been machined from special 'high-flow' panels. The high-flow panels experienced far higher levels of material flow during the compression molding process than normally occurs during production of a DFC actual part. Panels of three different thicknesses were produced and tested: 2.3 mm, 3.6 mm, and 5.8 mm (0.09 in, 0.140 in, and 0.230 in) (Tuttle et al., 2013, Summary).
>
> It was found that high levels of material flow had little or no impact on fiber volume fraction. Fiber/chip orientations were also found to remain nearly random, even in regions of the panel that had experienced substantial levels of material flow. Orientation did occur near the boundaries of the mold cavity. In these latter regions the fiber/chips tend to become aligned with the boundary, causing an increase in modulus measured parallel to the boundary (Tuttle et al., 2013, Summary).
>
> For a given panel thickness the nominal tensile modulus remained more-or-less constant throughout interior regions of the panel, reflecting essentially random fiber/chip orientation. Tensile modulus increased markedly in regions near the panel boundary, where fiber/chip alignment occurred. An unexplained observation was that the nominal tensile modulus increased with panel thicknesses. The nominal stiffness of the 5.8 mm thick panel was 31% higher than the nominal modulus measured of the 2.3 mm panel. The source of this increase in stiffness with panel thickness has not yet been identified (Tuttle et al., 2013, Summary).

Maintenance and Repair (M&R) Studies

M&R Study (1).

CACRC Depot Bonded Repair Investigation – Round Robin Testing[12] *(2013 Technical Review)* (J. Tomblin, L. Salah)

Summary and findings of the study.

The purpose and objectives of this study are as follows:

> Evaluate the existing CACRC standards for repair of composite structures using CACRC approved repair materials. Assess the repair process variability between depots, using the same SRM-like procedures (using CACRC repair techniques) provided to all the depots. Investigate the variability associated with technician training (minimal level of experience versus extensive experience) on the performance of the repair. Compare the strength of the different repairs (CACRC-R1/R2 field repairs vs. OEM-R1/R2 repairs) to a set of control "pristine" panels and to a set of open-hole panels. Evaluate the environmental effects on the static and residual strength after fatigue of bonded repairs (Tomblin & Salah, 2013, Presentation p. 4).

The findings and observations/considerations of this study are as follows:

> CACRC standards cannot be used as a sole document replacing an SRM: can be used along with an SRM, best practices/techniques for repair, part specific document required, difficulties interpreting the standards (wet lay-up repair standard), missing or incomplete information as well as outdated nomenclature (mushroom sanding disk holder).
>
> Perspective on OEM versus Airline Depot/ MRO: many repairs are performed on similar parts at an OEM, whereas at an airline depot a mechanic may only repair a given part occasionally (practice/training needed on the same part). Constraints to perform the

repair within a limited timeframe (AOG), and continuity between shifts (Tomblin & Salah, 2013, Presentation p. 20).

Technicians' perspective: need more accessibility to engineering documentation and data, need training with OEM documents and SRMs, training to particular repair manual, differences between aircraft to aircraft, no standard structural repair manual ("2 years to get familiar with one SRM"), need for standardized SRMs and for material standardization (more robust processes, improved efficiency "5 days spent gathering repair information and tooling/5 hours to complete the repairs") (Tomblin & Salah, 2013, Presentation p. 21).

Recommended topics to be included in training: working on example parts, history of composites, composite part identification (know what to look for, material type, style…), computer training for lead mechanics (access SRMs, find required documentation), understand the differences between wet lay-up and prepreg repairs (cure temperature and outcome on structure, performance of wet lay-up and prepreg resins), show examples of bad processes and the consequences, pass-fail criteria (Inadequate drying of a part, consequences of using wrong materials/bad material replacement).

Implications on safety: inspection required for critical steps, inspection points, and process verification coupons. Need for composite repair technician training and certification & periodic certification validation (Tomblin & Salah, 2013, Presentation p. 22).

[12] *The maintenance depot repair/technician experience data from this study was used for a linear regression and will be examined in the next section.*

M&R Study (2).

CACRC Depot Bonded Repair Investigation – Round Robin Testing (2012 Technical Review)
(J. Tomblin, L. Salah)

Summary and findings of the study.

The purpose and objectives of this study are as follows:

> To evaluate the static strength and residual strength after fatigue of OEM vs. field bonded repairs applied to composite sandwich structures, performed at different operator depots. Repair method evaluation (OEM/CACRC): variability/repeatability of repairs performed at different depots, evaluation of existing CACRC standards for repair implementation/ technician training, and residual strength/environmental durability. To evaluate the static strength and residual strength after fatigue of OEM vs. field bonded repairs subjected to impact damage and defective process parameters (Tomblin & Salah, 2012, Presentation p. 8).

The in-service experience/lessons learned of this study are as follows:

Outstanding performance where reliable processes were used. Rigorous surface preparation yielding a clean chemically active interface is necessary for a durable bond. Surface preparation must yield an interface resistant to degradation. Adhesion failures are caused by deficient processes (pre-bond contamination, poor surface preparation, and inadequate cure parameters) that inhibit the formation of strong chemical bonds. Cohesion failures are caused by poor design (thermal residual stresses, stiffness mismatch between adherends, poor material selection, inadequate repair overlap, and porous bondlines) (Tomblin & Salah, 2012, Presentation p. 11).

M&R Study (3-1).

Effect of Repair Procedures Applied to Composite Airframe Structures (J. Tomblin, L. Salah, and C. Yang), Laminate and sandwich structures.

Summary and findings of the study.

The purpose and objectives of this study are as follows:

> To assess the effects of different variables on the strength and durability of repairs applied to composite laminate and sandwich structures: substrate stiffness, lap length, thickness, repair materials, cure temperatures, and static/fatigue performance. To evaluate the strength and durability of poorly bonded repairs that passed NDI: poor surface preparation, pre-bond moisture, improper cure, and contamination. To validate existing CACRC standards and provide recommendations pertaining to proper repair process implementation. To develop an analysis method and corresponding failure criteria for structural sizing of bonded repairs (Tomblin, Salah, & Yang, 2006, Presentation p. 3).

The in-progress results of this study are as follows:

> Laminate mechanical testing to generate baseline repair data for various repair materials in progress. Laminate repair using ACG MTM45/T800 in progress. Panel Machining to generate mechanical data for contaminated coupons is in progress. Screening panels for the sandwich configuration have been tested and are being resized to induce failure in the repair. Improved analytical test results correlation with experimental data (3D FEM model) (Tomblin et al., 2006, Presentation p. 26).

M&R Study (3-2).

Effect of Repair Procedures Applied to Composite Airframe Structures (J. Tomblin, L. Salah, and C. Yang), Laminate scarf joints.

Summary and findings of the study.

The purpose and objectives of this study are as follows:

> To investigate different variables on the performance of repairs applied to solid laminates representative of 787 structure configurations. Basic scarf joint parameters: lap length, stiffness, thickness, and 4 different repair materials: factory (350°F cure) vs. field repairs (250°F cure). Effect of process parameters on the static and fatigue life of these joints (surface contamination, pre-bond moisture, cure cycle deviations) (Tomblin, Salah, & Yang, 2005, Presentation p. 3). The research methodology included 3 tasks that are outlined as follows:
>
> Task 1: Initial testing to define coupon width/geometry FEM Validation of Experimental results. Task 2: Establish repair strength baseline (OEM/field repairs), validation of standards required for composite repair and inspection technicians FEM validation of experimental results. Task 3: Investigate the effects of different repair process parameters on the strength and durability of repairs. Validate the inspection/surface preparation methods developed by the FAA "chemical characterization of adhesive joints" team (Tomblin et al., 2005, Presentation p. 4).

The task completion and in-progress results of this study are as follows:

> Task 1 (complete): Details of scarf machining procedure, OEM repair implementation, coupon tabbing and machining. Details of experimental results including ARAMIS strain maps/adhesive stress-strain data/SEM analysis of fractured surfaces. FEM Validation of the mechanical tests. Task 2 (in progress): Panels are being machined into sub panels

that will be subsequently repaired, tabbed, machined into specimens and tested to determine the static and fatigue properties of these repairs. Baseline repairs will be cured under pressure and vacuum bag (using the OEM proprietary vacuum debulking method) to establish the repair properties under both cure cycle variations. Details of experimental data characterizing the static and fatigue performance of the OEM repair under CTD, RTA and ETW conditions. Baseline repair data will also be generated for materials typically used in the field. FEM Validation of the mechanical tests (Tomblin et al., 2005, Presentation p. 26).

ANOVA and Linear Regression Review

Two separate ANOVA and two linear regression analyses[13] are performed using the data from the previously identified studies in Table 2. These analyses represent a statistical correlation of the data in the selected studies to the hypothesis/research question of this project. The ANOVA and linear regression descriptions of each selected study are explained in Table 3. The purpose of the ANOVA and linear regression analyses is to directly support and validate the findings of the applicable study in order to effectively argue the hypothesis/research question.

A limited number of studies presented for the qualitative meta-analysis contained useable data for a quantitative statistical analysis. Quantitative data evaluation was performed before a determination was made to use the identified studies for statistical analysis based on the robustness of the data presented, and if an actual analysis had been performed in the study. The studies identified and selected for statistical analyses in this project were also chosen based on their potential for quantitative contribution applicable to the hypothesis/research question and how they effectively supported this project’s goal.

[13] *ANOVA and linear regression modeling was performed using XLSTAT.*

Table 3

ANOVA and Linear Regression Analyses

ANOVA (1)

Study: *Durability of Adhesively Bonded Joints for Aircraft Structures* (D. Adams, K. DeVries, and C. Child)
Description: The ASTM D3762 *metal wedge crack durability test* data presented in this study is analyzed from four separate test conditions by comparing the variance found in each condition.
Purpose: To show statistical significance that supports the study's effectiveness of improving the ASTM D3762 test characteristics for adhesively bonded aircraft structures.

ANOVA (2)

Study: *NDT Inspection of Composites for In-Service Defects* (T. Marshall), [Study 4-2]
Description: The *non-destructive inspection* (NDI) C-Scan data presented in this study is analyzed from four typical composite structures by comparing the variance found in observed width and depth of *barely visible impact damage* (BVID) from manufactured defects and FAA prescribed impact damage testing.
Purpose: To show statistical significance that NDI testing is effective at detecting damage in typical composite structural components by correlating the results of variance in each structure.

Linear Regression (1)

Study: *CACRC Depot Bonded Repair Investigation – Round Robin Testing (2013 Technical Review)* (J. Tomblin, L. Salah)
Description: The maintenance depot repair/experience polling data presented in this study is analyzed to correlate the relationship between the dependent and explanatory variables that were identified in the maintenance experience poll.
Purpose: To model the estimated effects at the depot (airline) level of composite maintenance and repair to validate the findings of the study.

Linear Regression (2)

Study: *Structural Health Monitoring for Advanced Composite Structures* (I. Herszberg, et al.)
Description: The *structural health monitoring* (SHM) load data presented in this study is analyzed to correlate the relationship between the stress to cycles (S-N) fatigue properties.
Purpose: To model the estimated effects of fatigue in order to show the effectiveness of SHM for detecting fatigue damage growth in advanced composite structural components.

Results

Meta-Analysis

Validation Testing (VT) Studies

VT Study (1).

Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures Under Repeated Loading (J. Tomblin, W. Seneviratne)

This study exceeds the categorical evaluative criteria by identifying the methodology and approaches necessary for comprehensive process improvements of full-scale validation testing by determining fatigue life with respect to damage tolerance (life and load factors), evaluating impact threats with respect to load-life capability, and the incorporation of design changes without the addition of extra testing (Tomblin & Seneviratne, 2008). This is a methodology-based study that lays the groundwork for achieving *best practice* methods and procedures for full-scale testing of composite airframe structures (Tomblin & Seneviratne, 2008). The following benefits and advantages to aviation were identified:

> Incorporation of damage into scatter analysis. Load-Life-Damage: investigate large VID damage, further studies. Load-Life Shift: investigate different categories of damages/repairs in the same full-scale test article damage, design changes, i.e. gross weight increase, LEF during certification vs. improved LEF and reliability of designed life (Tomblin & Seneviratne, 2008, Presentation p. 29).

The future needs and direction were identified in the findings of the study[14] that points out the need for “reliable NDI and health monitoring techniques for damage characterization during full-scale testing and service” which should be noted that this correlates to the findings in other studies and validates the hypothesis/research question of this project.

[14] *The findings of this study can be found on p. 43 of this paper.*

VT Study (2).

Durability of Adhesively Bonded Joints for Aircraft Structures (D. Adams, K. DeVries, and C. Child)

This study meets the categorical evaluative criteria by identifying improvements for the ASTM D3762 *metal wedge crack durability test* characteristics for use with adhesively bonded composite joints which validates the need to improve this test for composite applications. This study is ongoing with future research required before new ASTM D3762 can be implemented. The methodologies for implementation and benefits to aviation have been identified as follows:

> As this research project progresses, test results and proposed additions and revisions to the ASTM D3762 standard will continue to be communicated regularly to ASTM Committee D14 on adhesives. In addition to proposing revisions to this standardized test method, research results from this investigation will be disseminated through an FAA technical report and journal publications. Expected benefits to aviation include an improved adhesive bond durability test method for use in assessing the reliability of adhesively bonded aircraft structures (Adams et al., 2011, p. 20).

The test data from this study is analyzed in the next section of this paper to validate the results and findings in order to show that the test was effective.

VT Study (3).

Damage Tolerance Test Method Development for Sandwich Composites (D. Adams, B. Kuramoto)

This study meets the categorical evaluative criteria by identifying needed standardized damage tolerance test methods for sandwich composites. The proposed methodology of this study focused on the “high level of maturity” of existing damage tolerance and damage resistance standards in-place for monolithic composite structures (Adams & Kuramoto, 2012, Presentation p. 4). This study's primary objective was to develop a standardized ASTM test method for structural sandwich composite components that (at present) does not exist. When this research is complete, its potential for implementation is high due to the immediate industry standard need of this test method which validates this study's effectiveness. The benefits and advantages to aviation have been identified as follows:

> Expected benefits to aviation from this research project include the development of standardized test methodologies for use in assessing the damage tolerance of sandwich composites used in aircraft structures. Other benefits include test results used to predict damage tolerance of sandwich composites, and research results on scaling of results towards composite sandwich structures (Adams & Kuramoto, 2012, p. 12), (Adams & Kuramoto, 2012, Presentation p. 23).

VT Study (4-1).

In-service Inspection Guidelines for Composite Aerospace Structures (J. Heida, D. Platenkamp)

This study meets the categorical evaluative criteria (with limitations) by identifying and evaluating in-service *non-destructive inspection* (NDI) testing methods and techniques used in the aerospace industry. Through this study's evaluation of in-service NDI methods and techniques, guidelines are proposed for their use of detecting damage in composite structures. The limiting factor of this study is that while it is highly informative as a guideline for use, it does not propose any new methods or techniques for NDI. However, due to the relevance of NDI as pointed out in other studies, this study's effectiveness for implementation as a standardized authoritative guide to aerospace NDI methods and techniques is suggested and can be adopted as such. The testing performed in this study was adapted from study 4-2 (below) and will be analyzed using the data from study 4-2 to show the effectiveness of NDI testing.

VT Study (4-2).

NDT Inspection of Composites for In-Service Defects (T. Marshall)

This study is used for quantitative analysis only and will be discussed in the next section. The summary and findings of this study can be found on p. 48-49 of this paper.

VT Study (5).

Boeing Composite Airframe Damage Tolerance and Service Experience (A. Fawcett, G. Oakes)

This study meets the categorical evaluative criteria (with limitations) by identifying and providing industry examples of design criteria for damage tolerant *carbon fiber reinforced polymer* (CFRP) primary aircraft structures used for commercial transport aircraft, and how the manufacturer (Boeing) has enabled its maintainability (Fawcett & Oakes, n.d.). The limiting factor of this study is that while it is highly informative and effective for the dissemination of in-service impact damage experience, it does not suggest or propose new methodologies for damage tolerance or damage detection. However, this study does contribute to industry collaboration for the promulgation of robust design criterion and standards for maintainable structures. It is also noted that this study found that Boeing's current *non-destructive testing* (NDT)[15] methods and techniques for detecting damage on in-service structures (737 and 777) have been validated and are effective. This study points out that current ***in-service use of non-destructive inspection (NDI) is effective for the detection of composite damage and component failure.***

[15] *The term NDT is synonymous with non-destructive inspection (NDI).*

VT Study (6).

Impact Damage Formation on Composite Aircraft Structures (H. Kim)

This study meets the categorical evaluative criteria by identifying and evaluating the impact damage vulnerability of aircraft composite structures specific to wide-area contact from *ground support equipment* (GSE), high-velocity hail/ice, and large radius metal tips. This study critically examines and investigates *non-visible impact damage* (NVID) on structural composite components in order to fully assess NVID caused by an impact event. The testing methodologies used in this study included *finite element analysis* (FEA) modeling of impact events that produced accurate damage simulation for analysis of typical aircraft composite structures that provides the industry with a better understanding of blunt-force impact damage (Kim, 2012). This study validates the need for impact damage testing due to the typical occurrence of sub-surface damage after an impact event without any visible surface indications. The benefits and advantages to aviation regarding wide-area blunt impact are as follows:

> GSE wide-area blunt impact: understanding of prospective damage produced from wide-area GSE impact events. Awareness of phenomena and possible internal failure modes for damage tolerance considerations. Provides key information on mode and extent of seeded damage, particularly *non-visible impact damage* (NVID) from blunt impact threats. Threat conditions causing significant damage – range of energy level needed. Establish FEA models that provide the capability to predict: full detailed failure process – large deformations, failure initiation, growth, key failure modes. Visibility of the damage produced – failure criteria for impact damage visibility. Small scale onset of cracks and delamination leading to greater damage and degradation of structural integrity. Establish methodologies to analyze whole composite aircraft vs. substructures: GSE impacts inducing whole-aircraft motion. Surrounding GSE secondary impact: identify how to detect/monitor occurrence of damaging events. What inspection technique should be used and where, e.g., video cameras and sensors that can help to determine impact energy (Kim, 2012, Presentation p. 12).

VT Study (7).

Structural Health Monitoring for Advanced Composite Structures (Herszberg, et al.)

This study is used for quantitative analysis only in-conjunction with the fatigue data from FAA AR-03/46 and will be discussed in the next section. The summary and findings of this study can be found on p. 51-52 of this paper.

Certification Standards (CS) Studies

CS Study (1).

Status of FAA's Actions to Oversee the Safety of Composite Airplanes (Government Accountability Office)

This report exceeds the categorical evaluative criteria by providing oversight for the certification of composite Part 25 aircraft. The report was conducted by the GAO to address the safety concerns associated with the increasing use of composites for commercial aircraft construction; specifically for primary structural applications such as wings and fuselage components. This report is directed towards the certification process of Boeing's 787 *Dreamliner* due to the 787 being the first large commercial transport aircraft constructed mostly with advanced composites (GAO, 2011). The GAO's methodology for conducting this report was extensive and is described as follows:

> This report addresses the Federal Aviation Administration's (FAA) and the European Aviation Safety Agency's (EASA) certification of airplanes using composite materials, specifically the agencies' processes for developing special requirements to ensure that Boeing demonstrates the 787 composite fuselage and wings meet current safety levels, and FAA's actions to address safety-related concerns associated with repairing and maintaining composite airplanes identified by literature and stakeholders. We focused on FAA's and EASA's actions as they relate to the certification of the Boeing 787 because it

> is the first large transport category airplane for commercial use with a composite airframe structure to undergo the certification process. To address these objectives, we reviewed FAA and EASA regulations, policies, and processes and Boeing certification documents for the special conditions and review items the agencies indicated were related to the 787's composite fuselage and wings. We conducted a literature search and reviewed 39 journal articles and technical papers related to the repair and maintenance of composite airplanes. We interviewed 11 stakeholders with expertise in the area of maintenance and repair of composite materials in airplanes and representing a variety of perspectives, including manufacturers, repair stations, academic researchers, and air carriers (GAO, 2011, Appendix I p. 40).

The methodologies and objectives also included the "review of FAA's process to develop special conditions for the 787 composite structures, EASA certification review process, and the identification of repair and maintenance concerns." (GAO, 2011, Appendix I p. 40-42).

The purpose and objectives of this report were warranted based on valid certification and safety concerns for this type of aircraft. The repair and maintenance concerns found by the GAO were also revealed in the supporting research performed by the *Commercial Aircraft Composite Repair Committee* (CACRC) and can be directly correlated. Although this report found that the FAA "followed its certification process in assessing the Boeing 787 airplane's composite fuselage and wings against applicable FAA airworthiness standards." (GAO, 2011, What GAO Found) However, due to the lack of applicable certification standards, the FAA "applied five special conditions when it found that its airworthiness standards were not adequate to ensure that the composite structures would comply with existing safety levels." (GAO, 2011, What GAO Found)

CS Study (2).

FAA Composite Safety and Certification Initiatives (L. Ilcewicz)

This study exceeds the categorical evaluative criteria by identifying and evaluating the FAA's methodologies used to address current industry concerns specific to safety and certification initiatives. The primary objectives for this study were to "work with industry, other government agencies, and academia to ensure safe and efficient deployment of composite technologies used in existing and future aircraft, and to update policies, advisory circulars, training, and detailed background used to support standardized composite practices." (Ilcewicz, 2010, Presentation p. 4). The goal to promote industry standardization is an important aspect of this study that validates the need for new composite aircraft certification standards. The summary of action stated in this study from 2006 to 2009 is as follows:

> Critical safety data shared in unique forum of practitioners – captured in web files, new CMH-17 content and FAA course. Five *categories of damage* were proposed for damage tolerance and maintenance consideration. Integrated efforts in structural substantiation, maintenance and operations interface help ensure complete coverage for safety. Coordinated inspection, engineering disposition and repair is needed for safe maintenance. Reporting by operations is essential for detection of critical damage from anomalous events. FAA is committed to CS&CI with industry, academia and government groups (~380 participants in three workshops). Damage tolerance and maintenance initiatives are active. Principles of safety management will continue to be used in future developments (policy, guidance and training) (Ilcewicz, 2010, Presentation p. 16).

CS Study (3).

Simplifying Certification of Discontinuous Composite Material Forms for Primary Aircraft Structures (M. Tuttle, et al.)

This study meets the categorical evaluative criteria by identifying and evaluating the certification methodology required for *discontinuous fiber composite* (DFC) parts that are "produced using compression molding and are being implemented in complex structural geometries in new generation commercial aircraft." (Tuttle et al., 2013, Abstract) Although DFC parts are not as common as traditional monolithic or sandwich components (at present), their use will undoubtedly increase for future applications based on their unique characteristics and design potential. Increase of DFC material use will mandate the requirement for adequate certification guidelines. This study reveals some initial data and results regarding the physical behavior of DFC material. While this study does not form conclusive certification guidelines for DFC material, it does (proactively) research and test the material behavior in order to begin a comprehensive approach for future certification guidance. The following is a summary of action for this study:

> A multi-year study with an ultimate goal of simplifying certification of Discontinuous Fiber Composite (DFC) parts has been undertaken by members of AMTAS (Advanced Materials for Transport Aircraft Structures), which is one of two university groups that together form the Joint Advanced Materials & Structures (JAMS) Center of Excellence. HexMC®, a DFC system produced by the Hexcel Corporation, is being used as a model material. The multi-year study will involve tests and analyses at both the coupon level and at the component level (Tuttle et al., 2013, Summary).

The benefits and advantages to aviation are as follows:

> FAA: Program objective supports safety regulations for design, production, and airworthiness certification of DFC parts. Industry: Program will contribute towards broader use of DFC structures at lower cost and lower weight. Academia: Represents an applied research project addressing an immediate need in industry and providing pertinent research & educational training for new aerospace engineers (Tuttle et al., 2013, Presentation p. 22).

Maintenance and Repair (M&R) Studies

M&R Study (1).

CACRC Depot Bonded Repair Investigation – Round Robin Testing (2013 Technical Review)
(J. Tomblin, L. Salah)

This study exceeds the categorical evaluative criteria by investigating and evaluating current depot (airline) level composite bonded repair. This was accomplished by comparing current industry standardized repair procedures (CACRC) with actual depot level repairs to analyze the variances based on technician experience and training. Material standardization and acquisition at the depot level was also investigated as well as a comparison of repair strength between CACRC field repairs with the same type of *original equipment manufacturer* (OEM) repair. This study's investigative and evaluative methodology proved to be effective at revealing process deficiencies with depot level repairs that included a lack of composite repair training programs, and a lack of inspection required for critical steps of the repair (Tomblin & Salah, 2013). This study validates the need for composite maintenance and repair standardization throughout the industry (at every repair level), and clearly identifies that composite repair standardization (currently) is a safety concern which was also identified in the GAO report previously evaluated. The maintenance technician polling data from this study is used for a linear regression in the next section of this paper to validate the study's findings and show the correlation between technician experience/maintenance actions performed vs. the amount of rework. This study concluded with the following benefits and advantages to aviation:

> Evaluate the completeness and adequacy of the existing CACRC standards (identify areas of improvement). Objective: robust/validated CACRC repair procedures/techniques standardized across different OEMs, airlines and repair stations. Provide recommendations pertaining to repair training, materials and standards to improve structural integrity of repaired composite components (robust infrastructure for maintenance and supportability). ***Need for composite repair technician training and certification, and periodic certification validation.*** Provide a measure of the structural integrity (static strength and residual strength after fatigue) of field repairs as compared to the OEM baseline repairs (Tomblin & Salah, 2013, Presentation p. 24).

M&R Study (2).

CACRC Depot Bonded Repair Investigation – Round Robin Testing (2012 Technical Review)
(J. Tomblin, L. Salah)

This study meets the categorical evaluative criteria by establishing and evaluating standardized (CACRC) composite repair methods and procedures that are used for the comparative standard in the 2013 continuation study previously evaluated. This study's methodology focuses on initial research and investigation of bonded repairs by establishing the program objectives that "evaluate the static strength and residual strength after fatigue of OEM vs. field bonded repairs applied to composite sandwich structures, performed at different operator depots, and evaluate the static strength and residual strength after fatigue of OEM vs.

field bonded repairs subjected to impact damage and defective process parameters.” (Tomblin & Salah, 2012, Presentation p. 8). This study concluded with the following benefits and advantages to aviation:

> To investigate the effectiveness of “OEM environment” vs. field repairs and the variability due to repair implementation at various operator depots. To understand the environmental durability and the residual strength after fatigue of bonded repairs subjected to various processes and environments. To identify key elements in the implementation of bonded repairs that ensures repeatability and structural integrity of these repairs. To provide recommendations pertaining to repair technician training and repair process control (Tomblin & Salah, 2012, Presentation p. 25).

M&R Study (3-1).

Effect of Repair Procedures Applied to Composite Airframe Structures (J. Tomblin, L. Salah, and C. Yang), Laminate and sandwich structures.

This study meets the categorical evaluative criteria by identifying and assessing the variable effects on the repair strength of laminate and sandwich structures, evaluating the “strength and durability of poorly bonded repairs that passed NDI”, and “validating existing CACRC standards” (Tomblin et al., 2006, Presentation p. 3). Further objectives also included “providing recommendations pertaining to proper repair process implementation” and “developing an analysis method and corresponding failure criteria for structural sizing of bonded repairs” (Tomblin et al., 2006, Presentation p. 3). The research methodology was task-oriented which effectively “generated baseline repair data for various laminate and sandwich materials” (Tomblin et al., 2006, Presentation p. 26).

The benefits and advantages to aviation are as follows:

> To assess the effects of surface contamination and process variations on the performance of bonded repairs. To develop rigorous repeatable repair processes that ensure structural integrity of bonded repairs. To gain confidence in bonded structural repairs. To provide guidance for analytical modeling of repairs (Tomblin et al., 2006, Presentation p. 27).

M&R Study (3-2).

Effect of Repair Procedures Applied to Composite Airframe Structures (J. Tomblin, L. Salah, and C. Yang), Laminate scarf joints.

This study meets the categorical evaluative criteria by identifying and assessing the variable effects "on the performance of repairs applied to solid laminates representative of 787 structure configurations" specific to laminate scarf joints (Tomblin et al., 2005, Presentation p. 3). The research methodology for this study was the same as M&R Study 3-1 (task-oriented) with the difference in tested structures (laminate scarf joints) for this study. This study was also effective at generating baseline repair data after the completion of each task, and concluded with the same benefits and advantages to aviation as M&R Study 3-1.

Both of these studies (3-1 and 3-2) validate the need for assessing the repair effects on these structures in order to identify a *best practice* repair method/technique applicable to each structure that yields the highest strength and longevity. This can be directly correlated to repair standardization and process improvement with respect to the category of composite maintenance and repair.

Note. *This concludes the meta-analysis results for composite materials studies, categorical results are given in the summary section of this project.*

ANOVA and Linear Regression Analysis

ANOVA (1)

Durability of Adhesively Bonded Joints for Aircraft Structures (D. Adams, K. DeVries, and C. Child)

The "weak" bonded specimen test data was analyzed to accept or reject the hypothesis that the effect of specimen orientation caused significant crack growth during environmental exposure. This was selected based on the data presented in study that suggests the following:

> Both the "ideal" bonded and the "weak" bonded specimens that received the PAA surface treatment performed similarly while the specimens that received the grit blast and prime treatment experienced additional crack extension. While the difference between surface preparations was very discernible, the variation caused by specimen orientation did not show any recurring trend (Adams et al., 2011, p. 18).

Two separate ANOVA analyses were performed using the data from the "weak" bonded specimens for the conditions: PAA without prime treatment, and grit blast. The results of both analyses are shown in Table 4 and Table 5 with complete statistical summaries in Appendix D. The extracted data from the study is shown in Figure C1 (Appendix C).

Table 4

ANOVA Results for PAA Specimen without Prime

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	0.454	0.151	0.118	0.949
Error	28	35.765	1.277		
Corrected Total	31	36.219			

Computed against model Y=Mean(Y)

Orientation / Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
O2 vs. O4	0.025	0.044	2.730	1.000	No
O2 vs. O1	0.150	0.265	2.730	0.993	No
O2 vs. O3	0.300	0.531	2.730	0.951	No
O4 vs. O1	0.125	0.221	2.730	0.996	No
O4 vs. O3	0.275	0.487	2.730	0.961	No
O1 vs. O3	0.150	0.265	2.730	0.993	No
Tukey's d critical value:			3.861		

Category	LS means	Groups
O2	38.063	A
O4	38.038	A
O1	37.913	A
O3	37.763	A

Table 5

ANOVA Results for Grit Blast Specimen

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	12.771	4.257	0.615	0.611
Error	28	193.734	6.919		
Corrected Total	31	206.505			

Computed against model Y=Mean(Y)

Orientation / Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
O3 vs. O1	0.563	0.428	2.730	0.973	No
O3 vs. O4	1.213	0.922	2.730	0.793	No
O3 vs. O2	1.663	1.264	2.730	0.593	No
O1 vs. O4	0.650	0.494	2.730	0.960	No
O1 vs. O2	1.100	0.836	2.730	0.837	No
O4 vs. O2	0.450	0.342	2.730	0.986	No
Tukey's d critical value:			3.861		

Category	LS means	Groups
O3	41.188	A
O1	40.625	A
O4	39.975	A
O2	39.525	A

Results:

The analyses of specimen orientation data revealed no significance in crack length. This rejects the hypothesis and supports the findings of the test in the study that states:

> "While crack growth and length during environmental exposure varied with surface preparation, specimen orientation caused no recurring trend in any of the three surface preparation methods tested to date." (Adams et al., 2011, p. 20)

Using ANOVA to validate the test results of this study confirms that the research presented was effective at evaluating the characteristics of the ASTM D3762 *metal wedge crack durability test* with the intent to "propose revisions to this standardized test method" which will be used to "assess the reliability of adhesively bonded aircraft structures." (Adams et al., 2011, p. 20)

ANOVA (2)

NDT Inspection of Composites for In-Service Defects (T. Marshall), [Study 4-2]

The NDI C-Scan BVID test data was analyzed to accept or reject the hypothesis that NDI testing is effective at consistently detecting impact damage in advanced composite structural components. The impactor test data presented in this study from four different test panels was sufficient to evaluate the observed NDI damage imagery for consistency. The study's test was conducted using standardized impact testing in accordance with FAA guidelines under AR-03/74 *Bonded Repair of Aircraft Composite Structures*. ANOVA analyses were performed for the width and depth delamination impact observations of each test panel: "thin" monolithic, "thick" monolithic, stringer, and honeycomb. The results for each panel are shown in Tables 6 through 13 with complete statistical summaries in Appendix E. The extracted data from the study is shown in Figures C2 through C5 (Appendix C).

Table 6

ANOVA Results for "Thin" Monolithic Panel (Width Observations)

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	14.330	4.777	1.415	0.265
Error	22	74.286	3.377		
Corrected Total	25	88.615			

Computed against model Y=Mean(Y)

Location / Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
R3 vs. R2	0.571	0.582	2.777	0.937	No
R3 vs.R4	1.714	1.677	2.777	0.359	No
R3 vs. R1	1.714	1.677	2.777	0.359	No
R2 vs. R4	1.143	1.118	2.777	0.683	No
R2 vs. R1	1.143	1.118	2.777	0.683	No
R1 vs. R4	0.000	0.000	2.777	1.000	No
Tukey's d critical value:			3.927		

Category	LS means	Groups
R3	3.714	A
R2	3.143	A
R1	2.000	A
R4	2.000	A

Table 7

ANOVA Results for "Thin" Monolithic Panel (Depth Observations)

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	413.538	137.846	3.735	0.026
Error	22	812.000	36.909		
Corrected Total	25	1225.538			

Computed against model Y=Mean(Y)

Location / Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
R2 vs. R3	0.000	0.000	2.777	1.000	No
R2 vs. R4	8.000	2.367	2.777	0.113	No
R2 vs. R1	8.000	2.367	2.777	0.113	No
R3 vs. R4	8.000	2.367	2.777	0.113	No
R3 vs. R1	8.000	2.367	2.777	0.113	No
R1 vs. R4	0.000	0.000	2.777	1.000	No
Tukey's d critical value:			3.927		

Category	LS means	Groups
R2	10.000	A
R3	10.000	A
R1	2.000	A
R4	2.000	A

Table 8

ANOVA Results for "Thick" Monolithic Panel (Width Observations)

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	13.687	4.562	1.331	0.290
Error	22	75.429	3.429		
Corrected Total	25	89.115			

Computed against model Y=Mean(Y)

Location / Tukey (HSD) / Analysis of the differences
between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
R3 vs. R2	0.714	0.722	2.777	0.887	No
R3 vs. R4	1.714	1.664	2.777	0.366	No
R3 vs.R1	1.714	1.664	2.777	0.366	No
R2 vs. R4	1.000	0.971	2.777	0.767	No
R2 vs. R1	1.000	0.971	2.777	0.767	No
R1 vs. R4	0.000	0.000	2.777	1.000	No
Tukey's d critical value:			3.927		

Category	LS means	Groups
R3	3.714	A
R2	3.000	A
R1	2.000	A
R4	2.000	A

Table 9

ANOVA Results for "Thick" Monolithic Panel (Depth Observations)

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	2326.242	775.414	2.984	0.053
Error	22	5717.143	259.870		
Corrected Total	25	8043.385			

Computed against model Y=Mean(Y)

Location / Tukey (HSD) / Analysis of the differences
between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
R3 vs. R2	2.857	0.332	2.777	0.987	No
R3 vs. R4	20.286	2.262	2.777	0.138	No
R3 vs. R1	20.286	2.262	2.777	0.138	No
R2 vs. R4	17.429	1.943	2.777	0.240	No
R2 vs. R1	17.429	1.943	2.777	0.240	No
R1 vs. R4	0.000	0.000	2.777	1.000	No
Tukey's d critical value:			3.927		

Category	LS means	Groups
R3	22.286	A
R2	19.429	A
R1	2.000	A
R4	2.000	A

Table 10

ANOVA Results for Stringer Panel (Width Observations)

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	54.638	18.213	14.767	0.000
Error	12	14.800	1.233		
Corrected Total	15	69.438			

Computed against model Y=Mean(Y)

Location / Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
R1 vs. R3	4.000	5.094	2.969	0.001	Yes
R1 vs. R4	4.300	5.772	2.969	0.000	Yes
R1 vs. R2	4.500	5.305	2.969	0.001	Yes
R3 vs. R4	0.300	0.403	2.969	0.977	No
R3 vs. R2	0.500	0.589	2.969	0.933	No
R4 vs. R2	0.200	0.247	2.969	0.994	No

Tukey's d critical value: 4.199

Category	LS means	Groups
R1	6.500	A
R3	2.500	B
R4	2.200	B
R2	2.000	B

Table 11

ANOVA Results for Stringer Panel (Depth Observations)

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	8896.500	2965.500	40.600	< 0.0001
Error	12	876.500	73.042		
Corrected Total	15	9773.000			

Computed against model Y=Mean(Y)

Location / Tukey (HSD) / Analysis of the differences
between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
R1 vs. R3	22.500	3.447	2.969	0.022	Yes
R1 vs. R2	57.000	8.168	2.969	< 0.0001	Yes
R1 vs. R4	58.500	9.680	2.969	< 0.0001	Yes
R3 vs. R2	34.500	5.285	2.969	0.001	Yes
R3 vs. R4	36.000	6.526	2.969	0.000	Yes
R2 vs. R4	1.500	0.248	2.969	0.994	No
Tukey's d critical value:			4.199		

Category	LS means	Groups
R1	60.000	A
R3	37.500	B
R2	3.000	C
R4	1.500	C

Table 12

ANOVA Results for Honeycomb Panel (Width Observations)

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	82.716	27.572	20.880	< 0.0001
Error	13	17.167	1.321		
Corrected Total	16	99.882			

Computed against model Y=Mean(Y)

Location / Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
R4 vs. R3	4.500	4.290	2.935	0.004	Yes
R4 vs. R2	5.333	5.684	2.935	0.000	Yes
R4 vs. R1	6.000	7.832	2.935	< 0.0001	Yes
R3 vs. R2	0.833	0.794	2.935	0.856	No
R3 vs. R1	1.500	1.670	2.935	0.377	No
R2 vs. R1	0.667	0.870	2.935	0.820	No
Tukey's d critical value:			4.151		

Category	LS means	Groups
R4	8.000	A
R3	3.500	B
R2	2.667	B
R1	2.000	B

Table 13

ANOVA Results for Honeycomb Panel (Depth Observations)

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	6575.863	2191.954	11.885	0.001
Error	13	2397.667	184.436		
Corrected Total	16	8973.529			

Computed against model Y=Mean(Y)

Location / Tukey (HSD) / Analysis of the differences between the categories with a confidence interval of 95%:

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
R2 vs. R4	0.833	0.080	2.935	1.000	No
R2 vs. R3	8.333	0.672	2.935	0.906	No
R2 vs. R1	41.333	4.496	2.935	0.003	Yes
R4 vs. R3	7.500	0.638	2.935	0.918	No
R4 vs. R1	40.500	4.870	2.935	0.002	Yes
R3 vs. R1	33.000	3.074	2.935	0.039	Yes
Tukey's d critical value:			4.151		

Category	LS means	Groups
R2	43.333	A
R4	42.500	A
R3	35.000	A
R1	2.000	B

Results:

The analyses of width and depth impact delamination observations in each panel revealed no significance for the “thin” and “thick” monolithic panels which accepts the hypothesis that NDI testing is effective at consistently detecting impact damage in advanced composite structural components (see note). However, significance was detected for both width and depth observations for the stringer and honeycomb panels which can be attributed to the construction characteristics of those panels causing variances to be observed at specific locations on the panels where irregular width and depth occurred. It should be noted that the significant variances in the impact observations only occurred at a rate of 58% (sum of both panels). This mathematically suggests that the study’s test results for the stringer and honeycomb panel supports the hypothesis and can be *conditionally accepted*[16] at an observation rate of 42% for the impact observations that did not show significance in width and depth observations.

Note. *The ANOVA results of “no significance” for the NDI C-Scan test results in this study is the desirable outcome in order to show that the NDI C-Scan is consistently detecting the damage created under test conditions with no variance. Significance in the data would prove that the NDI C-scan test results show variance in the observations which would suggest inconsistency for damage detection.*

[16] *The hypothesis is conditionally accepted with the assumption that panel construction characteristics caused the 58% rate of observed variances.*

Linear Regression (1)

CACRC Depot Bonded Repair Investigation – Round Robin Testing (2013 Technical Review) (J. Tomblin, L. Salah)

The depot level (airline) composite repair technician polling data from this study was used to perform two linear regressions that compare the following sets of variables: years of experience by percentage of rework, and number of repairs by percentage of rework. The results are shown in Figures 8 and 9. The extracted data[17] from this study is shown in Figure C6 located in Appendix C.

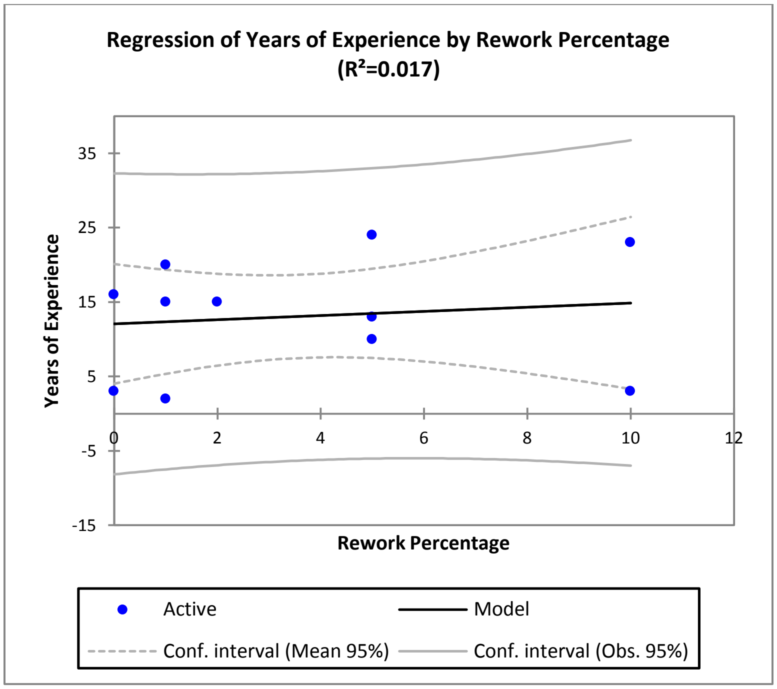

Figure 8. Linear regression showing years of experience by rework percentages for 11 out of 13 composite repair maintenance technicians. The R^2 coefficient value (0.017) in this model is quite low which does not represent a good fit for variability. However, the model shows a mean of 13 years with the least amount of rework occurring above the regression line within the confidence interval (Mean 95%) which suggests that technicians with more years of experience have less rework.

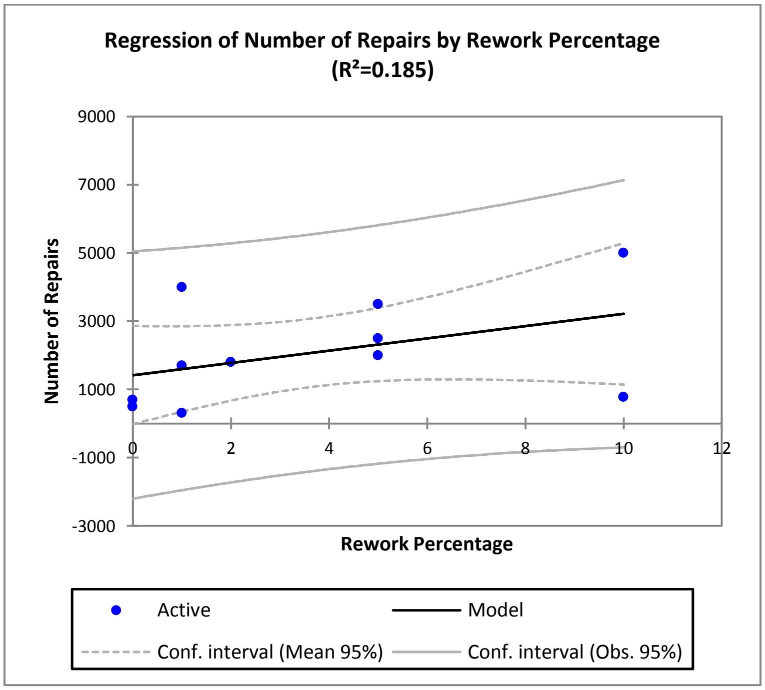

Figure 9. Linear regression showing number of repairs by rework percentages for 11 out of 13 composite repair maintenance technicians. The R^2 coefficient value (0.185) in this model is higher, but is also very low which does not represent a good fit for variability. However, the model shows a mean of 2,072 repairs with the highest amount of rework occurring above the regression line within the confidence interval (Mean 95%) which suggests that technicians performing a higher number of repairs experience more rework.

[17] *The data for Mechanic 2 and 9 from Figure C6 was removed from both regression models due to low reported values that would significantly alter the results of the predictions.*

Results:

The polling data presented in this study created a unique opportunity to determine if either technician experience or number of repairs were a good fit for variability with respect to the percentage of rework. Due to the low coefficient values in each regression model, this cannot be proven with the data that is provided. However, both models do suggest (through limited observation) that there is a correlation between the sets of variables based on what is observed either above or below the regression lines in each of the models.

Linear Regression (2)

Structural Health Monitoring for Advanced Composite Structures (I. Herszberg, et al.)

The fatigue data from *Damage Tolerance and Durability of Selectively Stitched, Stiffened Panels* (FAA AR-03/46) presented in this study is used to create a linear regression *stress to number of cycles* (S-N) curve to support the findings of the study that *structural health monitoring* (SHM) is effective for detecting fatigue damage growth in advanced composite structural components. The regression model is shown in Figure 10. The complete data set is shown in Figures C7 and C8 in Appendix C.

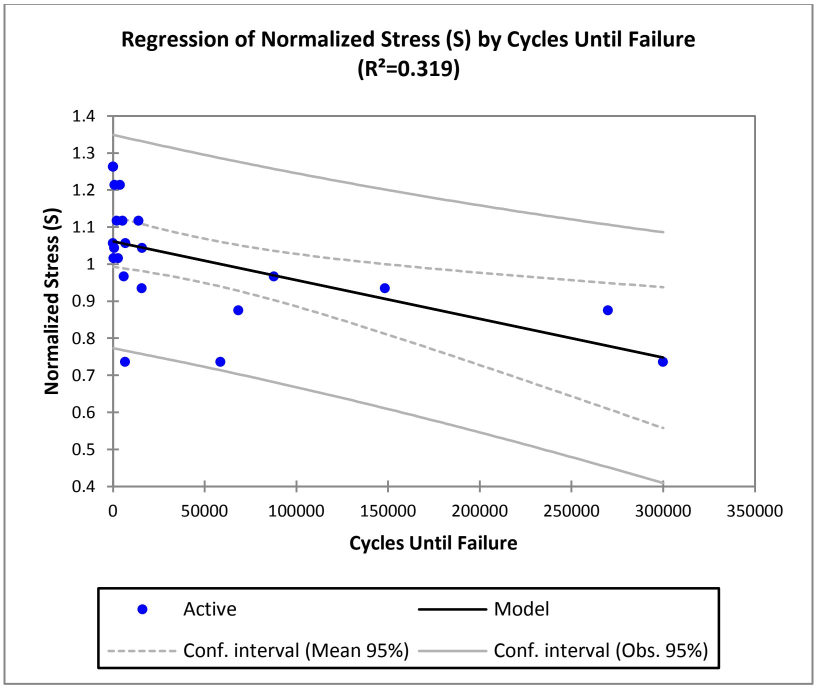

Figure 10. Linear regression S-N fatigue curve showing normalized stress by cycles until failure. The R^2 coefficient value (0.319) in this model represents a low fit for variability. However, the model shows a normalized stress mean of 1.013 with the highest concentration occurring just below the regression line within the confidence interval (Mean 95%) and then continuing to decrease below the confidence interval. The model also shows minimum observed normalized stress occurring at 0.735 close to the confidence interval (Obs. 95%) which directly correlates to the findings of the study regarding higher working strains.

Results:

The S-N linear regression fatigue curve revealed a normalized stress (minimum) observation of the FAA AR-03/46 fatigue data to be 73.5% (static strength) which directly correlates to the study's predicted fatigue curve for SHM damage growth detection of 70% to 75% and further states that:

> In the event that SHM systems facilitate the use of higher design allowables, the extent of these improvements may be limited by fatigue considerations. A no-growth approach to composite fatigue substantiation is practical because of low design allowables and correspondingly low operating strain levels together with the characteristic flat S-N curve for composite structures. For typical carbon fiber reinforced composites, significant fatigue damage occurs only at ***strain levels above approximately 60% of static strength***. However, once growth commences, its progression is generally rapid and, consequently, the no-growth option for composites is currently applied (Herszberg et al., n.d., para. 5.2).

Based on the findings in this study and the S-N regression modeling results for the AR-03/46 fatigue test data, SHM will be critical for the detection and monitoring of fatigue damage in structural composite components that are under higher design loads. As this study points out, significant fatigue damage in carbon fiber composite structures occurs at strain levels above 60% of the static strength. This is observed in the regression model which shows failure starting to occurring at 73.5% with the highest number of failure observations occurring just above 100%. However, it should be noted (as stated in the study) that due to the rapid progression of fatigue damage growth in composite structures, a no-growth approach must be maintained in order to prevent failure from occurring; SHM is the only enabler for this approach through early detection of fatigue damage and will prove to be vital in large applications such as the 787 and A350.

Analysis Summary

Composite Materials Studies Meta-Analysis

The findings of the meta-analysis revealed that industry-wide comprehensive process improvements and standardization are occurring for validation testing, certification standards, and maintenance/repair procedures of advanced composite structures used for the construction of commercial transport aircraft. However, it should be noted that even though significant progress is being made towards the standardization of composite maintenance and repair procedures by the CACRC, current deficiencies in technician experience, training, and repair inspection at the airline level do not presently support standardized composite maintenance and repair processes within the airline industry.

ANOVA and Linear Regression Analyses

ANOVA (1) proved that that the research presented was effective at evaluating the characteristics of the ASTM D3762 *metal wedge crack durability test* in order to propose effective revisions for this validation testing methodology to be used for future assessment and reliability testing of adhesively bonded aircraft structures. *ANOVA (2)* proved that *non-destructive inspection* (NDI) testing is effective at consistently detecting impact damage in advanced composite structural components by analyzing the C-Scan consistency of width and depth impact damage observations. *Linear Regression (1)* showed limited modeling prediction for airline composite repair technician experience and number of repairs variability with respect to the percentage of rework. *Linear Regression (2)* proved that *structural health monitoring* (SHM) will be critical for the detection and monitoring of fatigue damage in structural composite components that are under higher design loads.

Recommendations

Based on the interpretation and inferences of the findings in this project with respect to the identification and examination of current industry concerns and problems regarding the use of advanced composites in commercial transport aircraft applications, and current implementation of industry-wide comprehensive process improvements for the promulgation of improved structural validation testing, certification, and standardized repair procedures, the following recommendations are suggested for sustainment:

1. ***Manufacturer Collaboration.*** Boeing and Airbus will need to share and compare in-service structural data for the 787 *Dreamliner* and A350 *XWB* in order to identify commonalities pertaining to design, manufacturing, or maintenance concerns that have the potential to impact safety-of-flight. This should be accomplished through extensive NDI and SHM utilization.

2. ***Continued Standardization.*** Robust FAA partnership research and industry collaboration should continue in order to improve testing standardization and certification processes. Manufacturers need to collaborate with the CACRC and the airlines in order to partner for the development and establishment of standardized composite materials maintenance training and repair procedures for use throughout the industry – model training and certification programs (military) should be investigated and evaluated by the CACRC for potential industry-wide implementation.

3. ***Active Structural Evaluation.*** This should be implemented for the detection of defects, damage, and insipient failure. Robust NDI and SHM system utilization will be needed to create a preemptive evaluative approach. Implementing this type of methodology will allow for early detection and mitigation. Don’t wait until it breaks!

Conclusion

Accomplishments

Specific tasks and milestones were completed for this project. The first task and milestone involved a visit to the U.S. Navy's Advanced Composite Repair School at Naval Air Station North Island in San Diego, CA (December, 2012). This allowed for observation of artisan training, as well as advanced composite structures familiarization prior to literature review. The second task and milestone was the attendance of the 2013 JAMS/CMH-17 PMC meeting at the Boeing Future of Flight Facility in Everett, WA (April, 2013) where valuable research was conducted with over 200 industry participants which also allowed for interviews to be conducted with key research professionals and FAA Administrators. While attending the meeting, the author of this project was invited to join the CMH-17 sandwich composite working group and will be contributing to the technical review of MIL-23 Handbook chapters for the publishing of CMH-17 Volume 6.

Benefits to Aviation

Potential benefits to aviation from this research include the identification and validation of industry concerns associated with the continued use of advanced composites for structural aerospace applications. It is the desire of the project's author that the findings and recommendations from this research are reviewed by industry professionals in order to provide an independent exploratory perspective for future research.

Future Direction

This project contains many specific topics that can be researched independently and presented to the FAA's *Joint Advanced Materials & Structures Center of Excellence* for industry benefit. It is the desire of the project's author to continue this research with Embry-Riddle Aeronautical University under the Aviation Doctorate program of study.

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Appendix A

Capstone Project Guide

Table A1

Program Outcome Correlation to Project Section Heading/Sub-Heading with Location

Literature Review	
Program Outcome #1 (Fundamentals of Air Transportation)	
Validation Testing	13-14
FAA Certification Requirements	14-15
Structural Integration	15-17
Passenger Confidence	17-18
Environmental Impact	18-19
Regulatory Methodology	19-21
Program Outcome #3 (Fundamentals of Human Factors)	
Component Failure	21
Composite Repair Methods	22
Artisan Training and Experience	22-24
Non-Standard Repairs and Maintenance Malpractice	24-25
Program Outcome #5 (Aeronautics Topics)	
Performance and Design Innovation	25-28
Fatigue Life and Failure Mode	28-29
Lightning Strike Protection	29-31
Industry Concerns	32-37
Maintenance and Repair Standardization	37-39
Methodology	
Program Outcome #2 (Statistical Analysis)	
Validation Testing Studies	42-52, **64-69**
Certification Standards Studies	53-56, **69-73**
Maintenance and Repair Studies	57-62, **73-76**
ANOVA and Linear Regression	**77-90**
Recommendations	
Program Outcome #4 (Methodology Application)	
Manufacturer Collaboration	92
Continued Standardization	92
Active Structural Evaluation	92

Note. This table is provided as a reference to identify *Program Outcome* completion.

Table A2

List of Tables and Figures in the Order of Appearance or First Mentioned with Location

Tables

Figures

Appendix B

Illustrations

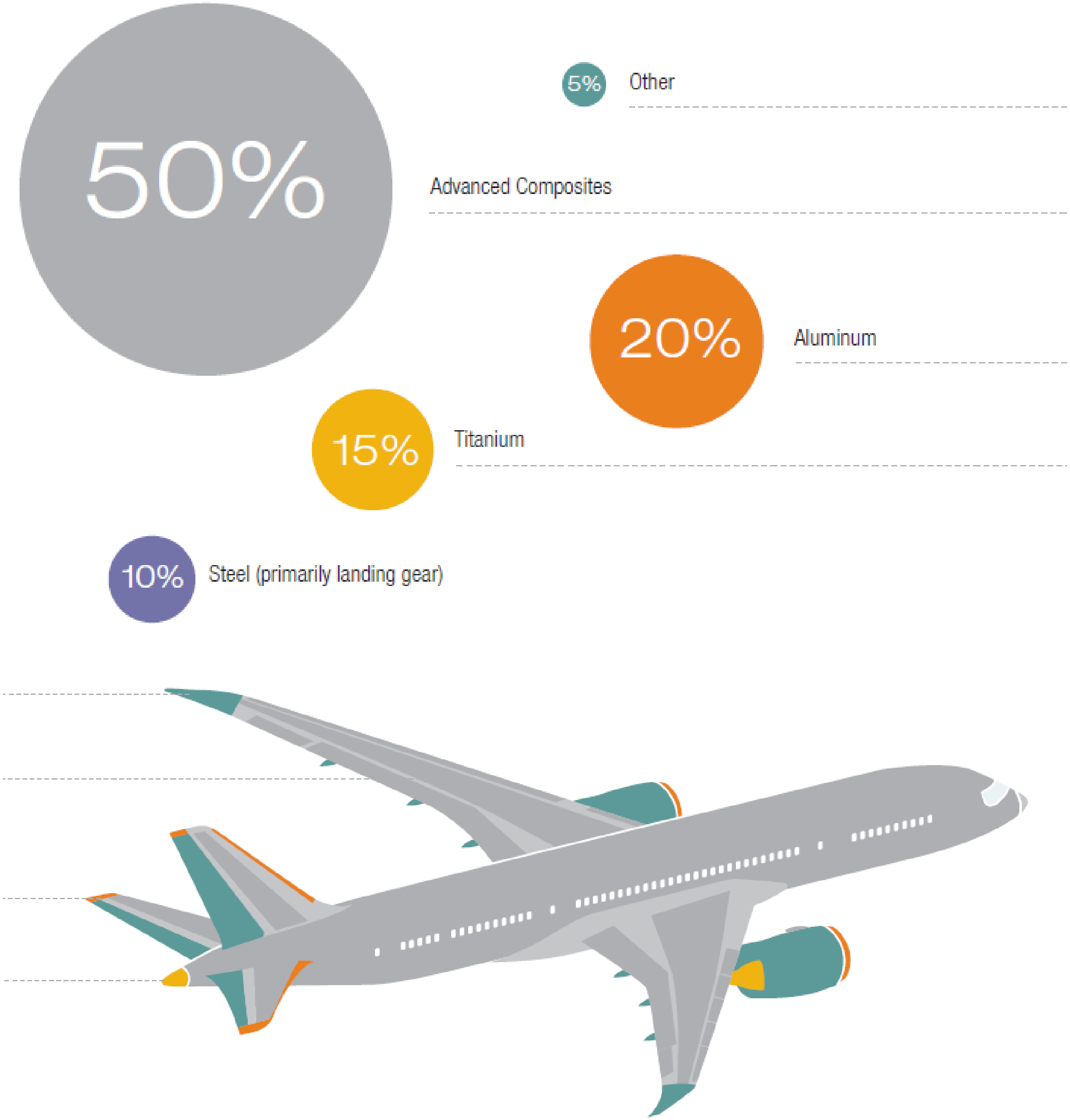


Figure B1. Materials used (by percentage and location) for the construction of the Boeing 787 *Dreamliner*. Reproduced from “Boeing 787 From the Ground Up – Composites in the Airframe and Primary Structure,” by J. Hale, 2006, *AERO Magazine*, *QTR_04*, p. 18-19. Copyright © 2006 by the Boeing Company. Reprinted with permission under the personal use agreement.

Figure B2. Illustration of Boeing 787 *Dreamliner* showing blended wing tips. Reproduced from the Boeing website. Copyright © 2013 by the Boeing Company. Reprinted with permission.

Figure B3. Illustration of Boeing 787 *Dreamliner* showing wing shape. Reproduced from the Wikipedia website. Copyright © 2007 by Y. Obara. Reprinted with permission under GFDL.

Figure B4

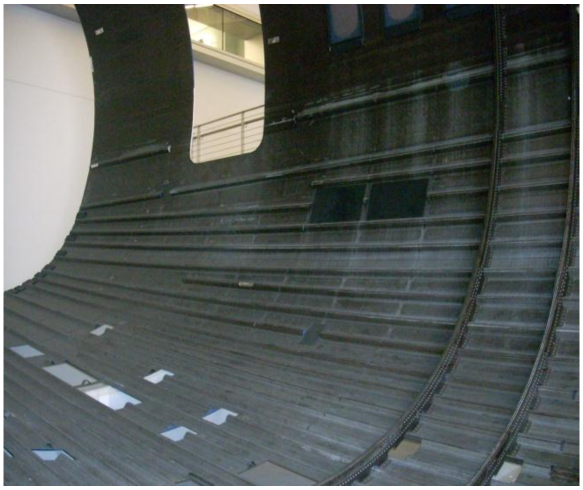


Figure B5

Figure B6

Figure B7

Figures B4-B7. Illustration of a Boeing 787 composite fuselage section showing monolithic *carbon fiber reinforced polymer* (CFRP) panel construction. Note the longitudinal and lateral *longeron-stringer* construction in Figure B6 and B7 which shows the multiple composite longerons bonded to the monolithic fuselage skin (no mechanical fasteners used) in comparison to the two composite stringers which are mechanically fastened (riveted) to the skin and reinforced with riveted composite doubler plates. By bonding all of the numerous composite longerons (as shown in Figure B5) to the monolithic skin with adhesive (vice riveting) throughout the entire fuselage significantly decreases the amount of mechanical fasteners used which decreases airframe weight. Photos taken by M. Severson at the Boeing Future of Flight Facility in Everett, WA (all rights reserved).

Appendix C

ANOVA and Linear Regression Data

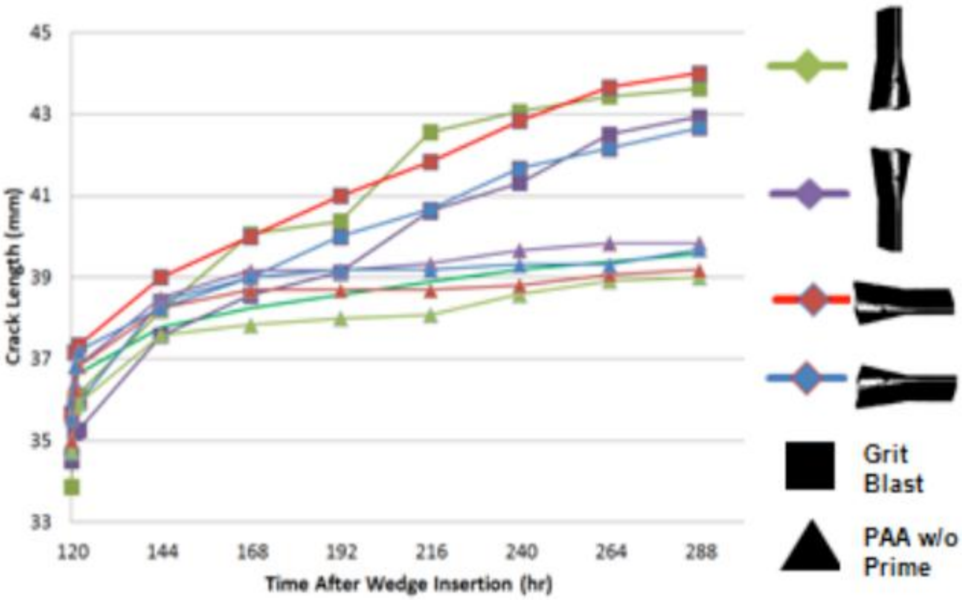


Figure C1. Crack length data for "weak" bonded specimens during environmental exposure. Reproduced from "Specimen Orientation," by D. Adams, et al., 2011, *Durability of Adhesively Bonded Joints for Aircraft Structures,* Figure 7, p. 18.

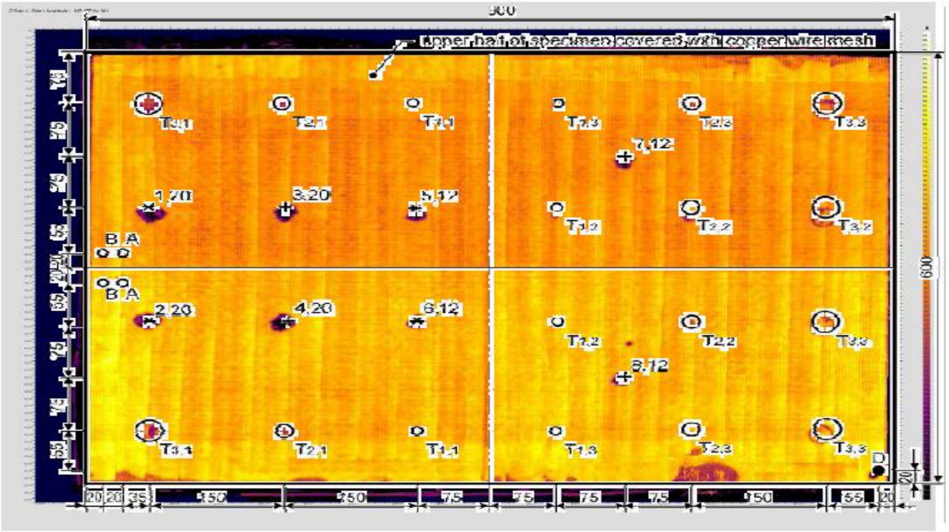


Figure C2. NDI C-Scan image of "thin" monolithic composite panel BVID testing data. Reproduced from "Aerospace Applications," by T. Marshall, Sonatest, Ltd., n.d., *NDT Inspection of Composites for In-Service Defects,* p. 28.

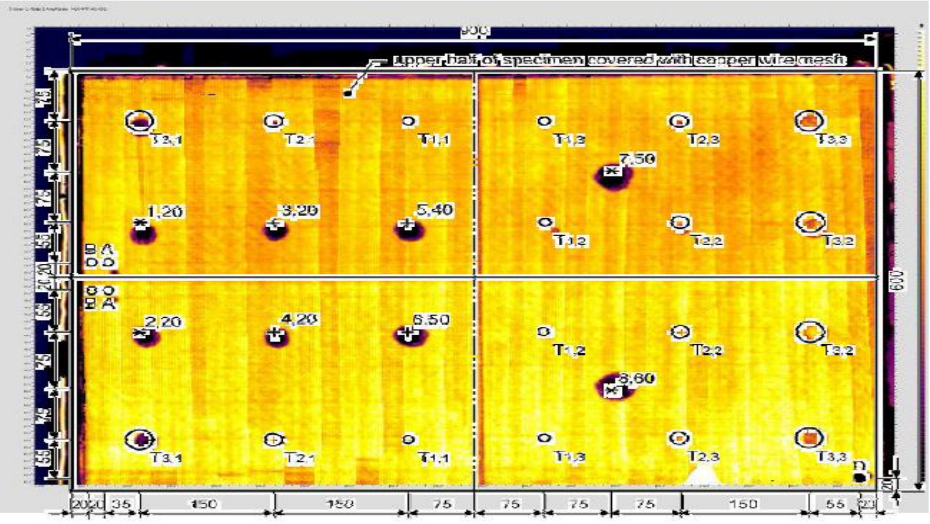


Figure C3. NDI C-Scan image of “thick” monolithic composite panel BVID testing data. Reproduced from “Aerospace Applications,” by T. Marshall, Sonatest, Ltd., n.d., *NDT Inspection of Composites for In-Service Defects,* p. 29.

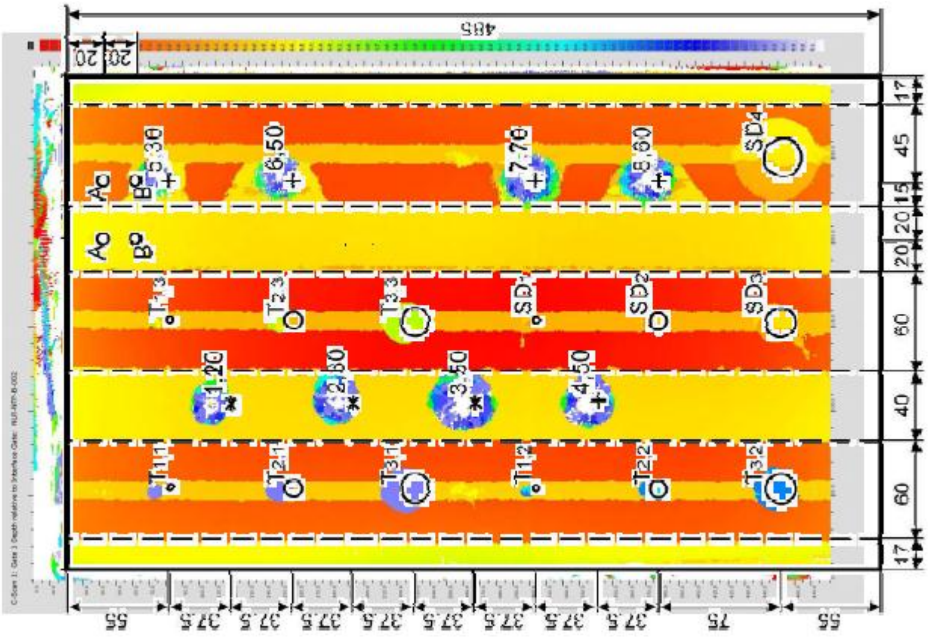


Figure C4. NDI C-Scan image of stringer composite panel BVID testing data. Reproduced from “Aerospace Applications,” by T. Marshall, Sonatest, Ltd., n.d., *NDT Inspection of Composites for In-Service Defects,* p. 30.

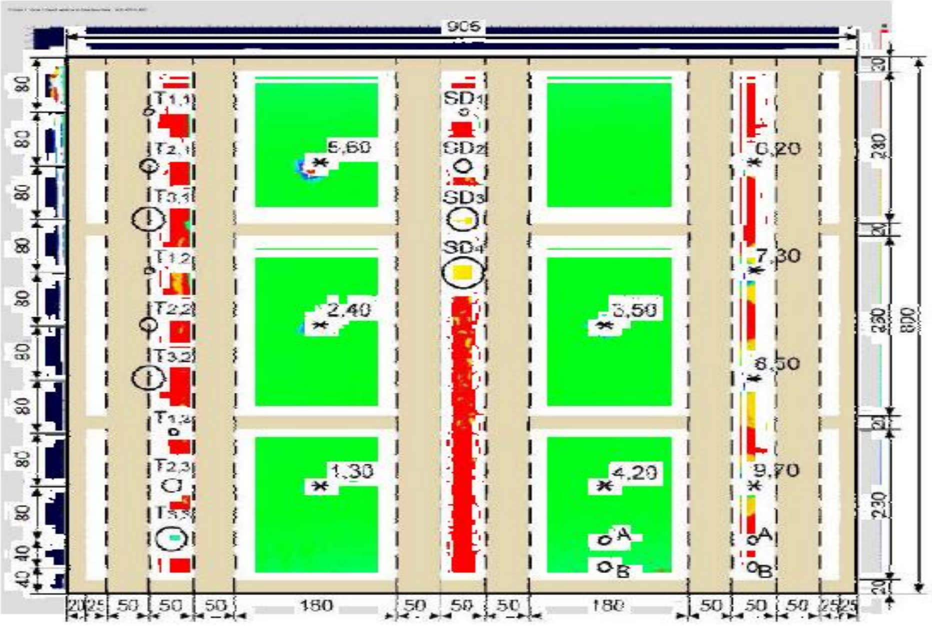
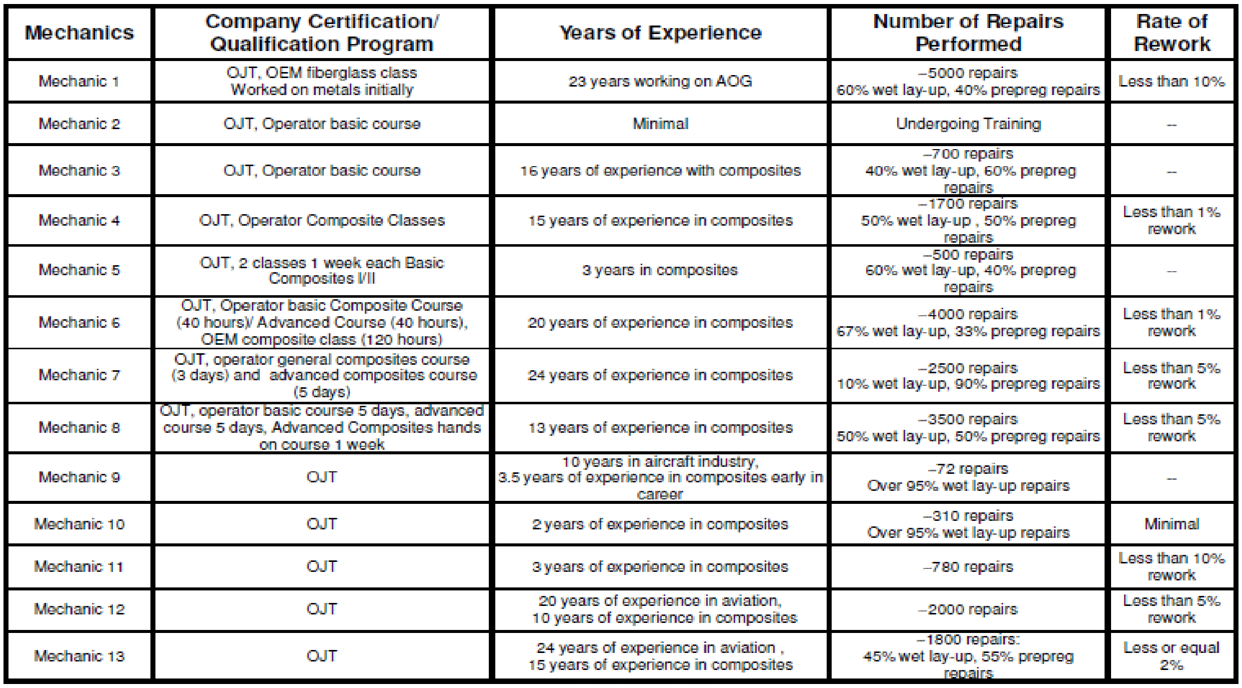
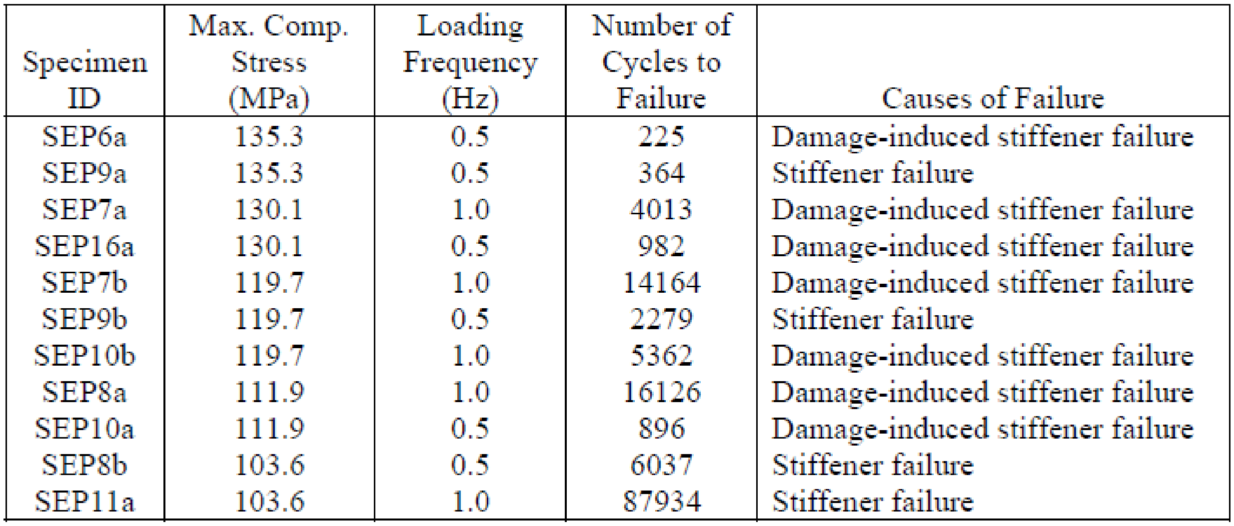


Figure C5. NDI C-Scan image of honeycomb composite panel BVID testing data. Reproduced from "Aerospace Applications," by T. Marshall, Sonatest, Ltd., n.d., *NDT Inspection of Composites for In-Service Defects,* p. 31.



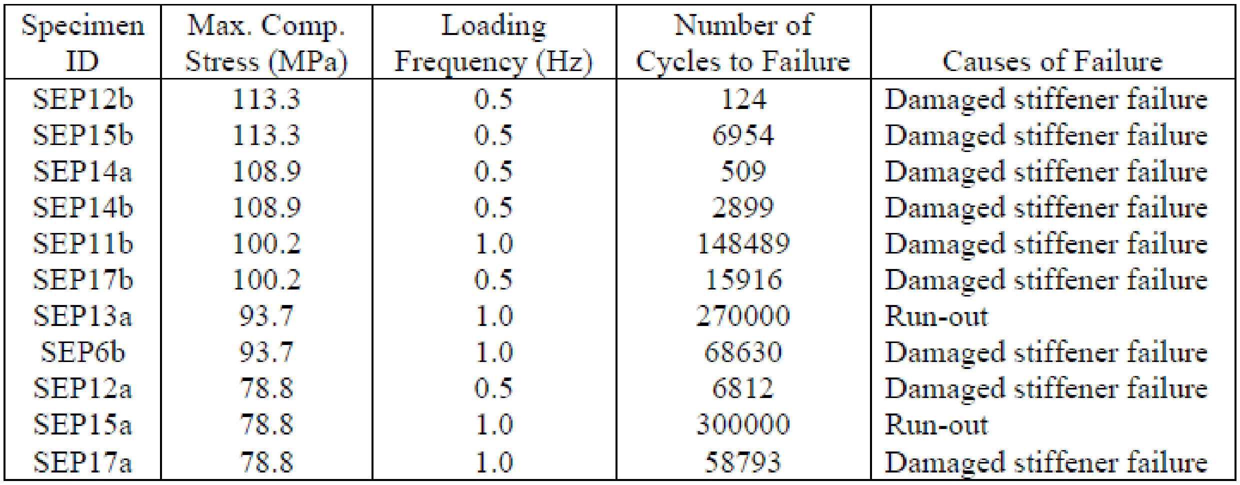
Mechanics	Company Certification/ Qualification Program	Years of Experience	Number of Repairs Performed	Rate of Rework
Mechanic 1	OJT, OEM fiberglass class Worked on metals initially	23 years working on AOG	–5000 repairs 60% wet lay-up, 40% prepreg repairs	Less than 10%
Mechanic 2	OJT, Operator basic course	Minimal	Undergoing Training	--
Mechanic 3	OJT, Operator basic course	16 years of experience with composites	–700 repairs 40% wet lay-up, 60% prepreg repairs	--
Mechanic 4	OJT, Operator Composite Classes	15 years of experience in composites	–1700 repairs 50% wet lay-up , 50% prepreg repairs	Less than 1% rework
Mechanic 5	OJT, 2 classes 1 week each Basic Composites I/II	3 years in composites	–500 repairs 60% wet lay-up, 40% prepreg repairs	--
Mechanic 6	OJT, Operator basic Composite Course (40 hours)/ Advanced Course (40 hours), OEM composite class (120 hours)	20 years of experience in composites	–4000 repairs 67% wet lay-up, 33% prepreg repairs	Less than 1% rework
Mechanic 7	OJT, operator general composites course (3 days) and advanced composites course (5 days)	24 years of experience in composites	–2500 repairs 10% wet lay-up, 90% prepreg repairs	Less than 5% rework
Mechanic 8	OJT, operator basic course 5 days, advanced course 5 days, Advanced Composites hands on course 1 week	13 years of experience in composites	–3500 repairs 50% wet lay-up, 50% prepreg repairs	Less than 5% rework
Mechanic 9	OJT	10 years in aircraft industry, 3.5 years of experience in composites early in career	–72 repairs Over 95% wet lay-up repairs	--
Mechanic 10	OJT	2 years of experience in composites	–310 repairs Over 95% wet lay-up repairs	Minimal
Mechanic 11	OJT	3 years of experience in composites	–780 repairs	Less than 10% rework
Mechanic 12	OJT	20 years of experience in aviation, 10 years of experience in composites	–2000 repairs	Less than 5% rework
Mechanic 13	OJT	24 years of experience in aviation , 15 years of experience in composites	–1800 repairs: 45% wet lay-up, 55% prepreg repairs	Less or equal 2%

Figure C6. CACRC polling data for airline composite repair technicians. Reproduced from "CACRC Depot Repairs – Technicians' Experience," by J. Tomblin and L. Salah, *CACRC Depot Bonded Repair Investigation – Round Robin Testing (2013 Tech. Review),* Presentation, p. 31.



Specimen ID	Max. Comp. Stress (MPa)	Loading Frequency (Hz)	Number of Cycles to Failure	Causes of Failure
SEP6a	135.3	0.5	225	Damage-induced stiffener failure
SEP9a	135.3	0.5	364	Stiffener failure
SEP7a	130.1	1.0	4013	Damage-induced stiffener failure
SEP16a	130.1	0.5	982	Damage-induced stiffener failure
SEP7b	119.7	1.0	14164	Damage-induced stiffener failure
SEP9b	119.7	0.5	2279	Stiffener failure
SEP10b	119.7	1.0	5362	Damage-induced stiffener failure
SEP8a	111.9	1.0	16126	Damage-induced stiffener failure
SEP10a	111.9	0.5	896	Damage-induced stiffener failure
SEP8b	103.6	0.5	6037	Stiffener failure
SEP11a	103.6	1.0	87934	Stiffener failure

Figure C7. S-N Fatigue Data (Set 1). Reproduced from “Constant-Amplitude Fatigue Results: Selectively Stitched CVSD Panels,” by H. Thomas Hahn, et al., *Damage Tolerance and Durability of Selectively Stitched, Stiffened Panels*, FAA AR-03/46, Table 17, p. 57.



Specimen ID	Max. Comp. Stress (MPa)	Loading Frequency (Hz)	Number of Cycles to Failure	Causes of Failure
SEP12b	113.3	0.5	124	Damaged stiffener failure
SEP15b	113.3	0.5	6954	Damaged stiffener failure
SEP14a	108.9	0.5	509	Damaged stiffener failure
SEP14b	108.9	0.5	2899	Damaged stiffener failure
SEP11b	100.2	1.0	148489	Damaged stiffener failure
SEP17b	100.2	0.5	15916	Damaged stiffener failure
SEP13a	93.7	1.0	270000	Run-out
SEP6b	93.7	1.0	68630	Damaged stiffener failure
SEP12a	78.8	0.5	6812	Damaged stiffener failure
SEP15a	78.8	1.0	300000	Run-out
SEP17a	78.8	1.0	58793	Damaged stiffener failure

Figure C8. S-N Fatigue Data (Set 2). Reproduced from “Constant-Amplitude Fatigue Results: Selectively Stitched CVSD Panels,” by H. Thomas Hahn, et al., *Damage Tolerance and Durability of Selectively Stitched, Stiffened Panels*, FAA AR-03/46, Table 18, p. 58.

Appendix D

ANOVA (1) Summary Statistics

Summary statistics for PAA without prime specimen:

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Crack Length	32	0	32	34.500	39.000	37.944	1.081

Variable	Categories	Frequencies	%
Orientation	O1	8	25.000
	O2	8	25.000
	O3	8	25.000
	O4	8	25.000

Correlation matrix:

Variables	Orientation-O1	Orientation-O2	Orientation-O3	Orientation-O4	Crack Length
Orientation-O1	**1.000**	-0.333	-0.333	-0.333	-0.017
Orientation-O2	-0.333	**1.000**	-0.333	-0.333	0.064
Orientation-O3	-0.333	-0.333	**1.000**	-0.333	-0.098
Orientation-O4	-0.333	-0.333	-0.333	**1.000**	0.051
Crack Length	-0.017	0.064	-0.098	0.051	**1.000**

Multicolinearity statistics:

Statistic	Orientation-O1	Orientation-O2	Orientation-O3	Orientation-O4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Crack Length:

Goodness of fit statistics:

Observations	32.000
Sum of weights	32.000
DF	28.000
R²	0.013
Adjusted R²	-0.093
MSE	1.277
RMSE	1.130
MAPE	2.027
DW	1.726
Cp	4.000
AIC	11.559
SBC	17.422
PC	1.270

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	0.454	0.151	0.118	0.949
Error	28	35.765	1.277		
Corrected Total	31	36.219			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Orientation	3	0.454	0.151	0.118	0.949

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Orientation	3	0.454	0.151	0.118	0.949

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	38.038	0.400	95.193	< 0.0001	37.219	38.856
Orientation-O1	-0.125	0.565	-0.221	0.827	-1.283	1.033
Orientation-O2	0.025	0.565	0.044	0.965	-1.133	1.183
Orientation-O3	-0.275	0.565	-0.487	0.630	-1.433	0.883
Orientation-O4	0.000	0.000				

Equation of the model:

Crack Length = 38.0375-0.124999999999997*Orientation-O1+0.025000000000001*Orientation-O2-0.275000000000003*Orientation-O3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Orientation-O1	-0.051	0.230	-0.221	0.827	-0.522	0.420
Orientation-O2	0.010	0.230	0.044	0.965	-0.461	0.481
Orientation-O3	-0.112	0.230	-0.487	0.630	-0.583	0.359
Orientation-O4	0.000	0.000				

Summary statistics for grit blast specimen:

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Crack Length	32	0	32	34.000	44.000	40.328	2.581

Variable	Categories	Frequencies	%
Orientation	O1	8	25.000
	O2	8	25.000
	O3	8	25.000
	O4	8	25.000

Correlation matrix:

Variables	Orientation-O1	Orientation-O2	Orientation-O3	Orientation-O4	Crack Length
Orientation-O1	**1.000**	-0.333	-0.333	-0.333	0.067
Orientation-O2	-0.333	**1.000**	-0.333	-0.333	-0.183
Orientation-O3	-0.333	-0.333	**1.000**	-0.333	0.195
Orientation-O4	-0.333	-0.333	-0.333	**1.000**	-0.080
Crack Length	0.067	-0.183	0.195	-0.080	**1.000**

Multicolinearity statistics:

Statistic	Orientation-O1	Orientation-O2	Orientation-O3	Orientation-O4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Crack Length:

Goodness of fit statistics:

Observations	32.000
Sum of weights	32.000
DF	28.000
R²	0.062
Adjusted R²	-0.039
MSE	6.919
RMSE	2.630
MAPE	5.111
DW	1.025
Cp	4.000
AIC	65.624
SBC	71.487
PC	1.206

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	12.771	4.257	0.615	0.611
Error	28	193.734	6.919		
Corrected Total	31	206.505			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Orientation	3	12.771	4.257	0.615	0.611

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Orientation	3	12.771	4.257	0.615	0.611

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	39.975	0.930	42.984	< 0.0001	38.070	41.880
Orientation-O1	0.650	1.315	0.494	0.625	-2.044	3.344
Orientation-O2	-0.450	1.315	-0.342	0.735	-3.144	2.244
Orientation-O3	1.213	1.315	0.922	0.364	-1.482	3.907
Orientation-O4	0.000	0.000				

Equation of the model:

Crack Length = 39.975+0.65*Orientation-O1-0.449999999999998*Orientation-O2+1.2125*Orientation-O3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Orientation-O1	0.111	0.224	0.494	0.625	-0.348	0.570
Orientation-O2	-0.077	0.224	-0.342	0.735	-0.536	0.383
Orientation-O3	0.207	0.224	0.922	0.364	-0.253	0.666
Orientation-O4	0.000	0.000				

Appendix E

ANOVA (2) Summary Statistics

Summary statistics for "thin" panel (width):

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Width	26	0	26	1.000	8.000	2.769	1.883

Variable	Categories	Frequencies	%
Location	R1	6	23.077
	R2	7	26.923
	R3	7	26.923
	R4	6	23.077

Correlation matrix:

Variables	Location-R1	Location-R2	Location-R3	Location-R4	Width
Location-R1	**1.000**	-0.332	-0.332	-0.300	-0.228
Location-R2	-0.332	**1.000**	-0.368	-0.332	0.123
Location-R3	-0.332	-0.368	**1.000**	-0.332	0.311
Location-R4	-0.300	-0.332	-0.332	**1.000**	-0.228
Width	-0.228	0.123	0.311	-0.228	**1.000**

Multicolinearity statistics:

Statistic	Location-R1	Location-R2	Location-R3	Location-R4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Width:

Goodness of fit statistics:

Observations	26.000
Sum of weights	26.000
DF	22.000
R²	0.162
Adjusted R²	0.047
MSE	3.377
RMSE	1.838
MAPE	64.857
DW	1.835
Cp	4.000
AIC	35.295
SBC	40.328
PC	1.143

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	14.330	4.777	1.415	0.265
Error	22	74.286	3.377		
Corrected Total	25	88.615			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	14.330	4.777	1.415	0.265

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	14.330	4.777	1.415	0.265

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	2.000	0.750	2.666	0.014	0.444	3.556
Location-R1	0.000	1.061	0.000	1.000	-2.200	2.200
Location-R2	1.143	1.022	1.118	0.276	-0.977	3.263
Location-R3	1.714	1.022	1.677	0.108	-0.406	3.834
Location-R4	0.000	0.000				

Equation of the model:

Width = 2+1.14285714285714*Location-R2+1.71428571428571*Location-R3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Location-R1	0.000	0.242	0.000	1.000	-0.502	0.502
Location-R2	0.275	0.246	1.118	0.276	-0.235	0.784
Location-R3	0.412	0.246	1.677	0.108	-0.098	0.921
Location-R4	0.000	0.000				

Summary statistics for "thin" panel (depth):

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Depth	26	0	26	1.000	20.000	6.308	7.002

Variable	Categories	Frequencies	%
Location	R1	6	23.077
	R2	7	26.923
	R3	7	26.923
	R4	6	23.077

Correlation matrix:

Variables	Location-R1	Location-R2	Location-R3	Location-R4	Depth
Location-R1	**1.000**	-0.332	-0.332	-0.300	-0.344
Location-R2	-0.332	**1.000**	-0.368	-0.332	0.326
Location-R3	-0.332	-0.368	**1.000**	-0.332	0.326
Location-R4	-0.300	-0.332	-0.332	**1.000**	-0.344
Depth	-0.344	0.326	0.326	-0.344	**1.000**

Multicolinearity statistics:

Statistic	Location-R1	Location-R2	Location-R3	Location-R4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Depth:

Goodness of fit statistics:

Observations	26.000
Sum of weights	26.000
DF	22.000
R²	0.337
Adjusted R²	0.247
MSE	36.909
RMSE	6.075
MAPE	133.333
DW	0.973
Cp	4.000
AIC	97.476
SBC	102.509
PC	0.903

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	413.538	137.846	3.735	0.026
Error	22	812.000	36.909		
Corrected Total	25	1225.538			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	413.538	137.846	3.735	0.026

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	413.538	137.846	3.735	0.026

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	2.000	2.480	0.806	0.429	-3.144	7.144
Location-R1	0.000	3.508	0.000	1.000	-7.274	7.274
Location-R2	8.000	3.380	2.367	0.027	0.990	15.010
Location-R3	8.000	3.380	2.367	0.027	0.990	15.010
Location-R4	0.000	0.000				

Equation of the model:

Depth = 2+7.99999999999999*Location-R2+7.99999999999999*Location-R3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Location-R1	0.000	0.215	0.000	1.000	-0.446	0.446
Location-R2	0.517	0.218	2.367	0.027	0.064	0.970
Location-R3	0.517	0.218	2.367	0.027	0.064	0.970
Location-R4	0.000	0.000				

Summary statistics for "thick" panel (width):

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Width	26	0	26	1.000	8.000	2.731	1.888

Variable	Categories	Frequencies	%
Location	R1	6	23.077
	R2	7	26.923
	R3	7	26.923
	R4	6	23.077

Correlation matrix:

Variables	Location-R1	Location-R2	Location-R3	Location-R4	Width
Location-R1	**1.000**	-0.332	-0.332	-0.300	-0.216
Location-R2	-0.332	**1.000**	-0.368	-0.332	0.088
Location-R3	-0.332	-0.368	**1.000**	-0.332	0.322
Location-R4	-0.300	-0.332	-0.332	**1.000**	-0.216
Width	-0.216	0.088	0.322	-0.216	**1.000**

Multicolinearity statistics:

Statistic	Location-R1	Location-R2	Location-R3	Location-R4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Width:

Goodness of fit statistics:

Observations	26.000
Sum of weights	26.000
DF	22.000
R²	0.154
Adjusted R²	0.038
MSE	3.429
RMSE	1.852
MAPE	65.229
DW	1.828
Cp	4.000
AIC	35.692
SBC	40.725
PC	1.154

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	13.687	4.562	1.331	0.290
Error	22	75.429	3.429		
Corrected Total	25	89.115			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	13.687	4.562	1.331	0.290

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	13.687	4.562	1.331	0.290

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	2.000	0.756	2.646	0.015	0.432	3.568
Location-R1	0.000	1.069	0.000	1.000	-2.217	2.217
Location-R2	1.000	1.030	0.971	0.342	-1.136	3.136
Location-R3	1.714	1.030	1.664	0.110	-0.422	3.851
Location-R4	0.000	0.000				

Equation of the model:

Width = 2+0.999999999999998*Location-R2+1.71428571428571*Location-R3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Location-R1	0.000	0.243	0.000	1.000	-0.505	0.505
Location-R2	0.240	0.247	0.971	0.342	-0.272	0.751
Location-R3	0.411	0.247	1.664	0.110	-0.101	0.923
Location-R4	0.000	0.000				

Summary statistics for "thick" panel (depth):

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Depth	26	0	26	1.000	60.000	12.154	17.937

Variable	Categories	Frequencies	%
Location	R1	6	23.077
	R2	7	26.923
	R3	7	26.923
	R4	6	23.077

Correlation matrix:

Variables	Location-R1	Location-R2	Location-R3	Location-R4	Depth
Location-R1	**1.000**	-0.332	-0.332	-0.300	-0.316
Location-R2	-0.332	**1.000**	-0.368	-0.332	0.251
Location-R3	-0.332	-0.368	**1.000**	-0.332	0.350
Location-R4	-0.300	-0.332	-0.332	**1.000**	-0.316
Depth	-0.316	0.251	0.350	-0.316	**1.000**

Multicolinearity statistics:

Statistic	Location-R1	Location-R2	Location-R3	Location-R4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Depth:

Goodness of fit statistics:

Observations	26.000
Sum of weights	26.000
DF	22.000
R²	0.289
Adjusted R²	0.192
MSE	259.870
RMSE	16.120
MAPE	258.330
DW	1.360
Cp	4.000
AIC	148.221
SBC	153.254
PC	0.969

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	2326.242	775.414	2.984	0.053
Error	22	5717.143	259.870		
Corrected Total	25	8043.385			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	2326.242	775.414	2.984	0.053

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	2326.242	775.414	2.984	0.053

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	2.000	6.581	0.304	0.764	-11.648	15.648
Location-R1	0.000	9.307	0.000	1.000	-19.302	19.302
Location-R2	17.429	8.969	1.943	0.065	-1.171	36.028
Location-R3	20.286	8.969	2.262	0.034	1.686	38.885
Location-R4	0.000	0.000				

Equation of the model:

Depth = 2.00000000000001+17.4285714285714*Location-R2+20.2857142857143*Location-R3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Location-R1	0.000	0.223	0.000	1.000	-0.462	0.462
Location-R2	0.440	0.226	1.943	0.065	-0.030	0.909
Location-R3	0.512	0.226	2.262	0.034	0.043	0.981
Location-R4	0.000	0.000				

Summary statistics for stringer panel (width):

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Width	16	0	16	1.000	8.000	3.313	2.152

Variable	Categories	Frequencies	%
Location	R1	4	25.000
	R2	3	18.750
	R3	4	25.000
	R4	5	31.250

Summary statistics (Validation):

Variable	Categories	Frequencies	%
Location	R1	0	0.000
	R2	0	0.000
	R3	0	0.000
	R4	1	100.000

Correlation matrix:

Variables	Location-R1	Location-R2	Location-R3	Location-R4	Width
Location-R1	**1.000**	-0.277	-0.333	-0.389	0.883
Location-R2	-0.277	**1.000**	-0.277	-0.324	-0.303
Location-R3	-0.333	-0.277	**1.000**	-0.389	-0.225
Location-R4	-0.389	-0.324	-0.389	**1.000**	-0.360
Width	0.883	-0.303	-0.225	-0.360	**1.000**

Multicolinearity statistics:

Statistic	Location-R1	Location-R2	Location-R3	Location-R4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Width:

Goodness of fit statistics:

Observations	16.000
Sum of weights	16.000
DF	12.000
R^2	0.787
Adjusted R^2	0.734
MSE	1.233
RMSE	1.111
MAPE	38.754
DW	2.053
Cp	4.000
AIC	6.753
SBC	9.843
PC	0.355

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	54.638	18.213	14.767	0.000
Error	12	14.800	1.233		
Corrected Total	15	69.438			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	54.638	18.213	14.767	0.000

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	54.638	18.213	14.767	0.000

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	2.200	0.497	4.430	0.001	1.118	3.282
Location-R1	4.300	0.745	5.772	< 0.0001	2.677	5.923
Location-R2	-0.200	0.811	-0.247	0.809	-1.967	1.567
Location-R3	0.300	0.745	0.403	0.694	-1.323	1.923
Location-R4	0.000	0.000				

Equation of the model:

Width = 2.2+4.3*Location-R1-0.200000000000001*Location-R2+0.299999999999999*Location-R3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Location-R1	0.894	0.155	5.772	< 0.0001	0.556	1.231
Location-R2	-0.037	0.152	-0.247	0.809	-0.369	0.294
Location-R3	0.062	0.155	0.403	0.694	-0.275	0.400
Location-R4	0.000	0.000				

Summary statistics for stringer panel (depth):

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Depth	16	0	16	1.000	70.000	21.750	25.525

Variable	Categories	Frequencies	%
Location	R1	3	18.750
	R2	3	18.750
	R3	4	25.000
	R4	6	37.500

Summary statistics (Validation):

Variable	Categories	Frequencies	%
Location	R1	1	100.000
	R2	0	0.000
	R3	0	0.000
	R4	0	0.000

Correlation matrix:

Variables	Location-R1	Location-R2	Location-R3	Location-R4	Depth
Location-R1	**1.000**	-0.231	-0.277	-0.372	0.743
Location-R2	-0.231	**1.000**	-0.277	-0.372	-0.364
Location-R3	-0.277	-0.277	**1.000**	-0.447	0.368
Location-R4	-0.372	-0.372	-0.447	**1.000**	-0.635
Depth	0.743	-0.364	0.368	-0.635	**1.000**

Multicolinearity statistics:

Statistic	Location-R1	Location-R2	Location-R3	Location-R4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Depth:

Goodness of fit statistics:

Observations	16.000
Sum of weights	16.000
DF	12.000
R²	0.910
Adjusted R²	0.888
MSE	73.042
RMSE	8.546
MAPE	26.362
DW	1.684
Cp	4.000
AIC	72.054
SBC	75.144
PC	0.149

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	8896.500	2965.500	40.600	< 0.0001
Error	12	876.500	73.042		
Corrected Total	15	9773.000			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	8896.500	2965.500	40.600	< 0.0001

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	8896.500	2965.500	40.600	< 0.0001

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	1.500	3.489	0.430	0.675	-6.102	9.102
Location-R1	58.500	6.043	9.680	< 0.0001	45.333	71.667
Location-R2	1.500	6.043	0.248	0.808	-11.667	14.667
Location-R3	36.000	5.517	6.526	< 0.0001	23.980	48.020
Location-R4	0.000	0.000				

Equation of the model:

Depth = 1.5+58.5*Location-R1+1.50000000000001*Location-R2+36*Location-R3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Location-R1	0.924	0.095	9.680	< 0.0001	0.716	1.132
Location-R2	0.024	0.095	0.248	0.808	-0.184	0.232
Location-R3	0.631	0.097	6.526	< 0.0001	0.420	0.841
Location-R4	0.000	0.000				

Summary statistics for honeycomb panel (width):

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Width	17	0	17	1.000	9.000	3.353	2.499

Variable	Categories	Frequencies	%
Location	R1	9	52.941
	R2	3	17.647
	R3	2	11.765
	R4	3	17.647

Summary statistics (Validation):

Variable	Categories	Frequencies	%
Location	R1	0	0.000
	R2	0	0.000
	R3	0	0.000
	R4	1	100.000

Correlation matrix:

Variables	Location-R1	Location-R2	Location-R3	Location-R4	Width
Location-R1	**1.000**	-0.491	-0.387	-0.491	-0.592
Location-R2	-0.491	**1.000**	-0.169	-0.214	-0.131
Location-R3	-0.387	-0.169	**1.000**	-0.169	0.022
Location-R4	-0.491	-0.214	-0.169	**1.000**	0.887
Width	-0.592	-0.131	0.022	0.887	**1.000**

Multicolinearity statistics:

Statistic	Location-R1	Location-R2	Location-R3	Location-R4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Width:

Goodness of fit statistics:

Observations	17.000
Sum of weights	17.000
DF	13.000
R²	0.828
Adjusted R²	0.788
MSE	1.321
RMSE	1.149
MAPE	41.249
DW	1.887
Cp	4.000
AIC	8.166
SBC	11.499
PC	0.278

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	82.716	27.572	20.880	< 0.0001
Error	13	17.167	1.321		
Corrected Total	16	99.882			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	82.716	27.572	20.880	< 0.0001

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	82.716	27.572	20.880	< 0.0001

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	8.000	0.663	12.058	< 0.0001	6.567	9.433
Location-R1	-6.000	0.766	-7.832	< 0.0001	-7.655	-4.345
Location-R2	-5.333	0.938	-5.684	< 0.0001	-7.360	-3.306
Location-R3	-4.500	1.049	-4.290	0.001	-6.766	-2.234
Location-R4	0.000	0.000				

Equation of the model:

Width = 8-6*Location-R1-5.33333333333333*Location-R2-4.5*Location-R3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Location-R1	-1.236	0.158	-7.832	< 0.0001	-1.576	-0.895
Location-R2	-0.839	0.148	-5.684	< 0.0001	-1.158	-0.520
Location-R3	-0.598	0.139	-4.290	0.001	-0.899	-0.297
Location-R4	0.000	0.000				

Summary statistics for honeycomb panel (depth):

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Depth	17	0	17	1.000	70.000	22.706	23.682

Variable	Categories	Frequencies	%
Location	R1	8	47.059
	R2	3	17.647
	R3	2	11.765
	R4	4	23.529

Summary statistics (Validation):

Variable	Categories	Frequencies	%
Location	R1	1	100.000
	R2	0	0.000
	R3	0	0.000
	R4	0	0.000

Correlation matrix:

Variables	Location-R1	Location-R2	Location-R3	Location-R4	Depth
Location-R1	**1.000**	-0.436	-0.344	-0.523	-0.850
Location-R2	-0.436	**1.000**	-0.169	-0.257	0.416
Location-R3	-0.344	-0.169	**1.000**	-0.203	0.195
Location-R4	-0.523	-0.257	-0.203	**1.000**	0.478
Depth	-0.850	0.416	0.195	0.478	**1.000**

Multicolinearity statistics:

Statistic	Location-R1	Location-R2	Location-R3	Location-R4
Tolerance	0.000	0.000	0.000	0.000
VIF	0.000	0.000	0.000	0.000

Regression of variable Depth:

Goodness of fit statistics:

Observations	17.000
Sum of weights	17.000
DF	13.000
R²	0.733
Adjusted R²	0.671
MSE	184.436
RMSE	13.581
MAPE	46.706
DW	1.421
Cp	4.000
AIC	92.134
SBC	95.466
PC	0.432

Analysis of variance:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	6575.863	2191.954	11.885	0.001
Error	13	2397.667	184.436		
Corrected Total	16	8973.529			

Computed against model Y=Mean(Y)

Type I Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	6575.863	2191.954	11.885	0.001

Type III Sum of Squares analysis:

Source	DF	Sum of squares	Mean squares	F	Pr > F
Location	3	6575.863	2191.954	11.885	0.001

Model parameters:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Intercept	42.500	6.790	6.259	< 0.0001	27.830	57.170
Location-R1	-40.500	8.316	-4.870	0.000	-58.467	-22.533
Location-R2	0.833	10.372	0.080	0.937	-21.575	23.242
Location-R3	-7.500	11.761	-0.638	0.535	-32.909	17.909
Location-R4	0.000	0.000				

Equation of the model:

Depth = 42.5-40.5*Location-R1+0.833333333333319*Location-R2-7.50000000000002*Location-R3

Standardized coefficients:

Source	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
Location-R1	-0.880	0.181	-4.870	0.000	-1.270	-0.490
Location-R2	0.014	0.172	0.080	0.937	-0.358	0.386
Location-R3	-0.105	0.165	-0.638	0.535	-0.461	0.251
Location-R4	0.000	0.000				