ADVANCED COMPOSITE AIR FRAME LIFE CYCLE COST ESTIMATING

DISSERTATION

Mohamed M. AlRomaihi, Colonel, Bahrain Defense Force

AFIT-ENS-DS-14-J-19

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENS-DS-14-J-19

ADVANCED COMPOSITE AIR FRAME LIFE CYCLE COST ESTIMATING

DISSERTATION

Presented to the Faculty

Department of Operation Sciences

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Doctor of Philosophy

Mohamed M. AlRomaihi, B.S., M.S.,

Colonel, BDF

June 2014

AFIT-ENS-DS-14-J-19

ADVANCED COMPOSITE AIR FRAME LIFE CYCLE COST ESTIMATING

Mohamed M. AlRomaihi, B.S., M.S.,

Colonel, BDF

Approved:

__________________//signed//________________ ____________________
Dr. Jeffery Weir (Chairman) Date

__________________//signed//________________ ____________________
Dr. Adedeji Badiru (Member) Date

__________________//signed//________________ ____________________
Dr. Som Soni (Member) Date

__________________//signed//________________ ____________________
Dr. Alfred E. Thal, Jr. (Member) Date

AFIT-ENS-DS-14-J-19

Abstract

Because of their versatility, advanced composite materials are being used at an increasing rate in the manufacturing of aircraft, as well as other products, such as autos, sporting goods, and medical products. Airframe structure materials used throughout aerospace manufacturing processes consist of significantly greater percentages of advanced composite materials. However, these manufacturing processes and the associated reduction in part counts are not considered in the aircraft procurement and life cycle cost (LCC) management processes in the United States Air Force (USAF) community or the Department of Defense (DoD). This situation led the leaders of USAF and DoD to restudy the LCC models that estimate the cost for most weapon systems. Most of the present LCC models and procurement processes were developed and established when the metals were used in airframe structures. Over the last three decades, a series of composite affordability initiatives (CAI) has culminated in a better quantifying system for calculating the influence of advanced composite materials in airframe structures. This research finds that significant relationships exist between part counts, touch labor hours of development, and production cost. The reduction in the part counts led to corresponding reductions in touch labor hours. This research effort was undertaken to update the cost estimating relationships (CERs) for airframes by including the part count percentage reduction (PCPR) cost factors of the above mentioned relationships. The results suggest that the reduction in part counts forces a related percentage reduction in touch labor hours cost categories. The output of this research is the recommendation that the present LCC estimation models for advanced composite aircraft be upgraded.

Dedication

First and foremost, I dedicate this work to God for giving me this opportunity and assisting me through the process of achievements. And, also, I dedicate this page to the soul of my father and lovely mother who taught me many life lessons and to my beautiful wife and four children for their efforts and sacrifices. Without their assistance and support, I would never have completed this endeavor.

Acknowledgments

I would like to express my deep, sincere appreciation to my dissertation advisor, Dr. Jeff Weir, who provided the proper insight and perspective to complete this research. His guidance throughout this arduous process has been invaluable. I am also deeply indebted to Dr. Som Soni, without whom I would never have pursued this project and who invested his time and efforts in guiding me academically and professionally. I would like also to express my gratitude to my committee members, Dr. Adedeji Badiru and Dr. Alfred E. Thal, Jr., who supported and assisted me to reach this stage of knowledge. I know that together we have achieved some significant advances in LCC and advanced composite materials, and along the way I have grown in understanding regarding their varied individual disciplines.

Mohamed M. AlRomaihi

Table of Contents

List of Figures

Page

List of Tables

ADVANCED COMPOSITE AIR FRAME LIFE CYCLE COST ESTIMATING

I. Introduction

Background and Motivation

Advanced composite materials are widely used in autos, medical products, sporting goods, and would also be used significantly more in aerospace if there was a more complete understanding of their performance capabilities. Composite materials are combinations of two or more different materials in which each constituent remains identifiable, but the mechanical properties of the combination are different from each of the original materials. Delamination is one of the most feared modes of failure in advanced composite materials and, unfortunately, is common. Z-pinning provides through-the-thickness reinforcements to reduce delamination, thus improving structural damage tolerance. The Composite Affordability Initiatives (CAI) by the United States Air Force (USAF) has identified joining and co-curing of advanced composite materials as important problems of interest. The increasing use of advanced composite materials in the aerospace industries has led to significant improvements in manufacturing methods and machinery for these new materials and structures. Despite advanced composite materials having been used in airframe structure manufacturing for a number of years, estimating costs strategies for aircraft using these large advanced composite material structures is still in its infancy; there are no universally accepted LCC models for advanced composite aircraft. This lack of a commonly agreed upon LCC model provides many opportunities for research in this field. While study continues in the field of advanced composite aircraft, further research is also needed on the effects of mechanization on LCC. Fiber placement machines are regularly being used in the manufacturing process to improve the effectiveness of advanced composite manufacturing in production. The effect on the development and production costs relative to the different touch labor hour parameters is not as well defined as the airframe structures of the aircraft manufacturing methods. The speed and weight cost estimation models used in estimating the aircraft cost may not be the best for composite material aircraft. This research proposes updating the LCC estimating model for aircraft using extensive composite materials with the latest information and available data. The proposed LCC model is of extreme value to new aircraft system procurements because new advanced materials and manufacturing processes require new cost elements in the LCC model to accurately project costs. The foundation of this research is from two cost analysis officers [26, and 27] who have conducted research in this field toward their master's theses. While [26, and 27] use prototype data, this research uses production aircraft data to determine if the exist a relationship between variables and empty wieght (EW) to build better cost estimation relationships (CERs). This research will help the acquisition process understand and utilize the latest aircraft system procurement technology and LCC estimation models.

The Advanced Composite Cargo Aircraft (ACCA) is a research cargo aircraft sponsored by the Air Force Research Laboratory (AFRL). In conjunction with that effort, it was decided to generate a cost analysis for using advanced composite materials on a large scale, focusing on the effects of the associated reduction in part counts. The unique effects of the manufacturing techniques for advanced composite materials have not been taken into consideration when establishing the procurement strategies and life cycle cost (LCC) model cost estimations. The current LCC models do not take into account the potential cost savings from the reduction in touch labor hours that result from the use of advanced composite materials in manufacturing airframe structures, and from the decrease in aircraft part counts.

Advanced Composite Materials

Man's desire to create advanced composites is not new. This is because biological composites, such as wood and bones, are complex; they are designed for specific functions and perform these functions especially well [19, 26, 27, and 30].

The desire of aerospace researchers is to construct materials, much like naturally-existing composites, that serve specific functions. In aerospace, light weight, yet strong and ductile materials are desired. These characteristics have been sought for some time now and began with fiberglass, one of the modern-day composites that is still used after its creation in the 1930s. Advanced filamentary and laminated composites followed fiberglass after research into composites gained popularity [26, 27, and 43].

The advantages of composites over more conventional aircraft materials are numerous. First, composites are typically lighter in weight. Often, composites have a longer life since they tend to be less corrosive. Additionally, composites can lessen the number of fasteners needed, thus reducing the cost when fewer pieces are required. Also, strength and stiffness can be tailored for specific aircraft. Composites are used on virtually all DoD weapon systems. The proven advantages of the composite structures result in improved range, improved payload capability, improved speed and maneuverability, and improved stealth. Frequently, when aircraft items are custom developed, assembly time is reduced since less time is spent touching the product. There is no question that composite materials are advantageous for any number of reasons. However, the cost of the raw materials can pose a drawback. It has been shown that the current LCC models frequently omit or ignore the impact of new composite manufacturing techniques. Because of this, composite materials may appear at a disadvantage when looking at metallic materials [6, 16, 19, 26, 27, 30, and 43].

Research Purpose

The purpose of this research is to investigate and improve the methods for evaluating the use of advanced composite materials in airframe structures. Specifically, the research addresses the effect of more realistic labor touch hour costs for the airframe structures, the effect of the total materials costs of the reduced part counts, effect of improving the cost estimation relationships (CERs), and develops a life cycle cost (LCC) model which includes those cost-drivers.

The main goal of this study is to review and propose modifications to the current LCC models used by the Air Force (AF) community, which better characterize the benefits and tradeoffs associated with the use of advanced composite materials in airframe structures. In addition, this research seeks to characterize the cost impacts of co-cured composite joints with and without Z-pin reinforcement.

Research Statement

This research reviews the different cost factors underlying the LCC models of military and civilian aircraft systems. To perform this review, one system is analyzed for the effect of selected parameters on its LCC estimate. The analysis uses realistic data obtained from composite manufacturers; data for determining the appropriate values to use for the parameters are derived from available inputs. The results are then analyzed for reliability using appropriate statistical analysis tools.

The effects of the manufacturing processes and part count reductions associated with advanced composites are not currently incorporated in existing LCC estimating models. However, those models are used for procurement of aircraft systems comprised substantially of advanced composite materials.

Research Criteria and Assumptions

The LCC of the advanced composite cargo aircraft (ACCA) airframe structure is calculated. This would normally include the acquisition (development and production) cost, operation and support (O&S) cost, and disposal cost. However, this research concentrates on the acquisition (development and production) cost only. In order to conduct this research, a time frame for the LCC had to be chosen; a 25 year time span, fiscal year FY 2014 through 2039 was chosen. The rationale is if the Air Force (AF) decided to buy the ACCA today, 25 years would approximate the expected airframe's service life.

This research also provides a cost analysis for determining when to purchase the ACCA based on the cost. This cost analysis takes into account the increased performance parameters of the new airframe structure. This research recommends upgrades to the cost estimating models for advanced composite material aircraft, resulting in more accurate cost comparisons to metallic aircraft.

Research Objectives

The two objectives of this dissertation are (1) to understand the effects of Z-pin reinforcement in advanced composite material manufacturing processes for aircraft applications, and (2) to develop a more accurate life cycle cost (LCC) estimating model for aircraft for which advanced composite materials comprise a significant portion of the airframe structure.

Research Questions

This research addressed the following questions:

1. How can we predict the reliability of tested advanced composite materials with and without Z-pinning?
2. What kind of advanced composite material data is available to be investigated and analyzed, and can it be used in our research?
3. Does a relationship exist between the percentage reduction of part counts and the percentage reduction of touch labor hours for certain cost categories, such as design, design support, tooling, manufacturing, testing, and quality assessment?
4. How can we define the relationship, if it exists?
5. How can we classify the relationship?
6. How can we implement that relationship into the RAND CERs and update the CERs?
7. How can we incorporate the updated CERs into the current LCC estimating model?
8. How can we determine the effect of the learning curves (LC) on the LCC estimating model?

Research Funding

This research project is supported, in part, by funding from AFRL/RX, AFRL/RB Wright Patterson Base (AFB), OH, and the Acquisition Management Research Program (AMRP) of the Naval Postgraduate School (NPS), Monterey, CA.

Deliverables

This analysis has investigated proprietary information and representative intellectual property that does not allow full disclosure. However, an unclassified, open literature synopsis and updated Microsoft EXCEL ® code developed by AFRL are both included. The method to develop the LCC estimation model for advanced composite materials used parametric statistical methods. The culmination of this effort is the development of an acceptable LCC model which improves accuracy and better characterizes the benefits and tradeoffs associated with composite aircraft design, development, and production.

Research Contributions

The following contributions that will be addressed:

- Better understanding of the damage tolerance of advanced composite materials with and without Z-pinning.
- Better understanding of the fatigue response and failure mechanisms in advanced composite materials with and without Z-pinning.

- Better understanding of the effect of part count reduction in the airframe structure using advanced composite materials on the LCC estimating model.
- Better understanding of the effect of the updated CERs on LCC estimating model.
- Updates to the LCC estimating model, including the new parameters accurately reflecting the use of advanced composite materials in airframes.
- Better understanding of the effect of the learning curves (LC) on the LCC estimating model.

Publications

As part of this research, three research papers were submitted and presented in peer reviewed journals/conference proceedings. These are presented in chapters III, IV, and V. Conference abstracts are given in Appendix A, and Appendix B.

Dissertation Overview

This dissertation is organized as follows:

- Chapter I : The Introduction reviews the background and motivation, briefly highlighting the advanced composite materials, the specific research emphasis, the research purpose, the research statement, the research criteria and assumptions, the research questions, the research funding, the research objectives, the deliverables, the research contributions, and the publications.
- Chapter II : Provides a Literature review of relevant writings to this research, organized in chronological order, with their key concepts highlighted.

- Chapter III: Presents the first conference paper (Analysis of Z-Pinned Laminated Composites Fatigue Test Data) which was presented in the International Conference on Agile Manufacturing, IIT (BHU), Varanasi, UP, India, December 16-19, 2012. This paper is one of the other topics of interest.
- Chapter IV: Presents the first journal paper (Fatigue Tests and Data Analysis of Z-Pinned Composite Laminates) which was submitted to the Tech Science Press Journal, Duluth, GA, USA, May 20, 2013. This paper is one of the other topics of interest.
- Chapter V: Presents the second journal paper (Cost Estimating Relationships between Part Counts and Advanced Composite Materials Aircraft Manufacturing Cost Elements) which was submitted to the Tech Science Press Journal, Duluth, GA, USA, January 20, 2014. This paper summarizes the results of the experimentation and presents final analysis. In addition, it presents the experimentation required to investigate and obtain the parameters required for the LCC model, and presents the data collection process to determine the parameter values required for each of the algorithms, and/or tables employed by the LCC estimating model.
- Chapter VI: The results are presented and analyzed. An LCC estimating model is introduced and developed.
- Chapter VII: Contains the summary and conclusions, and areas of future research.

- This dissertation is supported by two appendixes. Each appendix contains original products of research which support a particular chapter of the dissertation. They were not included in the main body, so as not to interrupt the flow and the readability of the document.

II. Literature Review

Introduction

This chapter provides a compilation of the important open literature that has been reviewed as part of this research. It summarizes the most relevant writings, organized in chronological order, and highlights their key concepts. The review begins by examining Z-Pin reinforcement and composite lamination. It discusses the composite affordability initiative (CAI). The review then looks at two examples of advanced composite aircraft: the Boeing 787 Dreamliner and the advanced composite cargo aircraft (ACCA). It also reviews the RAND report (R-4016-AF) for cost estimation methodology and other relevant literature pertaining to the life cycle cost (LCC). It then describes the data that has been investigated. It finishes with reviews of regression analysis and its methods, learning curve (LC) approaches, and sensitivity analysis. Table 1 through Table 4 provide a quick reference summary of the main sources which support the analysis and contribute to the original work that is presented in this dissertation.

Table 1 : Overview of Reviewed Literature Sources

	Primary Motivation								Methodology Areas											
					Life Cycle Cost				Cost Estimation Methodology										Data	
										Touch Labor Hours										
	Z-Pin reinforcement	Composite Affordability Initiative (CAI)	Boeing 787 Dreamliner	Advanced Composite Cargo Aircraft (ACCA)	Procurement	Development	O & S	Disposal	Cost Estimation Category	Non-Recurring Engineering (Design Hours)	Non-Recurring Tooling Hours	Non-Recurring Testing Hours	Recurring Engineering Hours (Development Desig	Recurring Manufacturing Labor Hours	Recurring Quality Assurance Hours	Recurring Material Cost	Cost Estimation Relationships (CERs)	Materials Cost Factors	Prototype Aircrafts	Monte Carlo Simulation
Desirtation Research		x		x	x	x				x	x	x	x	x	x		x	x	x	x
Al-Romaihi, M., et al	x																			
Al-Romaihi, M., et al		x			x	x			x	x	x	x	x	x	x		x		x	x
Badiru Adedeji B.																				
Barringer, H., et al					x	x	x	x												
Bock, Diana					x	x	x	x												
Boeing Company			x																	
Boren, H. Jr.					x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Boren, H. Jr., et al																				
Boren, H. Jr., et al																				
Boren, H. Jr., et al																				
Bowerman, B., et al																				
Brookfield, Bill																				
Butler, Brian		x																		
Castagne, S., et al																	x			
Freels, Jason K.	x																			
Griffin, C., et al				x																
Isom, J. L.																	x			
Kapoor H., et al	x																			
Kilic, H., et al	x																			
Klumpp, Joseph J.																	x			
Koury, Jennifer		x																		
Kutner, M.,et al																				
Lambert, Daniel		x	x	x	x	x			x	x	x	x	x	x	x		x	x	x	

Table 2 : Overview of Reviewed Literature Sources

	Primary Motivation								Methodology Areas											
					Life Cycle Cost				Cost Estimation Methodology										Data	
										Touch Labor Hours										
	Z-Pin reinforcement	Composite Affordability Initiative (CAI)	Boeing 787 Dreamliner	Advanced Composite Cargo Aircraft (ACCA	Procurement	Development	O & S	Disposal	Cost Estimation Category	Non-Recurring Engineering (Design Hours)	Non-Recurring Tooling Hours	Non-Recurring Testing Hours	Recurring Engineering Hours (Development D	Recurring Manufacturing Labor Hours	Recurring Quality Assurance Hours	Recurring Material Cost	Cost Estimation Relationships (CERs)	Materials Cost Factors	Prototype Aircrafts	Monte Carlo Simulation
Lemke, Aaron		x	x	x	x				x					x			x	x	x	
Liao, S. S.																				
Liu, et al	x																			
Myers, R., et al																				
Neumeier, P., et al				x																
Raymer, Daniel																	x			
Resetar S., et al					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Russell, John.				x																
Russell, John	x	x																		
Russell, John.		x																		
Russell, John		x																		
Soni, S., et al	x																			
Soni, S., et al	x																			
Soni, S., et al	x																			
Stewart, R., et al																				
The AFSC&CEHBS					x	x	x	x												
Walz, Martha			x																	
Wright, T.P.																				
Younossi, O., et al					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Zelinski, Peter.				x																
Zenith Aviation.				x																

Table 3 : Overview of Reviewed Literature Sources

	Primary Motivation								Methodology Areas											
					Life Cycle Cost				Parametric Cost Estimating								L C			S A
									Stat. Test				Regression				LC Models			
	Z-Pin reinforcement	Composite Affordability Initiative (CAI)	Boeing 787 Dreamliner	Advanced Composite Cargo Aircraft (ACCA)	Procurement	Development	O & S	Disposal	Regression Analysis	R-square (R2)	Adjusted R2	Analysis of Variance (ANOVA)	Linear Regression Model	Logarithmic Regression Model	Exponential Regression Model	Power Regression Model	Learning curve sectors	Cumulative Average Learning Curve Model	Unit Learning Curve Model	Sensitivity Analysis
Desirtation Research		x		x	x	x				x	x	x				x	x	x		x
Al-Romaihi, M., et al	x																			
Al-Romaihi, M., et al		x			x	x			x	x	x	x				x				
Badiru Adedeji B.																		x		
Barringer, H., et al					x	x	x	x												
Bock, Diana					x	x	x	x		x	x	x	x	x	x	x				
Boeing Company			x																	
Boren, H. Jr.					x	x	x	x										x		
Boren, H. Jr., et al																		x		
Boren, H. Jr., et al																		x		
Boren, H. Jr., et al																		x		
Bowerman, B., et al									x	x	x	x	x	x	x	x				
Brookfield, Bill																		x		
Butler, Brian		x																		
Castagne, S., et al																				
Freels, Jason K.	x																			
Griffin, C., et al				x																
Isom, J. L.																				
Kapoor H., et al	x																			
Kilic, H., et al	x																			
Klumpp, Joseph J.												x	x	x	x	x		x		x
Koury, Jennifer		x																		
Kutner, M.,et al									x	x	x	x	x	x	x	x				
Lambert, Daniel		x	x	x	x	x												x		

Table 4 : Overview of Reviewed Literature Sources

	Primary Motivation								Methodology Areas											
					Life Cycle Cost				Parametric Cost Estimating								LC			SA
									Stat. Test				Regression				LC Models			
	Z-Pin reinforcement	Composite Affordability Initiative (CAI)	Boeing 787 Dreamliner	Advanced Composite Cargo Aircraft (ACCA	Procurement	Development	O & S	Disposal	Regression Analysis	R-square (R2)	Adjusted R2	Analysis of Variance (ANOVA)	Linear Regression Model	Logarithmic Regression Model	Exponential Regression Model	Power Regression Model	Learning curve sectors	Cumulative Average Learning Curve Model	Unit Learning Curve Model	Sensitivity Analysis
Lemke, Aaron		x	x	x	x															
Liao, S. S.																		x	x	
Liu, et al	x																			
Myers, R., et al									x	x	x	x	x	x	x	x				
Neumeier, P., et al				x																
Raymer, Daniel																				
Resetar S., et al					x	x	x	x	x	x	x	x								
Russell, John.				x																
Russell, John	x	x																		
Russell, John.		x																		
Russell, John		x																		
Soni, S., et al	x																			
Soni, S., et al	x																			
Soni, S., et al	x																			
Stewart, R., et al																	x			
The AFSC&CEHBS					x	x	x	x												
Walz, Martha			x																	
Wright, T.P.																		x		
Younossi, O., et al					x	x	x	x	x	x	x	x								
Zelinski, Peter.				x																
Zenith Aviation.				x																

Z-Pin Reinforcement and Composite Laminates

Delamination is one of the most significant modes of failure in laminated composites. Z-pin reinforcement in composite laminates is to avoid the delamination mode of failure. Z-pin reinforcement is one of the latest methods intended to combat delamination and hence to enhance structural damage tolerance [1, 17, 21, 22, 29, 39, 40, and 41].

Delamination severely impairs the load-carrying capacity and structural integrity of composite structures. Since composites naturally lack reinforcement in the thickness direction, delamination is a predominant failure mode. While composites have shown great promise for achieving the performance and cost goals of future military aircraft, their use may be limited by their susceptibility to delamination and the need to meet survivability requirements. Advanced processing techniques, interlaminar reinforcement technologies, and innovative design concepts have been developed in recent years and provide significant improvements toward achieving survivable, all-composite structures while minimizing increases in weight and cost [17, 21, 22, 29, and 41].

The Composite Affordability Initiative (CAI) by the United States Air Force (USAF) and Aerospace Industry has identified joining and co-curing of advanced composite materials as important problem areas of interest [37]. Estimating the reliability of Z-pinned composite components is a complex process and requires more knowledge of the failures that might occur at various scales of implementation [1, 39, and 40].

A Z-pin is a small diameter cylindrical rod which is embedded in a composite material and oriented perpendicular to the layer interface, enhancing the interlaminar strength of co-cured composite joint structures [17, 21, 22, 29, and 41]. Figure 1 shows the Z-pins being inserted into a test panel at the Advanced Materials Lab, Air Vehicles Directorate, Wright-Patterson Air Force Base, OH [17].

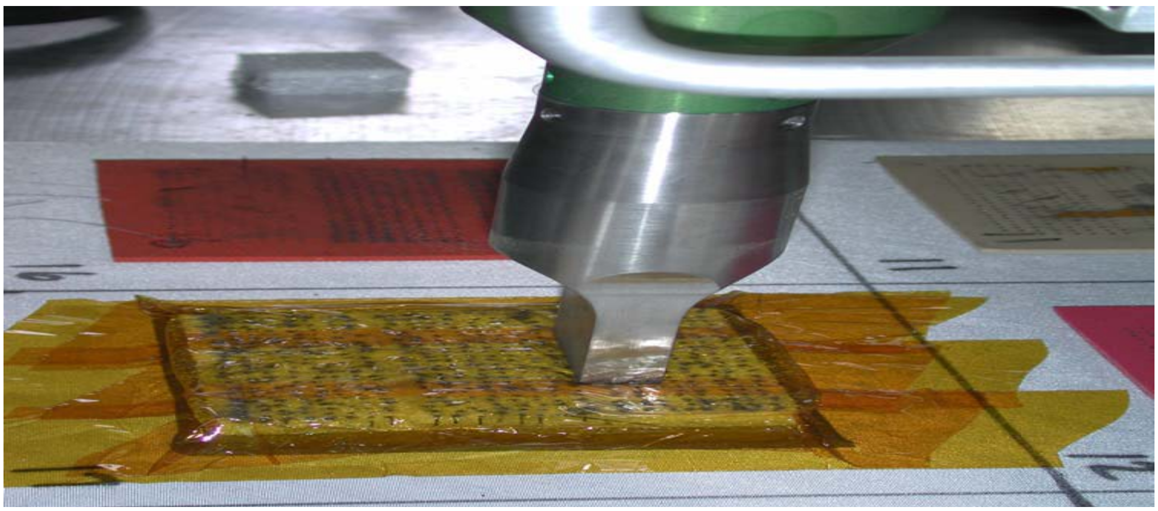


Figure 1 : Insertion of Z-pins onto Test Panel [17]

Composite Affordability Initiative (CAI)

An extensive amount of analytical and experimental work was done on the mechanics of advanced composite materials and structures. Still there was significant resistance by Original Equipment Manufacturers (OEM) to the use of advanced composite materials for primary structures. Based on that, several composite manufacturers began to leave the composite materials business [2].

In the mid-1990s, the Air Force Research Laboratory (AFRL) observed that, despite the potential of the advanced composite materials to drastically reduce airframe structural weight compared to conventional metal airframe structures, most aircraft companies were resistant or opposed to proceeding with advanced composite materials for new aircraft structures. Due to the unwillingness of both industry and the AF to incorporate advanced composite materials in aircraft structures, AFRL and industry started the Composites Affordability Initiative (CAI) to minimize the perceived risks of and barriers to using advanced composite materials [2, 24, 26, 27, 36, 37, and 38]. The initiative was started primarily to develop an accurate database of advanced composite materials performance characteristics to enable the designers to make reliable predictions of the LCC when using advanced composite materials. Other contributing factors behind the decision to form the CAI were: lack of LCC data, lack of design data related to the reliability aspects of composite structures, and a significant decrease in composite material manufacturing suppliers (and expertise) due to the lack of product demand [2].

The CAI was established to significantly reduce cost, development cycle time, and weight of military aircraft. The main goal of the CAI team was to develop the techniques and the tools necessary to enable aircraft designers to design an all-composite airframe utilizing innovative design and manufacturing concepts, and to enable breakthrough reductions in cost, schedule, and weight [2, 14, 24,26, 27, 36, 37, and 38]. The major source of labor and rework in aircraft structures is drilling holes and installing fasteners. By significantly reducing the number of fasteners, the cost of the structural assembly and cycle time would be drastically reduced. The CAI team pursued part integration and structure assembly by bonding to achieve this goal [2, 14, 24, 26, 27, 36, 37, and 38].

Commercial Products with Advanced Composite Materials Application

Boeing Corporation is one of the leading aviation manufacturing companies for both commercial and military aircraft. With the new Boeing 787 Dreamliner (originally 7E7 for "Efficient"), the corporation has also become the leader in advanced composite aircraft manufacturing. Boeing announced that the new 787 Dreamliner would be made of 80 percent advanced composite materials by structure and 50 percent by weight. This includes all-composite wings and fuselage [7, 26, 27, and 45].

Based on the cost considerations, the Boeing Corporation decided to incorporate advanced composite materials into the majority of the 787 Dreamliner structure. The lower weight would enable the 787 Dreamliner to use 20 percent less fuel, provide more cargo revenue capacity, and lower the landing fees, which are often based on the weight of the aircraft. So, the Boeing Corporation made the tactical decision that the new aircraft would be more fuel efficient [26, 27, and 45]. The favorable weight to strength ratios of advanced composite materials was one of the more compelling reasons for Boeing Corporation to incorporate advanced composite materials into a significant percentage of the 787 Dreamliner structure [7, 26, 27, and 45]. Figure 2 shows how heavily the Boeing Corporation invested in using large amount of advanced composite materials in the 787 Dreamliner.

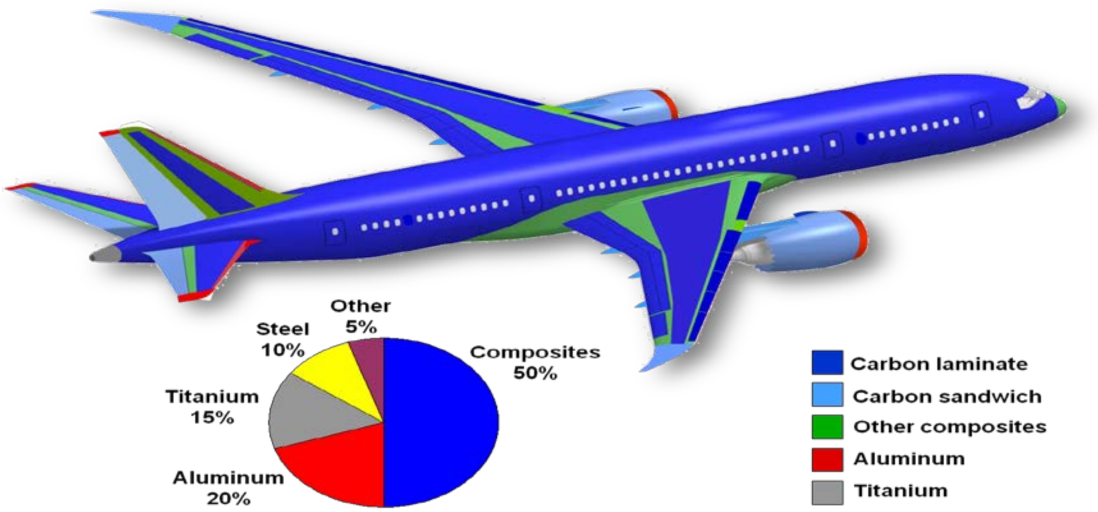


Figure 2 : Boeing 787 Dreamliner External Skin Makeup [7]

Using advanced composite materials in the 787 Dreamliner brings benefits to every stage of the aircraft's life. By using a large composite barrel for the fuselage section, Boeing was able to reduce the number of aluminum sheets by 1,500 and use 40,000 to 50,000 less fasteners in the fuselage section alone. This represents an 80% reduction in fasteners over a non-composite barrel structure and reduces the number of drilled holes in the fuselage to fewer than 10,000 instead of one million [26, 27, and 45]. Figure 3 shows the fuselage structure section, consisting of a large composite barrel.

Figure 3 : Boeing 787 Dreamliner Composite Fuselage Barrel [45]

The Boeing Corporation relied on tape fiber placement machines in the production process to reach maximum efficiency in manufacturing the large advanced composite structures. These machines automate the layup of laminates which are made of combinations of other ply angles rather than just the conventional 0 degrees, 45 degrees and 90 degrees. They also provide consistent costs per unit of production [7, 26, 27, and 45]. Figure 4 shows the tape fiber placement machine.

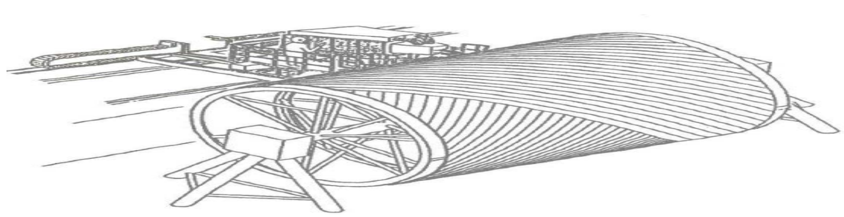


Figure 4 : Boeing 787 Dreamliner Tape Fiber Placement Machine [7]

Even though Boeing Corporation was not the first company to start using this process, it was the first company to start building large scale advanced composite commercial aircraft with this process. Although the methods and applications for using the advanced composite materials are unique to the Boeing 787 Dreamliner, the company did not start without internal rate of return or profit projections [7, 26, 27, and 45].

Advanced Composite Cargo Aircraft (ACCA)

Even though the Composite Affordability Initiative (CAI) demonstrated advance technologies for making large, integrated and bonded advanced composite aerospace structures, the CAI had achieved minimal transition to actual military systems. The only CAI hardware flying is the C-17 main landing gear door as shown in Figure 5. The CAI team agreed that a demonstration aircraft flying such structures would be necessary to obtain the confidence of the military aerospace community [18, 26, 27, and 35].

Figure 5 : One Piece Main Landing Gear Doors Adopted by C-17 [35]

In 2006, the Secretary of the Air Force gave instructions to Air Force Research Laboratory (AFRL) to submit a proposal for building a complete military transport aircraft made primarily of advanced composite materials. His directive was that funding should not exceed one hundred million USD and time limit should not exceed 18 months for the aircraft to fly [18, 26, 27, 35, and 48]. In 2007, the AFRL released a Broad Agency Announcement (BAA) requesting proposals for the Advanced Composite Cargo Aircraft (ACCA) with funding was not to exceed 50 million USD and with first flight by October 2008 [26, 27, 35, and 48].

AFRL selected the Lockheed Martin's proposal (Dornier Do-328J) based on its low risk approach. This approach replaced approximately 40% of the total vehicle structure with integrated and bonded advanced composite structures [18, 26, 27, 35, 48, and 49]. Figure 6 shows the major structural components for ACCA. In order to transform the DO-328J into a military cargo aircraft, certain modifications necessary for military use were also incorporated into the reconfigured design of the ACCA. The most important modifications were enlarging the fuselage and modifying the cargo door [18, 26, 27, 35, 48, and 49].

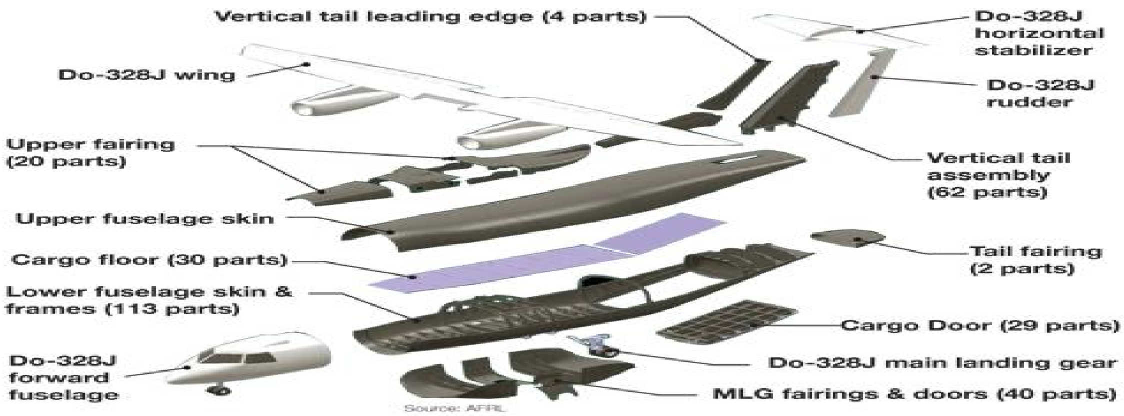


Figure 6 : ACCA Major Structural Parts [35]

The first flight of ACCA, now called the X-55A, was in May 2009, nine months later than scheduled. But all of the other major technical program goals were met: a large, integrated body aircraft with an advanced composite airframe (nearly the size of the C-130 aircraft), and delivered for less than 50 million USD [26, 27, 32, 35, and 48]. The ACCA production study lists the costs of most of the program and offers several insights into how large, integrated composite structures affect cost [26, 27, 32, 35, and 48].

This research shows how the use of advanced composite materials affected the cost of the ACCA. The ACCA study showed that the fewer and larger part counts decreased both non-recurring and recurring costs [26, 27, and 48]. One specific area that needed to be addressed in this research was the nature of the costs and exactly how these findings may affect the current cost estimation relationships (CERs) used to predict the LCC when advanced composite materials are to be used. The current CERs are not reflective of the cost reductions due to reduction in part counts. This research addressed this deficiency in the current LCC estimation models [18, 26, 27, and 35].

Cost Estimation Methodology

The RAND report R-4016-AF is considered the most inclusive report. It attempts to quantify and develop a methodology for estimating costs associated with the use of advanced composite materials in aircraft production [2, 26, 27, and 34]. The report includes a discussion of material types and characteristics, advanced composite materials usage, associated design and manufacturing processes, and cost information [2, 8, 26, 27, 34, and 47].

The data for the report was collected by an industry survey rather than statistical analysis. The report survey requested aerospace companies respond to questions on corporate history, material usage within aircraft, recurring and nonrecurring cost information, and other general questions [8, 26, 34, and 47]. Data collected was for three time periods: the late 1980s, and the mid 1990s. The data collected from the late 1980s reflected the aerospace companies' current experiences, while the mid 1990s data represented the aerospace companies' best forecasts of the future use of composite materials in terms of design and manufacturing techniques [8, 26, 34, and 47]. The 2000's data represented cost implications of the predicted production (in airframe labor hours) and technology in the upcoming decade [47].

The studies reported in chapters IV and V of the RAND report are of most interest to this research. Chapter IV discusses the cost information in the responses from reporting aircraft companies, and Chapter V discusses the recommended methodology for assessing the effect of structural material composition on the cost of an aircraft [2, 26, 27, and 34].

Cost Estimation Categories

The RAND report categorizes costs into two major cost elements. The non-recurring (development) costs and the recurring (production) costs are featured [2, 8, 26, 27, 34, and 47]. The report also provides separate cost estimation relationships (CERs) for nine cost sub elements within the non-recurring (development) and recurring (production) cost elements. The cost elements that are of particular interest to this current research are non-recurring and recurring engineering hours, non-recurring and recurring tooling hours, recurring manufacturing labor hours, and recurring quality assurance hours [2], as shown in Table 5.

Table 5 : Touch Labor Hours Cost Elements [34]

Non-Recurring Cost (Development)	Recurring Cost (Production)
Engineering Hours Cost	Engineering Hours Cost
Tooling Hours Cost	Tooling Hours Cost
Development Support Hours Cost	Manufacturing labor Hours Cost
Testing Hours Cost	Manufacturing Material Cost
	Quality Assurance Hours Cost

Touch Labor Hours

Non-Recurring Engineering (Design Hours)

Non-recurring engineering hours (design hours) include all the time spent on engineering the piece. This can include the building, testing, and everything and anything else. In the 1980s, when composites weren't as familiar, the engineering hours needed for composites was 40 to 70 percent higher than when using metals. Speculating about the reasons for this, one can conclude that since composites were rather new, this was unfamiliar ground that was being covered. Also, during this time, universal material standards and safety margins didn't exist [2, 8, 26, 34, and 47].

Non-Recurring Tooling Hours

Also explained in the RAND report were the reasons, exposure to high temperatures and pressures in the autoclave, for a spike in tooling hour costs. New tools to withstand the high heat and pressure were created and are needed for the composites. They continue to be made of graphite, steel and other electroplated nickel materials. Tools used for non composites have typically been made of aluminum [2, 8, 26, 34, and 47].

Non-Recurring Testing Hours

The RAND report treated the non-recurring testing hours as a separate element because it was tracked as a different account by the contractors. The RAND report includes all allowable costs incurred by the contractors in flight-test operations except the production of test aircraft [2, 8, 26, 34, and 47].

Recurring Engineering Hours (Development Design Hours)

Of real interest to this research is the recurring engineering hours (development design hours) and how to reduce the cost by reducing the hours needed. Data from the 1980s estimated that engineering hours to be as high as three times the hours needed for other non composite materials. The information in the RAND study was obtained from industry respondents [2, 8, 26, 27,34, and 47].

Recurring Tooling Hours

Another cost to consider is the recurring tooling hours, the time needed to keep the tools in working order. If the same tools that are used for aluminum are used for the composites, the wear is greater. However, if tools that withstand the high heat and pressure necessary for composites are used, this cost is reduced [2, 8, 26, 34, and 47].

Recurring Manufacturing Labor Hours

Recurring manufacturing labor hours per aircraft pound vary with the material types. The RAND report shows the average of the recurring manufacturing hours per aircraft pound which is based on the minimum and the maximum values [2, 8, 26, 27, 34, and 47].

Recurring Quality Assurance Hours

Quality assurance hours are also to be taken into consideration. This was an issue in the 1980's when composites were relatively new. It was believed that additional testing would be needed and thus created an additional cost. Metallic structures when a known entity and composites were not as familiar. A standard set of testing procedures was not yet determined in the early days of composites. Therefore, this tended to increase the cost or at least the perception of the cost associated with composites [2, 8, 26, 34, and 47].

Recurring Manufacturing Material

The RAND study identified the three elements that determine total material cost: raw material cost, the buy-to-fly ratio, and the material burden rate. The element of total material cost that is notable for composite materials is the buy-to-fly ratio. The buy-to-fly ratio is the amount of material purchased to complete a pound of finished part that "flies". Composite materials have a much lower buy-to-fly ratio due to composite manufacturing techniques that eliminate scrap material and allow custom manufacturing of parts thereby eliminating fastener and joining costs. The lower buy-to-fly ratios for composite materials reflect one of the advantages of using composite materials rather than metallic materials. This lower ratio coupled with weight savings and reduced part counts has led to increased research by both the government and industry for incorporating composite materials into aircraft production in a cost effective manner [2, 8, 26, 27, 34, and 47].

Cost Estimation Relationships (CERs)

Cost Estimating Relationships (CERs) is a mathematical expiration which relates time (hours) or costs as the dependent variable to one or more independent time (hours) or cost-driver variables [23, and 23]. The RAND CERs were applied to two hypothetical aircraft, both fighter aircraft. The first aircraft was manufactured with aluminum whereas the second aircraft was constructed with 45 percent advanced composite materials and 55 percent aluminum [2, 8, 23, 26, 27, 34, and 47]. The resulting projections seem to be contrary to the expectations of lower non-recurring costs. The RAND report is the best available source that addresses the CERs of advanced composite materials. The RAND report baseline CERs equations are listed below [8, 23, 26, 27, 33, 34, and 47].

Non-recurring (development) cost elements are:

$$CER_{NREDS} = 0.0168(EW)^{\wedge 0.747} * (MS)^{\wedge 0.800} \quad (1)$$

$$CER_{NRTL} = 0.0186(EW)^{\wedge 0.810} * (MS)^{\wedge 0.579} \quad (2)$$

$$CER_{NRDS} = 0.0563(EW)^{\wedge 0.630} * (MS)^{\wedge 0.130} \quad (3)$$

$$CER_{NRT} = 1.54\ (EW)^{\wedge 0.325} * (MS)^{\wedge 0.822} * (TEST)^{\wedge 0.1.21} \quad (4)$$

Recurring (production) cost is normalized for 100 air vehicles and made up of the following elements:

$$CER_{RED(100)} = 0.000306(EW)^{\wedge 880} * (MS)^{\wedge 0.1.12} \quad (5)$$

$$CER_{RTL(100)} = 0.00787(EW)^{\wedge 0.707} * (MS)^{\wedge 0.813} \quad (6)$$

$$CER_{RML(100)} = 0.141(EW)^{\wedge 0.820} * (MS)^{\wedge 0.484} \quad (7)$$

$$CER_{RMM(100)} = 0.54(EW)^{\wedge 0.921} * (MS)^{\wedge 0.621} \quad (8)$$

$$CER_{RQA(100)(Cargo)} = 0.076(CER_{RML(100)}) \quad (9)$$

$$CER_{RQA(100)(non\text{-}Cargo)} = 0.133(CER_{RML(100)}) \quad (10)$$

Where:

CER_{NREDS} is CER for Non-recurring engineering hours

CER_{NRTL} is CER for Non-recurring tooling hours

CER_{NRDS} is CER for Non-recurring development support

CER_{NRT} is CER for Non-recurring testing hours

$CER_{RED(100)}$ is CER for recurring engineering (100) hours

$CER_{RTL(100)}$ is CER for recurring tooling (100) hours

$CER_{RML(100)}$ is CER for recurring manufacturing labor (100) hours

$CER_{RMM(100)}$ is CER for recurring manufacturing material (100) hours

$CER_{RQA(100)(Cargo)}$ is CER for recurring quality assurance (100) hours (cargo)

$CER_{RQA(100)(non\text{-}Cargo)}$ is CER for recurring quality assurance (100) hours (non-cargo)

EW is aircraft empty weight (lb)

MS is maximum speed (kn)

TEST is number of flight-test aircraft

(100) is cumulative recurring hours for 100 aircraft

MNLBR is manufacturing labor

The cost elements that are of particular interest to this current research are non-recurring and recurring engineering hours, non-recurring and recurring tooling hours, recurring manufacturing labor hours, and recurring quality assurance hours [2].

Material Cost Factors

The RAND report methodology developed weighted material cost factors which were applied to baseline the CERs assumed to be representative of an aluminum aircraft. The necessary inputs to develop the costing model are: aircraft empty weight, maximum speed, number of flight test aircraft, type of aircraft (cargo or non-cargo), total structural weight by material type, and the percentage of functional cost elements attributable to the aircraft structure [8, 26, 27, and 47]. The average material cost factors were used to characterize the labor hour and cost effects of different design and manufacturing processes. RAND uses material cost factors to determine the effects of various materials by structural cost element. The industry average material cost factors are represented for each material type with aluminum serving as the baseline. The other six additional materials are given a cost factor for the late 1980s, the mid-1990s, and mid-2000s [34, and 47]. Table 6, Table 7, and Table 8 show the average material cost factors (hours per pound ratios) [34, and 47].

Table 6 : RAND Material Cost Factors for Late 1980s [34]

Material Type	NRE	NRT	RE	RT	RML	RMM	RQA
Aluminum	1.0	1.0	1.0	1.6	1.0	2.5	1.7
Al-lithium	1.1	1.2	1.1	1.7	1.1	4.2	1.8
Titanium	1.1	1.4	1.4	3.0	1.6	3.0	2.7
Steel	1.1	1.1	1.1	2.3	1.2	2.1	2.4
Graphite/epoxy	1.4	1.6	1.9	3.6	1.8	1.9	4.1
Graphite/bismaleimide	1.5	1.7	2.1	3.7	2.1	1.9	4.3
Graphite/thermoplastic	1.7	2.0	2.9	3.9	1.8	1.9	4.4

Table 7 : RAND Material Cost Factors for Mid 1990s [34]

Material Type	NRE	NRT	RE	RT	RML	RMM	RQA
Aluminum	1.0	1.0	0.9	1.5	0.9	2.2	1.5
Al-lithium	1.0	1.1	1.0	1.7	1.0	2.7	1.7
Titanium	1.0	1.4	1.2	2.6	1.4	3.0	2.4
Steel	1.1	1.1	1.1	2.3	1.2	2.1	2.4
Graphite/epoxy	1.2	1.4	1.5	3.2	1.5	1.8	3.1
Graphite/bismaleimide	1.3	1.5	1.6	3.3	1.8	1.8	3.6
Graphite/thermoplastic	1.4	1.6	1.4	3.8	1.6	1.8	3.4

Table 8 : RAND Material Cost Factors for Mid 2000s [47]

Material Type	NRE	NRT	RE	RT	RML	RQA
Aluminum	1.00	0.88	0.91	0.86	0.82	0.95
Al-lithium	1.00	0.99	0.94	0.97	0.87	1.04
Titanium	1.00	1.26	0.97	1.26	1.29	1.18
Steel	1.02	0.97	1.02	1.12	1.05	1.12
Graphite/epoxy	1.14	1.21	1.18	1.33	1.17	1.50
Graphite/bismaleimide	1.16	1.29	1.21	1.44	1.24	1.52
Graphite/thermoplastic	1.14	1.44	1.15	1.50	1.27	1.58
Others	1.14	1.21	1.18	1.33	1.17	1.50

In this research, we used the RAND material cost factors for mid-2000s [47]. As per Table 8**,** we can formulate the materials cost factors as follows:

Non-Recurring Engineering Cost Factor (Design Support) (NREDS):

$$NREDS= (1*Pal +1*PAli+1* PctTi +1.02* PctStl +1.14* PctGrEp +1.16* PctGRrBMI +1.14*PctGrTh +1.14* PctOther)/100 \quad (11)$$

Recurring Engineering Cost Factor (Design) (RED):

$$RED= (0.91* PctAl +0.94* PctAlLi +0.97* PctTi +1.02* PctStl +1.18*PctGrEp+1.21* PctGRrBMI +1.15* PctGrTh +1.18* PctOther)/100 \quad (12)$$

Non- Recurring Tooling Material Cost Factors (NRTL):

$$\mathrm{NRTL= (0.88* PctAl +0.99* PctAlLi +1.26* PctTi +0.97* PctStl +1.21* PctGrEp +1.29* PctGRrBMI +1.44* PctGrTh +1.21* PctOther)/100} \quad (13)$$

Recurring Tooling Material Cost Factor (RTL):

$$RTL= (0.86* PctAl +0.97* PctAlLi +1.26* PctTi +1.12* PctStl +1.33* PctGrEp +1.44* PctGRrBMI +1.5* PctGrTh + 1.33* PctOther)/100 \quad (14)$$

Recurring Manufacturing Labor Cost Factor (RML):

$$\mathrm{RML = (0.82* PctAl +0.87* PctAlLi +1.29* PctTi +1.05* PctStl +1.17* PctGrEp+1.24* PctGRrBMI +1.27* PctGrTh +1.17* PctOther)/100} \quad (15)$$

Recurring Quality Assurance Cost Factor (RQA):

$$\mathrm{RQA = (0.95* PctAl +1.04* PctAlLi +1.18* PctTi +1.12* PctStl +1.5*PctGrEp +1.52* PctGRrBMI +1.58* PctGrTh +1.5* PctOther)/100} \quad (16)$$

Where:

PctAl = Percent Aluminum

PctAlLi = Percent Al-lithium

PctTi = Percent Titanium

PctStl = Percent Steel

PctGrEp = Percent Graphite Epoxy

PctGRrBMI = Percent Graphite BMI

PctGrTh = Percent Graphite Thermo

PctOther = Percent Other Material

The RAND cost model has many advantages. The CERs are based on relatively current information and can be easily applied to all aerospace companies. Also, the average material cost factors allow great flexibility in their application [2, 15, 20, 23, 26, and 27]. The primary disadvantage to the RAND cost model is the accuracy of the mid-1990's projections. At the time, there was a huge amount of optimism within the defense aerospace companies. There were several defense related companies available, and there was confidence that the cost of advanced composite materials would be reduced. But this has not been the case. The current environment has not realized the predicted gains in experience nor did it anticipate the huge outlays for automation and capital equipment. Further, the expected availability of cheaper and abundant advanced composite materials was not realized [2, 15, 20, 23, 26, and 27].

The two primary reasons that advanced composite materials costs could be reduced for several of the cost elements are reduced part counts and a simplified overall design process. Two overarching trends factor into the higher advanced composite materials cost for each cost element: the impact of autoclave curing and the lack of experience that engineers have with advanced composite materials [2, 15, 20, and 23].

Life Cycle Cost (LCC)

Life cycle costs (LCC) are all costs from project inception to disposal of the system. LCC applies to both equipment and projects. LCC costs are determined by an analytical study of the total costs expected during the life of the equipment or project. With LCC, all major costs are estimated in advance. All of the owning and operating expenses throughout a project's working life are included, not just the initial purchase price. When the true costs are analyzed, the results can be surprising. Apparent savings can turn out not to be savings at all [2, 4, 26, and 27].

The LCC model needs to be explained in order to fully understand the potential cost effectiveness of advanced composite materials. As per the Air Force Systems Command (AFSC) Cost Estimating Handbook, LCC captures the acquisition cost of development, production, operation and support, and disposal of a product or a project. The cost effectiveness of using advanced composite materials can be defined for the development, production, operation, support, and disposal phases [2, 8, 26, 27, 34, 44, and 47]. This research analyzes the cost effectiveness of using advanced composite materials for the

Development and Production phase only [2, 8, 26, 27, 34, and 47]. Figure 7 shows the elements within the total life cycle cost.

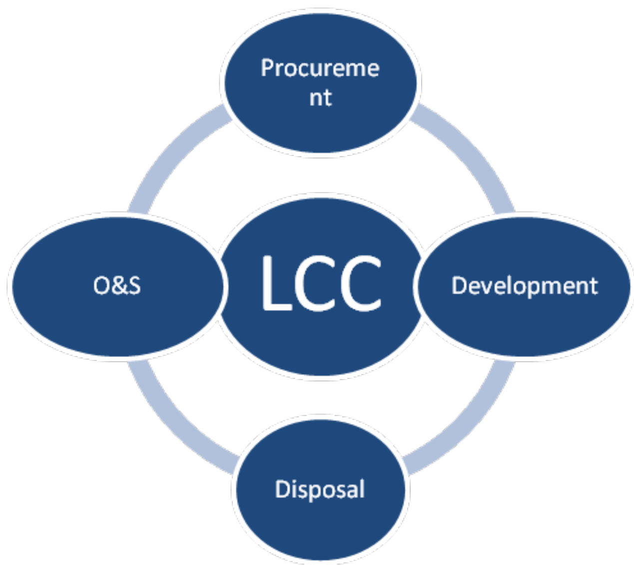


Figure 7 : Cost Elements of Life Cycle Cost [26]

Data Collections

This research validated both the data sets used for the analysis and the methodology used to investigate the relationships between the part counts and design, design support, testing, tooling, manufacturing, and quality assurance touch labor hours. In addition, all appropriate relationships that were discovered have been incorporated into proposed upgrades to the LCC models [2, 26, and 27].

Prototype Data

The data for this research came from the Advanced Composite Cargo Aircraft (ACCA) program work breakdown structure and from an aerospace company which will be referred to as "Aerospace Company" to protect the company's proprietary information. The ACCA was funded entirely by the Air Force Research Laboratory (AFRL) and the data is entirely accessible to the Department of Defense (DoD) and DoD contractors [2, 26, 27, 34, and 47].

The aerospace company's data set consists of aircraft prototype data and production data for development, manufacturing, and material costs for a variety of metallic, composite, and combined metallic/composite military and civilian aircraft. The data set for the prototype is subdivided into the following cost categories or variables: design, design support, testing, tooling, logistics, manufacturing, and quality assurance touch labor hours. The data set also contains various aircraft empty weights, part counts, and average part sizes. While the data set has numerous additional research uses, this research effort focused on the touch labor hours for design, design support, testing, tooling, manufacturing, quality assurance, part counts, empty weight, and average part sizes for military and civilian aircraft that used advanced composite materials either exclusively or in conjunction with metallic. The number of aircraft also had to be large enough to assure a sufficient sample size for valid statistical analysis [2, 26, 27, 34, and 47].

Monte Carlo Simulations

The aircraft data not included in the Aerospace Company's data set was determined by extrapolation using the available relationships between them and empty weight. Due to the limitation of the data set related to large scale advanced composite material part counts and to the small amount of data on the aircraft from the Aerospace Company, additional data items were generated by using the Monte Carlo technique, which is available in Microsoft EXCEL ®. The NORMINV function was used by taking the mean and the standard deviation to simulate the random normal variables. Using this formula, we calculate the number of part counts as well as the touch labor hours for all variables of interest. The NORMINV formula used is given below:

$$NORMINV\ (RAND\ (),\ MEAN,\ ST.DEV.) \tag{17}$$

Parametric Cost Estimating

Parametric statistical methods were used to develop the life cycle cost (LCC) model for the use of advanced composite materials. Parametric cost estimating is a method employing one or more CERs to calculate costs related to the production, manufacture, development, and/or adaptation of a particular end item based on its technical, or physical attributes [2, 12, 25, and 31]. The Least Square Method (LSM) was used for all regression analysis [2].

Regression Analysis

The goal of determining a regression is to obtain an equation from which one variable can be predicted based upon another variable. Regression analysis is a statistical process for predicting and forecasting the relationships between one or more independent variables (usually denoted by X) and a dependent variable (usually denoted by Y) [2, 12, 25, and 31]. The LSM is a statistical regression technique to determine the best line fit for a model. The LSM is specified by an equation where the equation's parametric values are determined by the observed data. This method is extensively used in regression analysis and estimation [2, 12, 25, 31, 34, and 47].

Statistical Tests

The significance level or the level of confidence (often referred to as a "good fit") is used to assess the applicability of the model chosen based on the analyst's judgment. The model chosen depends on the judgment of the analyst and the nature of the data [6]. There are many tests to be considered in regression analysis, including R-Square (R^2), Adjusted R-Square (R^2), and analysis of variance (ANOVA) test which itself includes the F-value test, T-value test, and P-value test [2, 6, 12, 25, 31, 34, and 47].

R-square (R^2)

R-square (R^2) measures the percentage of variance of the dependent variable (Y) that is explained by the independent variable (X) and the chosen regression line. An R-square (R^2) value near 100% shows a strong relationship between the dependent variable (Y) and the independent variable (X) in the model and may indicate a “good fit” [2, 6, 12, 25, 31, 34, and 47].

Adjusted R^2

Adjusted R^2 is similar to R^2. Adjusted R^2 measures the fit between the dependent variable and the combined effect of all the independent variables. The adjusted R^2 can be used to determine the significance of any specific independent variable by running the test with and without the specific independent variable and comparing the results. The closer an adjusted R^2 value is to 100%, the more precise your model will be when used for predicting or forecasting [2, 6, 12, 25, 31, 34, and 47].

Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) is used in the statistical assessment of the correctness of estimating relationships between the independent variables (X) and the dependent variable (Y). The T-value test shows how statistically significant an independent variable is in the model. The F-value test shows the importance of the model. The p-value tests whether R^2 is different from 0. A p-value lower than 0.05

indicates that the relationship between (X) and (Y) is statistically significant [2, 6, 12, 25, 31, 34, and 47].

Regression Models

Regression models are often used to estimate the relationship between corresponding data elements. It is essential to understand how to select a regression model which will be a "good fit" for the chosen data elements. For this research, regression model choices were limited to linear, logarithmic, exponential, and power models [2, 6, 12, 23, 25, and 31]. First, visually evaluate the graph of the data relative to the graphs of the various models (i.e., look for similar patterns in the graphs). To do that, first prepare a scatter plot and study the graph. Identify the common shapes of regression models. Check which regression model appears to best characterize of the scatter plot of the data. Choose only those regression models that appear to fit the observed points reasonably well, when trying to select a model [2, 6, 12, 23, 25, and 31].

Linear Regression Model

The linear regression model has the equation: $y_x = a + bx$. The linear regression uses one independent variable to explain and/or predict the outcome of Y. The linear regression is a method for fitting a straight line to a set of plotted data on Cartesian coordinates. From the graph, determine whether the plotted data looks like a straight line or not and determine whether the slope is positive or negative. The linear regression model is the most popular because it is easy to read and interpret [6, 12, 23, 25, and 31].

Logarithmic Regression Model

The logarithmic regression model has the equation: $y_x = a + b(\ln x)$. The logarithmic regression uses one independent variable to explain and/or predict the outcome of Y. The logarithmic regression is a method for fitting a logarithmic curve to a set of plotted data on Cartesian coordinates. From the graph, determine whether the plotted data rises quickly to the left but levels off toward the right. Keep in mind that the natural logarithmic function crosses the x-axis at 1 and the domain x is greater than zero [6, 12, 23, 25, and 31].

Exponential Regression Models

The exponential regression model has the equation: $y_x = ae^{bx}$. The exponential regression uses one independent variable to explain and/or predict the outcome of Y. The exponential regression is a method for fitting an exponential curve to a set of plotted data on Cartesian coordinates. From the graph, can be determined whether the plotted data declines (or rises) by a percentage decrease (or increase). It is useful for values that grow by percentage increase [6, 12, 23, 25, and 31].

Power Regression Models

The power regression model has an equation: $y_x = ax^b$. The power regression uses one independent variable to explain and/or predict the outcome of Y. The power regression is a method for fitting an exponential power curve to a set of plotted data on Cartesian coordinates. From the graph, determine whether the plotted data possess characteristics which are not seen in the first three models, and not a straight line, but a more steady change than exponential [2, 6, 12, 23, 25, and 31].

Learning Curve (LC)

LC theory is based on the assumption that as the quantity of units which are produced doubles, the direct labor time (hours) or costs to produce the quantity of units is reduced by a constant percentage; the amount of improvement in productivity also increases. Each unit takes less direct labor time (hours) or costs than the preceding unit. The constant percentage rate of reduction in labor is the slope of LC when plotted on a log-log scale [3, 8, 9, 10, 11, 23, and 26].

A LC graph (illustrated in Figure 8) displays time (or labor hours) per unit versus cumulative repetitions. From this we see that the time labor hours needed to produce a unit decreases, usually following the negative exponential curve, as the company manufactures more units [3, 8, 9, 10, 11, 23, and 26].

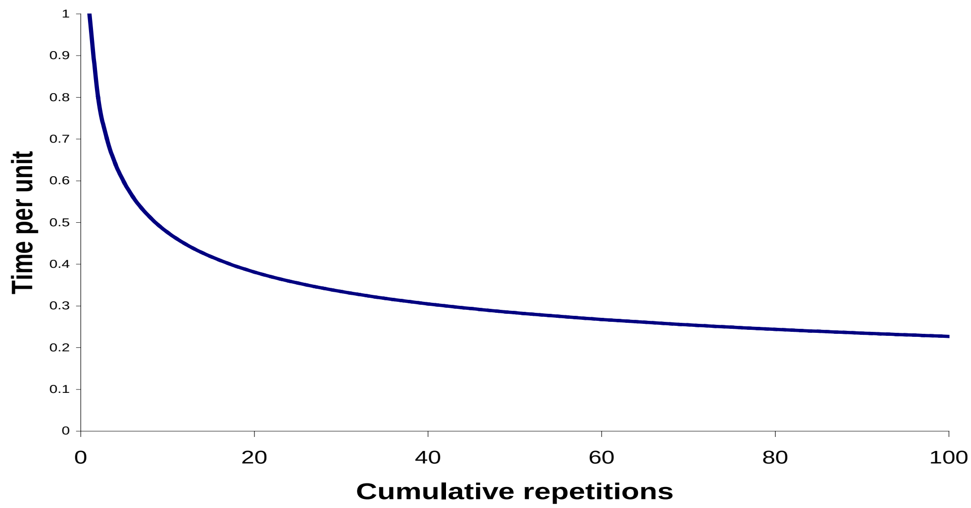


Figure 8 : Learning Curve [3, 8, 9, 10, 11, and 23]

Learning curve (LC) sectors

The learning curve's percentage is usually calculated by a statistical analysis of similar manufacturing sectors. In general, the majority of LC rates range between 70% and 100%. A LC is rarely lower than 70%. A LC rate equal to 100% means that there is no learning. Stewart and Wyskida (1987) give the following percentage guidelines for LC rates in different sectors [42]:

- Aerospace sectors 85%
- Shipbuilding sectors 80-85%
- Complex machine tools for new models sectors 75-85%
- Repetitive electronics manufacturing sectors 90-95%
- Repetitive machining or punch-press operations sectors 90-95%

- Repetitive electrical operations sectors 75-85%
- Repetitive welding operations sectors 90%
- Raw materials sectors 93-96%
- Purchased Parts sectors 85-88%

Learning Curve (LC) Models

The learning curve (LC) relationship is usually modeled parametrically as a nonlinear power function model. The function that best represents this data is the Basic Power Model or log-linear function. The variables in this equation, given in terms of unit cost, are first unit cost and the "slope" of the LC. Using this equation, one can estimate the cost of a lot from the cost of the first unit, or given the cost of a lot one can derive the cost of the first unit [3, 8, 9, 10, 11, 13, 23, 28, and 46].

There are two different basic models of LC: 1) the original model was a cumulative average learning curve theory which was proposed by T.P. Wright [46] in a published article in 1936 on LC theory. He was credited as the first one to publish LC theory while working for Curtiss Aeroplane Company (CAC). In the journal of the Aeronautical Sciences, "Factors Affecting the Cost of Airplane," he showed that as the quantity of aircraft produced increases, the cumulative average direct labor time to produce the aircraft decreases at a constant rate. This theory is known as the Wright curve. 2) the second model is the unit LC theory proposed by Crawford in 1947 while working for Lockheed Martin Corporation. He showed that as the quantity of aircraft produced increases, the unit labor time to produce that aircraft decreases at a constant rate. This theory is known as the Crawford curve [3, 8, 9, 10, 11, 13, 23, 28, and 46].

Cumulative Average Learning Curve (LC) Model

The first model is the cumulative average LC formulation, often associated with T.P. Wright's cumulative average model [28, and 46].

In Wright's Cumulative Average Model, the LC formulation is defined by the equation:

$$Y_x = Ax^b \tag{18}$$

Where:

Y_x = the cumulative average time (or cost) per unit x (dependent variable).

x = the cumulative number of units produced (independent variable).

A = time labor (hour) or cost required to produce the first unit (CFU; T1; or Y1)

b = learning index or slope (slope = 2b) of the function when plotted on log-log paper or learning curve exponent (a constant).

Learning index, b, is related to the learning rate, r.

$$b = \text{log of the learning rate (log } r\text{) /log of 2} \tag{19}$$

Learning Parameter

In practice, $-0.5 \leq b \leq -0.05$ represents the improvement seen as repetitions increase. For b = 0, the equation simplifies to Y = A which means any unit costs the same as the first unit. In this case, the learning curve is a horizontal line and there is no learning, referred to as a 100% learning curve.

Unit Learning Curve (LC) Model

The second model is the unit LC formulation, often associated with James Crawford's unit learning curve model [28].

In the James Crawford's Unit LC Model, the learning curve formulation is defined by the equation:

$$Y_x = AK^b \tag{20}$$

Where:

Y_x = the incremental unit time (or cost) of the lot midpoint unit.

K = the algebraic midpoint of a specific production batch or lot.

X (i.e., the cumulative number of units produced) can be used in the equation instead of K.

Since the relationships are non-linear, the algebraic midpoint requires solving the following equation:

$$K = [L\ (1+b)/\ (N21+b\ -\ N11+b)]-1/b \tag{21}$$

Where:

K = the algebraic midpoint of the lot.

L = the number of units in the lot.

b = log of learning rate / log of 2

N1 = the first unit in the lot minus 1/2.

N2 = the last unit in the lot plus 1/2.

Sensitivity Analysis

Sensitivity analysis is the procedure of varying the input parameters of a LCC model over their practical range and observing the relative change in the LCC model output. Sensitivity analysis is a significant part of decision making. The purpose of the sensitivity analysis is to determine the sensitivity of a model outcome to uncertainty in the input data. It provides valuable insight into the quality of a given model and its robustness with respect to changes in input parameters. Most LCC models are an estimation of uncertainty. So, the outputs of the sensitivity analysis of each input parameter are very valuable. However, in many cases, it's more practical to analyze sensitivity intuitively rather than systematically [23].

III. Analysis of Z-Pinned Laminated Composites Fatigue Test Data

S. R. Soni, PhD

M. Al-Romaihi, Col. BDF

A. B. Badiru, PhD

J. D. Weir, PhD

J. R. Wirthlin, PhD

Stephen Clay, PhD

AFIT-ENS-DS-14-J-19

Abstract

There are various benefits of using composite materials (as demonstrated by extensive use in aerospace, sports, auto and medical industries) if used with complete understanding of their performance capabilities. One of the most feared modes of failure in composites is delamination. The Composites Affordability Initiative (CAI), reference 37, by US Air Force and Aerospace Industry has identified joining and co-curing of composites as an important problem area of interest. Delamination is common in such composites and z-pinning provides through-the-thickness reinforcements, to improve structural damage tolerance. Being a relatively new application for joint design, estimating the reliability of z-pinned composite components is quite a complex process and requires knowledge of the uncertainties that occur at various scales. Further it is well known that fatigue is the main reason of mishaps in majority of cases. To understand response characteristics of composites with/without z- pins, numerous tests are conducted using different z-fiber diameters and loading conditions to determine the fatigue life of layered composite laminates. Commonly used laminate, quasi isotropic, has been considered with and/or without z-pins. The material used is IM7/977-3 prepreg. The variation of z-pin diameter, area covered and location of the z-pin area influence the fatigue response. The data reveals that there exists a combination of these parameters for long fatigue life of composites with z- pins and reduced delamination.

Introduction

Because of their layered structure, polymer matrix composites (PMC's) do not, in general, have the ability to deform plastically like metals, thus the energy absorption mechanism of composites is different from that of metals. In composites, energy is absorbed by matrix cracking and the creation of large fracture surfaces at the lamina interfaces, a phenomenon known as delamination. Delamination severely impairs the load-carrying capacity and structural integrity of composite structures and since composites naturally lack reinforcement in the thickness direction, delamination is a predominant failure mode. While composites have shown great promise achieving the performance and cost goals of future aircraft industry, their use may be limited by their susceptibility to delamination and the need to meet survivability requirements. Advanced processing techniques, interlaminar reinforcement technologies and innovative design concepts have been developed in recent years and provide significant improvements towards achieving survivable, all-composite structures while minimizing any increase in weight and cost. At the present time several 3D technologies are under investigation toward this end, namely: stitching, tufting, 3D weaving and z-pinning.

Jason Freels' thesis describes [17] the results of a combined experimental and analytical study to:

- Investigate mode I, mode II and mixed mode failure response of various composite specimen geometries with through-thickness reinforcement, and

- Verify the DYNA3D smeared property finite element model developed by Adtech Systems Research Inc. (ASRI) by comparing simulation and experimental results.

In references [17, 22, and 41] specimen geometries tested include: T-section (T-SEC) components as well as double cantilever beam (DCB) specimens each with and without through-thickness reinforcement. Experiments were conducted "in-house" under low strain rate loading conditions using ASRI and AFRL test facilities.

Problem Description

The goal of this research work is to understand the fatigue response of co-cured composite laminate specimens with and without z-pin reinforcement.

Table 9 shows representative z-pin configurations. For clarity, test data tables contain the specific details of configurations considered. The following parameters are considered:

- Test 9''x1' specimens reinforced with 0.011" & 0.02" diameter Z-pins
- Compare response of 0.02" diameter Z-pin reinforcement to that of 0.011" diameter Z-pins
- Investigate the influence of maximum load as % of ultimate static strength of the laminate without Z-pin fibers.

Table 9 : Z-pinned Specimen Configurations

Configuration Type	Diameter of Z-pin	% of reinforcement	Area of Z-pin
A	0.011 inch	2.0	1 inch x 1 inch
B	0.011 inch	4.0	1 inch x 1 inch
C	0.020 inch	2.0	1 inch x 1 inch
D	0.020 inch	4.0	1 inch x 1 inch
E	0.011 inch	2.0	2 inch x 1 inch
F	0.011 inch	4.0	2 inch x 1 inch
G	0.020 inch	2.0	2 inch x 1 inch
H	0.020 inch	4.0	2 inch x 1 inch

Experiments and Data Analysis

We started conducting tests of specimens with 1” end tab material. To start we made 18 specimens. It was observed that specimens started failing at the end tab. To make the best use of the machined specimens, we decided to use those specimens by including stress raisers in the form of a hole (in case of laminate without z-pins) or three holes in the case of laminate with z-pins at appropriate locations. That helped avoid failure of specimens at end tabs. Tests provided additional insight in to the failure mechanisms in the Z-pin area or without z- pin area.

Figure 9 shows the classes of parameters considered including stress raisers (hole diameters .1” and .2”) and z-pin diameter (.011”, .02”). Other parameters considered were % ultimate loads (60%, 70% and 80%) and z-pin surface area (2% and 4%). All these parameters influence the lifecycle (number of cycles to failure) of the laminate. For illustration purposes, Figure 10 shows the specimen after fatigue loading and failure of one specimen. The reader can easily visualize the specimen before loading. Each test was conducted by using 20 kips servo hydraulic test system using different loads with R=.1 and 4 hertz frequency. In order to understand the damage progression in the specimens at different cycles; specimens were fatigued till a specific number of cycles, unloaded and x-rayed. From the x- ray images a percent damage area was calculated by using imaging software developed by the Department of Health Researches [50]. Resulting cycle and load dependent damage data is given in Table 10, and Table 15 below. In Table 10, Na, Nb and Nc represent numbers of cycles at which specimens were unloaded and x-rayed. Damage % area for each unloading is given in the next column. Table 11-Table 16 show other results of experiments conducted for fatigue loading of specimens with different parameters.

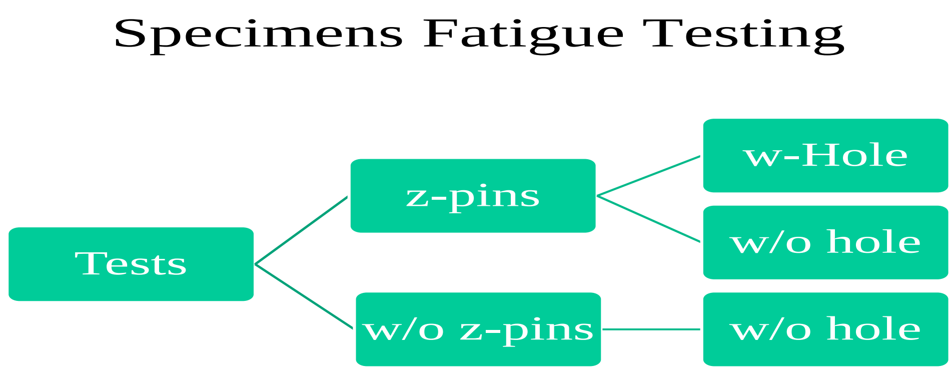


Figure 9 : Specimen Fatigue Tests Considered Investigation

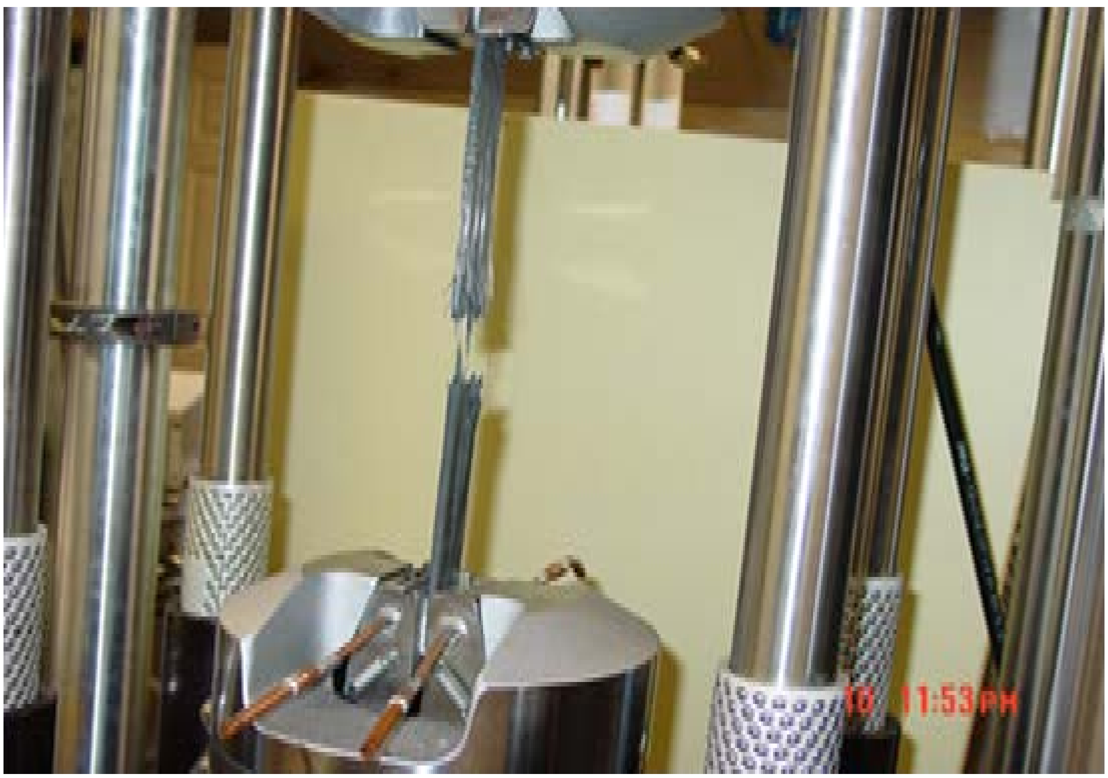


Figure 10 : Specimen Test Fixture after Fatigue Failure [41]

Table 10 : Example Data for Nine Specimens Tested at Different Loads

Sample ID	Max Stress (ksi)	% Ultimate	Cycles N_a	Damage Area a (%)	Cycles N_b	Damage Area b (%)	Cycles N_c	Damage Area c (%)
5-1	92	80	8,907	100		100		
5-2	92	80	20,453	44	21,453	100		
5-3	92	80	18,404	100		100		
5-4	80.5	70	188,636	64	253,931	90	267,122	100
5-5	80.5	70	187,376	65	202,224	61		
5-6	80.5	70	242,378	62	251,428	61	296,450	100
5-7	69	60	328,026	53	407,688	60		
5-8	69	60	121,710	37	246,552	61	311,000	100
5-9	69	60	242,165	47	325,148	63	400,000	100

Table 11 : Specimens with Different Loading Conditions

Sample ID	Stress (Ksi)	Cycles (N_f)	Failure Mode	Hole
B2-1	87.8	63,568	Delam	No hole
B2-2	87.8	15,006	Hole-Zpin	0.2” dia
B2-4	87.8	40,565	Hole-Zpin	0.2” dia
B2-5	87.8	3,863	Hole-Zpin	0.2” dia
B2-6	87.8	15,120	Hole-Zpin	0.2” dia
B2-7	87.8	7,834	Hole-Zpin	0.2” dia
B2-8	87.8	378	Tap	

1X1 represent 1"x1" z-pin area, 2T represent z-pin area starts at 2" away from Tab both side of the specimen.

Table 12 : Specimens with Different Loading Conditions

Sample ID	Max Stress (Ksi)	Cycles (N_f)	Failure Mode	Hole
XB-1	92	1,836	Delam	N/A
XB-2	80.5	35,250	Delam	N/A
XB-3	80.5	41,963	Delam	N/A
XB-4	80.5	32,298	Delam	N/A
XB-5	80.5	53,589	Delam	N/A
XB-6	80.5	100,946+	Delam	N/A
XB-7	69	122,031+	Delam	N/A
XB-8	69	122,138+	Delam	N/A
XB-9	80.5	32,729	Delam	N/A

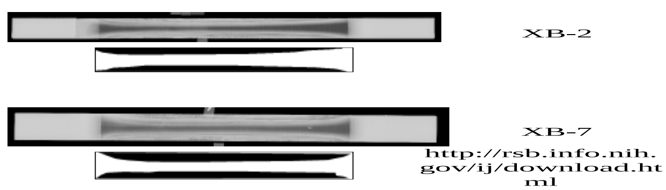


Figure 11 : X-Ray Samples XB-2 & XB-7 with Corresponding Damage Image [50]

Table 13 : Specimens with different loading conditions

Sample ID	Max Stress (Ksi)	Cycles (N_f)	Failure Mode	Hole
XC1-1	69	100,500+	Delam	N/A
XC1-2	69	111,005+	Delam	N/A
XC1-3	69	109,931+	Delam	N/A
XC1-4	69	114,108+	Delam	N/A
XC1-5	69	121,669+	Delam	N/A
XC1-6	80.5	112,861+	Delam	N/A
XC1-7	80.5	160,621+	Delam	N/A
XC1-9	80.5	114,821	Delam	N/A

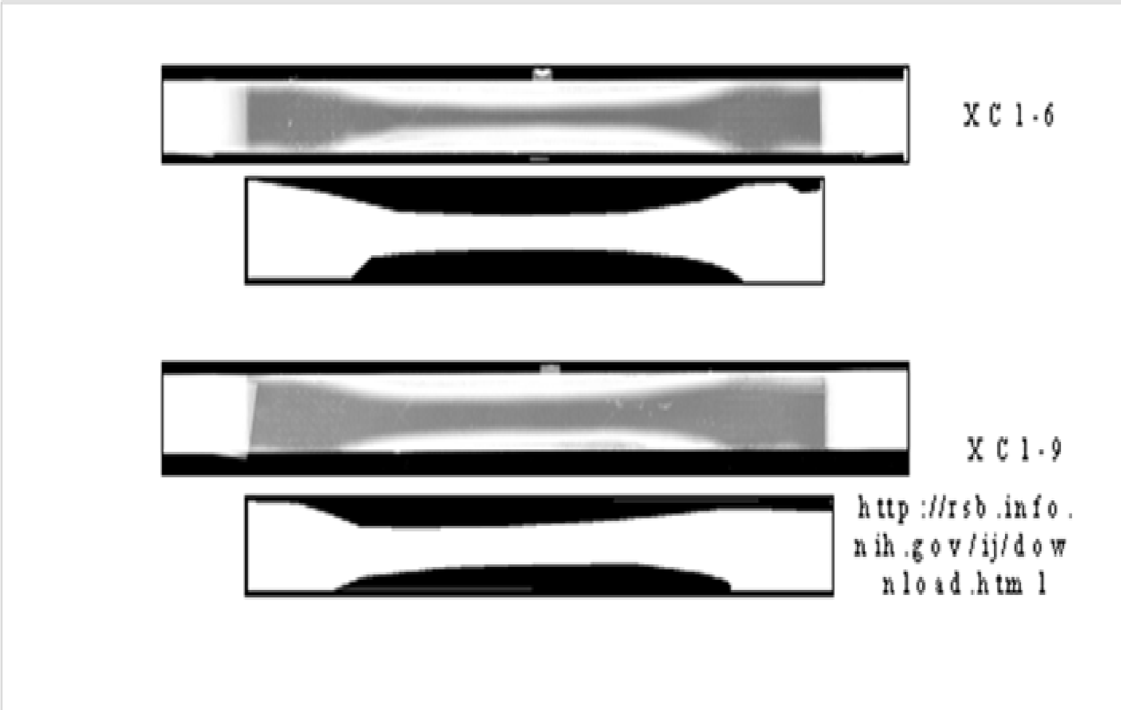


Figure 12 : X-Ray Samples XC1-6 & XC1-9 with Corresponding Damage Image [50]

Table 14 : Test Results Summary

Sample ID	**Max Stress (Ksi)**	**Cycles (N_f) Mean**	**Cycles (N_f) Median**	**Cycles (N_f) St. Dev.**	**Failure Mode**
B2-1 to B2-8	87.8	16,477	15,006	14,300	Hole-Z-pin
C2-1 to C2-4	86.0	283,658	294,845	90,263	Center Hole
C2-6 to C2-9	87.8	70,286	58,063	39,203	Hole-Z-pin
H1-2,7& I1-1,2	92	2,388	2,595	2,162	Failure near Z region
H1-3,6 & I1-3,4	80.5	6,745	6,653	5,282	Failure near Z region
H1-4,5 & I1-5,6	69	75,443	68,947	63,926	Failure near Z region
H2-5 to H2-9	84.0	95,327	91,541	13,313	Hole-Z-pin
H2-5		Centered at	113,5	Cycles	

Table 15 : Damage Area Specimens with or without Z-pins

Z-Pins	% Ultimate	Cycles	Damage Area
NO	60	328,026	53
		121,710	37
		242,165	47
		407,688	60
		246,552	61
		325,148	63
		100,946	23
		122,031	50
Yes		114,108	3
		121,669	5
NO	70	188,636	64
		187,376	65
		242,378	62
		253,931	90
		202,224	61
		251,428	61
		35,250	43
		41,963	35
Yes		112,581	43
		160,621	51
NO	80	8,907	100
		20,453	44
		18,404	100
		21,453	100

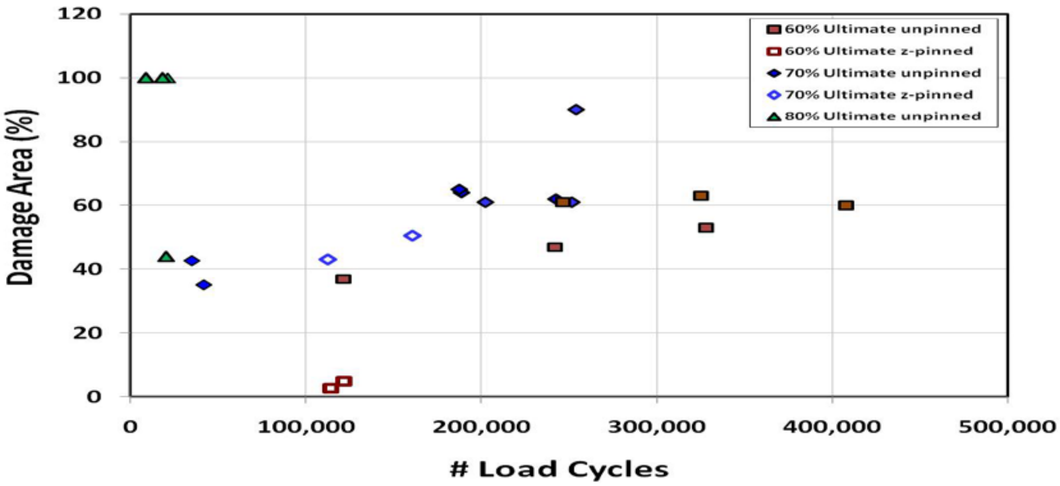


Figure 13 : Damage Area Specimens Tested at Different Cycles

A set of specimens consisting of Series H1, J1 and I1 were tested for 80%, 70%, 60% and 50% of ultimate strength. Because of limited resources, we tested 9 specimens in each class. The following data (Table 16) for 60% and 50% of ultimate strength (i.e. 69 ksi and 57.5 ksi) speaks to the fact that there is a benefit of using the J1 configuration of the specimen which uses .011" diameter and 2% z-pins.

Table 16 : Fatigue Cycles for H1, J1 and I1 Specimen Series

Load	Specimens	Corresponding Cycles
69 Ksi	H1-4;5;9	1,845;45,250;66,508
	J1-5;6	161,150+;181,150+
57.7 Ksi	I1-5;6;7	71,386;159,653;80,514
	5-7;8;9	328,026+;121,710;242,165+
	H1-8	320,842
	J1-7;8	750,000+;763,000+
	I1-8;9	458,219;563,760+

+ Represents the specimen was censored at this cycle number.

This work is on progress and additional results will be provided in forthcoming publications.

Future Research

The work will continue to develop additional data using a Monte Carlo technique. Further tests will be done to prove that the random data generated by the Monte Carlo technique represents the additional experimental test data. We also plan to investigate the cost implications of using Z-pins in composite airframe structure life cycle estimates.

IV. Fatigue Tests and Data Analysis of Z-Pinned Composite Laminates

M. Al-Romaihi, Col. BDF

S. R. Soni, PhD

A. B. Badiru, PhD

J. D. Weir, PhD

J. R. Wirthlin, PhD

Barth Shenk, PhD

AFIT-ENS-DS-14-J-19

Abstract

One of the most feared modes of failure in composites is onset of delamination. The Composites Affordability Initiative (CAI), reference [37], by US Air Force and Aerospace Industry has identified joining and co-curing of composites as an important problem area of interest. Delamination is common in such composites and z-pinning provides through-the-thickness reinforcements, to improve structural damage tolerance. Being a relatively new application for joint design, estimating the reliability of z-pinned composite components is quite a complex process and requires knowledge of the uncertainties that occur at various scales. Further it is well known that fatigue is the main reason of mishaps in majority of cases. To understand response characteristics of composites with/without z-pins, numerous tests are conducted using different z-fiber diameters and loading conditions to determine the fatigue life of layered composite laminates. Commonly used laminate, quasi isotropic, has been considered with and/or without z-pins. IM7/977-3 prepreg is used to make the required laminates. The variation of z-pin diameter, area covered and location of the z-pin area influence the fatigue response. The data reveals that there exists a combination of these parameters for long fatigue life of composites with z-pins and reduced delamination.

Introduction

Because of their layered structure, polymer matrix composites (PMC's) do not, in general, have the ability to deform plastically like metals, thus the energy absorption mechanism of composites is different from that of metals. In composites, energy is absorbed by matrix cracking and the creation of large fracture surfaces at the lamina interfaces, a phenomenon known as delamination. Delamination severely impairs the load-carrying capacity and structural integrity of composite structures and since composites naturally lack reinforcement in the thickness direction, delamination is a predominant failure mode. While composites have shown great promise achieving the performance and cost goals of future aircraft industry, their use may be limited by their susceptibility to delamination and the need to meet survivability requirements.

Advanced processing techniques, interlaminar reinforcement technologies and innovative design concepts have been developed in recent years and provide significant improvements towards achieving survivable, all-composite structures while minimizing any increase in weight and cost. At the present time several 3D technologies are under investigation toward this end, namely: stitching, tufting, 3D weaving and z-pinning.

Jason Freels' thesis [17] describes the results of a combined experimental and analytical study to:

- Investigate mode I, mode II and mixed mode failure response of various composite specimen geometries with through-thickness reinforcement, and

- Verify the DYNA3D smeared property finite element model developed by Adtech Systems Research Inc. (ASRI) by comparing simulation and experimental results.

In references [17, 22, and 41] specimen geometries tested include: T-section (T-SEC) components as well as double cantilever beam (DCB) specimens each with and without through-thickness reinforcement. Experiments were conducted “in-house” under low strain rate loading conditions using ASRI and AFRL test facilities. Both analytical and experimental research was conducted [39] addressing the response of specimens under low velocity impact conditions.

The goal of this research work is to understand the fatigue response of co-cured composite laminate specimens with and without z-pin reinforcement. Table 17 shows representative z-pin configurations. For clarity, test data tables contain the specific details of configurations considered. The following parameters are considered:

- Test 9’’x1” specimens reinforced with 0.011” & .02” diameter Z-pins
- Compare response of 0.02” diameter z-pin reinforcement to that of 0.011” diameter z-pins
- Investigate the influence of maximum load as % of ultimate static strength of the laminate without z-pin fibers on fatigue life of the specimen considered.
- Percent damage analysis is done for different cases after fatigue loading/ unloading and reloading.

Table 17 : Z-pinned Specimen Configurations

Configuration Type	Diameter of Z-pin	% of Reinforcement	Area of Z-pin
A	0.011 inch	2.0	1 in x 1 in
B	0.011 inch	4.0	1 in x 1 in
C	0.020 inch	2.0	1 in x 1 in
D	0.020 inch	4.0	1 in x 1 in
E	0.011 inch	2.0	2 in x 1 in
F	0.011 inch	4.0	2 in x 1 in
G	0.020 inch	2.0	2 in x 1 in
H	0.020 inch	4.0	2 in x 1 in

Experiments and Relevant Data

We started conducting tests of specimens with 1" end tab material. To start with 18 specimens were machined. Each test was conducted by using a 20 kips servo hydraulic test system (Figure 14) using different loads with R=0.1 and 4 hertz frequency. On testing specimens, it was observed that specimens started failing at the end tabs. To make the best use of the machined specimens, we decided to use those specimens by including stress raisers in the form of a hole (in case of specimens without z-pins) or three holes in the case of laminate with z-pins at appropriate locations. That helped avoid failure of specimens at end tabs. Figure 14 shows a specimen after fatigue loading and failure of the specimen. One can easily visualize the specimen before loading. Tests provided useful insight in to the failure mechanisms in the z-pin area or without z-pin area. Figure 15 shows the classes of parameters considered including stress raisers (hole diameters 0.1” and 0.2”) and z-pin diameter (0.011”, 0.02”). Other parameters considered were % ultimate loads (50%, 60%, 70% and 80%) and z-pin surface area (2% and 4%). All these parameters influence the lifecycle (number of cycles to failure) of the laminate.

Figure 14 : Specimen Test Fixture after Fatigue Failure [41]

Figure 15 : Specimen Fatigue Tests Considered Investigation

In order to understand the damage progression in the specimens at different cycles; specimens were fatigued until a specific number of cycles, unloaded and x-rayed.

From the x-ray images a percent damage area was calculated by using imaging software developed by the Department of Health researchers [50].

Results and Discussion

This paper includes the following 4 key elements: (1) Fatigue tests of numerous specimens, (2) X-ray exams to detect damage after fatigue testing at given # of cycles, (3) Imaging technique used to calculate % damage after x-ray testing and (4) a Monte Carlo technique for obtaining additional data. Resulting cycle and load dependent damage data is given in Table 18 to Table 26 below. Table 18 is for specimens number 5-i (i=1 to 9). These specimens are without z-pins. Symbols Na, Nb and Nc represent numbers of cycles at which specimens were unloaded and x-rayed for each loading (at 60%, 70% and 80% of ultimate). Damage % area for each unloading is given in the next column.

Table 18 : Example Data for Nine Specimens Tested at Different Loads

Sample ID	Max Stress (Ksi)	% Ultimate	Cycles N_a	Damage Area a (%)	Cycles N_b	Damage Area b (%)	Cycles N_c	Damage Area c (%)
5-1	92	80	8,907	100		100		
5-2	92	80	20,453	44	21,453	100		
5-3	92	80	18,404	100		100		
5-4	80.5	70	188,636	64	253,931	90	267,122	100
5-5	80.5	70	187,376	65	202,224	61		
5-6	80.5	70	242,378	62	251,428	61	296,450	100
5-7	69	60	328,026	53	407,688	60		
5-8	69	60	121,710	37	246,552	61	311,000	100
5-9	69	60	242,165	47	325,148	63	400,000	100

One can see the damage progression depending upon cycles, load and specimen ID. Table 19 shows testing data for specimens B2-i (i=1 to 8) with stress raiser holes at three locations. Applied stress in this case is 87.8 ksi. Most of the specimens failed at a location in Z-pin region at the hole. As expected, the inherent variability in properties and specimen preparation procedure is reflected in the failure cycle of the specimens.

Table 20 shows experimental results of XB series 9 specimens with different loading. X-ray images and corresponding damage area images are given in Figure 16 below. Table 21 to Table 26 show other results of experiments conducted for fatigue loading of specimens with different parameters.

Table 19 : Specimens with Different Loading Conditions

Sample ID	Stress (Ksi)	Cycles (N_f)	Failure Mode	Hole
B2-1	87.8	63,568	Delam	No hole
B2-2	87.8	15,006	Hole-Zpin	0.2” dia
B2-4	87.8	40,565	Hole-Zpin	0.2” dia
B2-5	87.8	3,863	Hole-Zpin	0.2” dia
B2-6	87.8	15,120	Hole-Zpin	0.2” dia
B2-7	87.8	7,834	Hole-Zpin	0.2” dia
B2-8	87.8	378	Tap	

1X1 represent 1"x1" z-pin area, 2T represent z-pin area starts at 2" away from Tab both side of the specimen.

Table 20 : Specimens with Different Loading Conditions

Sample ID	Max Stress (ksi)	Cycles (N_f)	Failure Mode	Hole
XB-1	92	1,836	Delam	N/A
XB-2	80.5	35,250	Delam	N/A
XB-3	80.5	41,963	Delam	N/A
XB-4	80.5	32,298	Delam	N/A
XB-5	80.5	53,589	Delam	N/A
XB-6	80.5	100,946+	Delam	N/A
XB-7	69	122,031+	Delam	N/A
XB-8	69	122,138+	Delam	N/A
XB-9	80.5	32,729	Delam	N/A

The use of reference [50] gives the percent damage number. Some of the relevant % damage numbers are given in Table 18 and Table 22. Table 21 shows fatigue cycles and corresponding failure mode observed for XC1 series of specimens. The specimens had z-pins inserted as given in the table.

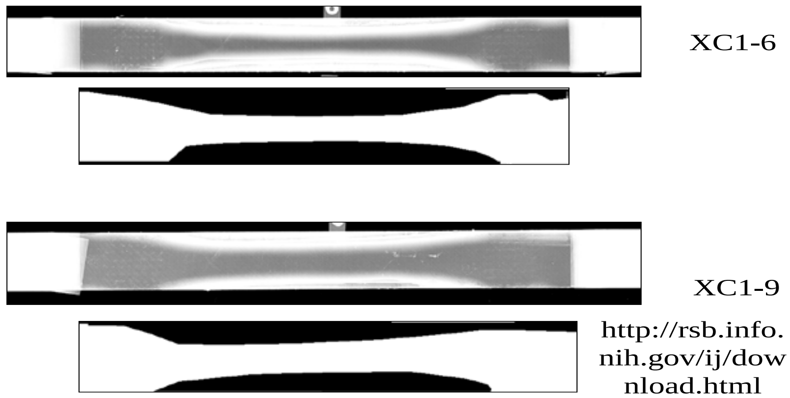


Figure 17 **:** X-ray Images and Corresponding Damage Images for Two Specimens [50]

Table 21 gives percent damage calculations using [50] for specimens with or without Z-pins for different loading conditions. It is observed that % damage created during fatigue loading is relatively less amongst specimens with Z-pins as compared to those without Z-pins. Same data is shown in Figure 18.

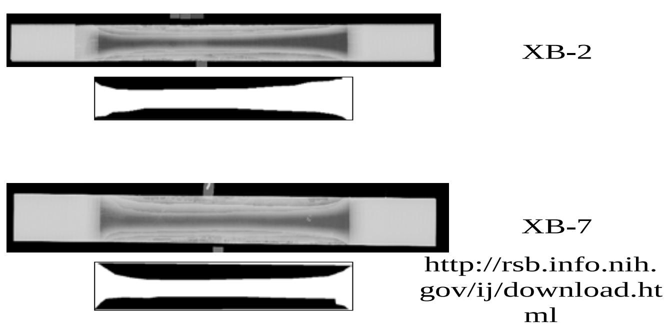
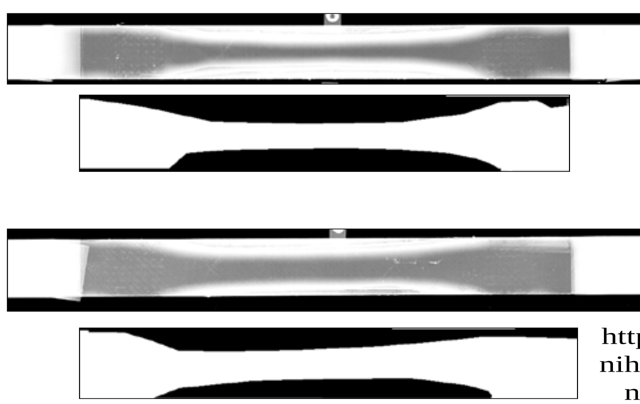


Figure 16 : X-Ray Samples XB-2 & XB-7 with Corresponding Damage [50]

Table 21 : Specimens with Different Loading Conditions

Sample ID	Max Stress (ksi)	Cycles (N_f)	Failure Mode	Hole
XC1-1	69	100,500+	Delam	N/A
XC1-2	69	111,005+	Delam	N/A
XC1-3	69	109,931+	Delam	N/A
XC1-4	69	114,108+	Delam	N/A
XC1-5	69	121,669+	Delam	N/A
XC1-6	80.5	112,861+	Delam	N/A
XC1-7	80.5	160,621+	Delam	N/A
XC1-9	80.5	114,821	Delam	N/A



XC1-6

XC1-9

http://rsb.info.nih.gov/ij/download.html

Figure 17 : X-Ray Samples XC1-6 & XC1-9 with Corresponding Damage [50]

Table 22 : Damage Area Specimens with or without Z-pins

Z-Pins	% Ultimate	Cycles	Damage Area
NO	60	328,026	53
		121,710	37
		242,165	47
		407,688	60
		246,552	61
		325,148	63
		100,946	23
		122,031	50
Yes		114,108	3
		121,669	5
NO	70	188,636	64
		187,376	65
		242,378	62
		253,931	90
		202,224	61
		251,428	61
		35,250	43
		41,963	35
Yes		112,581	43
		160,621	51
NO	80	8,907	100
		20,453	44
		18,404	100
		21,453	100

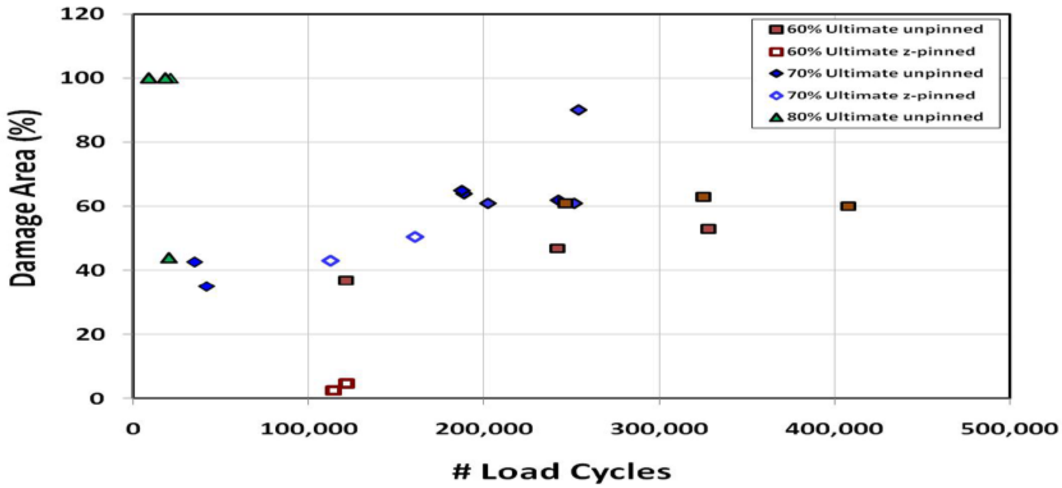


Figure 18 : Damage Area Specimens Tested at Different Cycles

The Table 23 below shows the test results summary of the number of cycles to failure [NF] mean, median, and standard deviation of experiments of corresponding specimens conducted for given fatigue loading and failure modes.

Table 23 : Test Results Summary

Sample ID	**Max Stress (Ksi)**	**Cycles (N_f) Mean**	**Cycles (N_f) Median**	**Cycles (N_f) St. Dev.**	**Failure Mode**
B2-1 to B2-8	87.8	16,477	15,006	14,300	Hole-Z-pin
C2-1 to C2-4	86.0	283,658	294,845	90,263	Center Hole
C2-6 to C2-9	87.8	70,286	58,063	39,203	Hole-Z-pin
H1-2,7 & I1-1,2	92.0	2,388	2,595	2,162	Failure near Z region
H1-3,6 & I1-3,4	80.5	6,745	6,653	5,282	Failure near Z region
H1-4,5 & I1-5,6	69.0	75,443	68,947	63,926	Failure near Z region
H2-5 to H2-9	84.0	95,327	91,541	13,313	Hole-Z-pin
XB-5 to XB-8	69.0	106,377	122,156	35,110	Delamination, no Holes
H2-5	Centered at 113,508 Cycles				

Table 24 : Monte Carlo Based Fatigue Data

SPECIMEN #	MAX STRESS (Ksi)	Nf CYCLES	Max LOAD (LBS)	R ratio	SPEC THICK (IN)	SPEC WIDTH (IN)	SPEC AREA (IN^2)
XB-1	69.0	65390	11250	0.1	0.169	1	0.169
XB-2	69.0	125266	11250	0.1	0.169	1	0.169
XB-3	69.0	61561	11250	0.1	0.169	1	0.169
XB-4	69.0	203648	11250	0.1	0.169	1	0.169
XB-5	69.0	53841	11250	0.1	0.169	1	0.169
XB-6	69.0	127356	11250	0.1	0.169	1	0.169
XB-7	69.0	122060	11250	0.1	0.169	1	0.169
XB-8	69.0	122252	11250	0.1	0.169	1	0.169
XB-9	69.0	177151	11250	0.1	0.169	1	0.169
XB-10	69.0	81259	11250	0.1	0.169	1	0.169
XB-11	69.0	106490	11250	0.1	0.169	1	0.169
XB-12	69.0	42036	11250	0.1	0.169	1	0.169
XB-13	69.0	88783	11250	0.1	0.169	1	0.169
XB-14	69.0	99123	11250	0.1	0.169	1	0.169
XB-15	69.0	176234	11250	0.1	0.169	1	0.169
XB-16	69.0	132527	11250	0.1	0.169	1	0.169
XB-17	69.0	283238	11250	0.1	0.169	1	0.169
XB-18	69.0	109714	11250	0.1	0.169	1	0.169
XB-19	69.0	89146	11250	0.1	0.169	1	0.169
XB-20	69.0	147181	11250	0.1	0.169	1	0.169

Table 25 : Monte Carlo Based Test Results Summary

SPECIMEN #	STRESS (Ksi)	NF Cycles Mean	NF Cycles Median	NF Cycles ST. Dev.	FAILURE Mode
B2-1 TO B2-20	87.8	16923	14296	13079	Hole-Z-pin
AC2-1 TO AC2-20	86.0	290944	315996	93501	Center Ho
BC2-1 TO BC2-20	87.8	70122	63813	40651	Hole-Z-pin
AH1-1 TO AH1-20	92.0	2407	1725	2232	Failure near Z region
BH1-1 TO BH1-20	80.5	6829	7085	4032	Failure near Z region
CH1-1 TO CH1-20	69.0	76610	73980	42037	Failure near Z region
AI1-1 TO AI1-20	92.0	2890	2361	2174	Failure near Z region
BI1-1 TO BI1-20	80.5	7215	8319	4027	Failure near Z region
CI1-1 TO CI1-20	69.0	78930	59122	60293	Failure near Z region
H2-1 TO H2-20	84.0	95312	95827	13596	Hole-Z-pin
XB-1 TO XB-20	69.0	120712.8	115887	57148.42	Delamination, no holes

Experimental research consists of various steps. One has to procure the required material as prepreg, layup a laminate, insert z-pins, cure the laid up laminate, machine the specimens and apply end tabs. For getting meaningful data one needs to test an adequate number of replicates at each load case (at least 3). Figure 19 shows some of the parameters considered for the execution of this research.

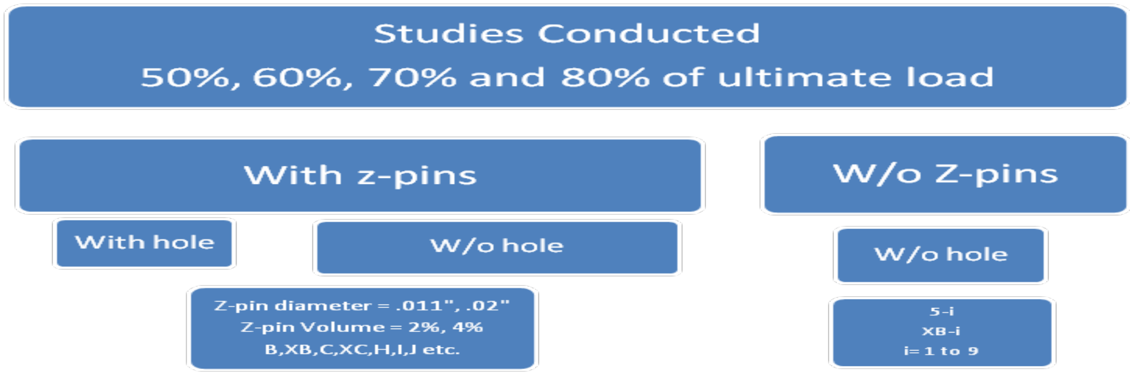


Figure 19 : High Lights Parameters

We tested the specimens as given in the tables. As mentioned above testing of specimens is an expensive affair. For that reason, we used a Monte Carlo technique available in the EXCEL program to generate more data by using the NORMINV function. We used the above, Table 23, NF Cycles mean and NF Cycles standard deviation to simulate the random normal variables. NORMINV formula NORMINV [RAND (), MEAN, ST. DEV.] was used to calculate the random numbers of cycles to failure (life cycle), Table 24. The Table 25 shows the test results summary of the NF Cycles mean, NF Cycles median, and NF Cycles standard deviation of random and the original numbers combined.

We prepared two sets of panels for each of seven configurations given in test summary Table 23. This amounts to 14 panels with Z-pins. Also 2 panels of laminates with no Z-pins were prepared. Each panel gives 9 specimens therefore resulting in (9x16=) 144 specimens. Testing time of each specimen depends upon load and number of cycles, and takes between 10 minutes to 60 hours. When we started the experimental work, we prepared about 18 specimens with 1" long end tabs. Testing results were not as expected. The specimens were failing at the end tabs. To avoid this type of failure and utilize the specimens prepared we inserted stress raisers by drilling a hole in the middle/ or at z-pin region of the specimen. The data thus generated is given in tables.

A set of specimens consisting of Series H1, J1 and I1 were tested for 80%, 70%, 60% and 50% of ultimate strength. Because of limited resources, we tested 9 specimens in each class. The following data (Table 26) for 60% and 50% of ultimate strength (i.e. 69 ksi and 57.5 ksi) speaks to the fact that there is a benefit of using the J1 configuration of the specimen which uses .011" diameter and 2% z-pins.

Table 26 : Fatigue Cycles for H1, J1 and I1 Specimen Series

Load	Specimens	Corresponding Cycles
69 Ksi	H1-4;5;9	1,845;45,250;66,508
	J1-5;6	161,150+;181,150+
57.7 Ksi	I1-5;6;7	71,386;159,653;80,514
	5-7;8;9	328,026+;121,710;242,165+
	H1-8	320,842
	J1-7;8	750,000+;763,000+
	I1-8;9	458,219;563,760+

+ Represents the specimen was censored at this cycle number.

This is work in progress and additional results will be provided in forthcoming publications.

Future Research

The work is on process to develop additional data using Monte Carlo technique. Further tests will be done to prove that the random data generated by Monte Carlo technique represents the additional experimental test data. Using experimental data and Monte Carlo technique, we will investigate the reliability aspects of the specimens used. Further, we plan to investigate the cost implications of using Z-pins in composite airframe structure life cycle cost estimates.

Concluding Remarks

This research is a step forward to understand the fatigue response of composite materials in the presence of z-pins to reduce or eliminate delamination. A quasi- isotropic laminate configuration representing Pai joints [17] is used for investigating the effect of z-pin diameter, volume fraction, loading etc. on fatigue life of the specimens. Damage progression is observed via X-ray analysis and damage calculation approach developed for medical diagnostics [50]. It is expected that the future research will show that there exists an optimum z-pinning configuration for long fatigue life of composite without delamination. We hope to continue work in this area in the near future.

Acknowledgements

This publication was partially developed under work supported by the Naval Postgraduate School Acquisition Research Program Assistance Agreement No. 2011-138

awarded by the Naval Supply Systems Command (NAVSUP) Fleet Logistics Center San Diego (NAVSUP FLC San Diego). It has not been formally reviewed by NPS. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the NPS or NAVSUP FLC San Diego. The NPS and NAVSUP FLC San Diego do not endorse any products or commercial services mentioned in this publication.

V. Cost Estimating Relationships between Part Counts and Advanced Composite Aircraft Manufacturing Cost Elements

M. Al-Romaihi, Col. BDF

S. R. Soni, PhD

J. D. Weir, PhD

A. B. Badiru, PhD

A. E. Thal, Jr., PhD

Barth Shenk, PhD

AFIT-ENS-DS-14-J-19

Abstract

Advanced composite materials comprise significantly greater percentages of airframe structural materials used throughout the aerospace manufacturing industry. This increased usage has led many individuals within the Air Force (AF) and Department of Defense (DoD) communities to restudy the life cycle cost (LCC) models used to estimate the costs for most weapon systems. A series of composite affordability initiatives (CAI) have culminated in significant evidence over the last three decades which aids in better quantifying the cost impact of advanced composite materials in airframe structures. This research found that a significant relationship exists between the reductions in part counts and the large-scale use of advanced composite materials used in LCC models for aircraft structures. The percentage reductions in part counts led to reductions in the percentages of touch labor hours in design, design support, testing, tooling, manufacturing, and quality assurance. This percentage of reduction affects most development and production cost categories.

Introduction

The available life cycle cost (LCC) models and procurement strategies do not take into consideration the varied manufacturing techniques for advanced composite materials. The increased use of advanced composite materials in aerospace manufacturing and the corresponding decrease in aircraft part counts create potential cost savings, due to reduced touch labor hours, which are not captured by current LCC models. Lack of research on the potential savings associated with reduced part counts and the integration of large-scale advanced composite materials into aerospace manufacturing has resulted in an information vacuum, causing consumers and industry officials to perceive advanced composite materials use as being riskier and more expensive when compared to the use of traditional metallic materials. Because of this perception, the majority of the advanced composite materials usage has been focused on the components of airframe structures [8, 26, and 27].Therefore, the purpose of this paper is to investigate and improve the methods for evaluating the cost implications associated with the use of advanced composite materials on airframe structures. In particular, we will address the effect of more realistic labor touch hour costs related to manufacturing processes, i.e. total design cost of part count reductions.

Background Information

The RAND report R-4016-AF [34] is the most comprehensive report that attempts to quantify and develop a methodology for estimating an advanced composite materials cost in aircraft manufacturing. The report includes a basic background of advanced composite materials usage, advanced composite material types and characteristics, design and manufacturing processes, and cost information. The data for the report was gathered by an industry survey that requested aerospace contractors respond to questions on corporate history, material usage within aircraft, recurring and nonrecurring cost information, and general questions. Data was gathered for the time period from the late 1980s to the mid 1990s. The data from the late 1980s reflected the aerospace contractors' current experiences, while the mid 1990s data represented the aerospace contractors' best forecast of the future use of the materials in terms of design and manufacturing techniques [34]. The studies reported in chapters IV and V of the RAND report are of most interest to this paper. Chapter IV addresses the cost information responses, and Chapter V addresses the suggested methodology for assessing the effect of structural material composition on overall airframe cost [34]. The 2000s data was based on the cost implications of the prediction of production in airframe labor hours and technology in the upcoming decade [47]. Further, it provides distinct Cost Estimation Relationships (CERs) and material indexes for the nine cost elements with categories of nonrecurring and recurring costs as listed in Table 27.

Table 27 : Non-Recurring Cost and Recurring Cost Elements [34]

Non-Recurring Cost (Development)	**Recurring Cost (Production)**
Engineering Hours Cost	Engineering Hours Cost
Tooling Hours Cost	Tooling Hours Cost
Development Support Hours Cost	Manufacturing labor Hours Cost
Testing Hours Cost	Manufacturing Material Hours Cost
	Quality Assurance Hours Cost

The overwhelming reason that advanced composite material costs may be reduced for several of these cost elements is that design utilization will reduce part count and simplify the overall design process. Furthermore, autoclave and/or out-of-autoclave curing combined with lack of experienced advanced composite materials skill sets factor into higher composite cost. The RAND report developed CERs for two hypothetical fighter aircraft. The first aircraft was made of aluminum, but the composition of the second aircraft was 45% advanced composite materials and 55% aluminum. The advanced composite fighter was projected to have four percent higher nonrecurring costs according to the RAND report prediction [34]. This projection seems to be contrary to the expectations of lower non-recurring costs.

Composite Affordability Initiative (CAI)

An extensive amount of analytical and experimental work has been done in the mechanics of advanced composite materials and structures. Still there has been significant resistance by Original Equipment Manufacturers (OEM) to the use of the advanced composite materials for primary structures. Based on that, several composite manufacturers began to leave the composite materials business.

In the mid 1990s, the Air Force Research Laboratory (AFRL) observed that, despite the potential of the advanced composite materials to drastically reduce the airframe structural weight compared to conventional metal airframe structures, most aircraft companies were resistant or opposed to proceeding with advanced composite materials for new aircraft structures. Because of the lack of willingness from both the industry partners and the Air Force to adopt advanced composite materials in aircraft structures, AFRL and industry established the composite affordability initiative (CAI) to minimize the perceived risks of and barriers to using advanced composite materials [37]. This initiative was started because of an inadequate database for the advanced composite materials performance characteristics to enable designers to make reliable predictions of the LCC for advanced composite materials. Other contributing factors behind the decision to form the CAI were: lack of LCC data, lack of design data related to reliability aspects of composite structures, and a decrease in composite material manufacturing expertise because of not generating worthwhile business levels for advanced composite manufacturers [37].

Data Sources

The data set for this paper comes from an aerospace company which will be referred to as “Aerospace Company” to protect the company’s proprietary information. The Aerospace Company’s data set consists of aircraft prototype data and production data for development, manufacturing, and costs for a variety of metallic, composite, and combined military and civilian aircraft. This data set for the prototype is subdivided into various cost categories or variables which consist of design, design support, testing, tooling, logistics, manufacturing, and quality assurance touch labor hours. The data set also contains various aircraft empty weights, part counts, and average part sizes. While the data set has numerous potential research uses, we are primarily interested in the touch labor hours for design, design support, testing, tooling, manufacturing, quality assurance, part counts, empty weight, and average part sizes for the advanced composite materials and, combined with metallics, for military and civilian aircraft with sufficient sample numbers for the statistical analysis.

For the new data which are not included in the Aerospace Company's data set, we extrapolated the data for required variables by using the available relationships between them and empty weight. Due to the limitation of the data set related to large scale advanced composite materials parts and to the small amount of data on the aircraft from the Aerospace Company, we have generated more data items by using the Monte Carlo technique, which is available in the Microsoft EXCEL ®. We used the NORMINV function by taking the mean and the standard deviation to simulate the random normal variables. The NORMINV formula used is given below:

$$NORMINV\ (RAND\ (),\ MEAN,\ ST.DEV.) \tag{22}$$

Using this formula we calculated the numbers of the part counts as well as the touch labor hours for all variables of our interest. We used the Least Square Method (LSM) for all regression analysis.

Relationship Development

In this paper, we test many types of regression models to find out which one is the best line of fit. We find that, the power regression model is a "good fit" for most relationships. So, we use the power regression model for all relationships among our variables of interest because these relationships are not a straight line, but are gradually increasing or decreasing by a certain percentage.

Identify the Relationship

The relationship between part counts of the aircraft structure and the air vehicle empty weight is taken from the Defense Contractor Planning Report (DCPR) weight [8]. This weighing was done by the aerospace company using statistical methods. In order to create a relationship between touch labor hours and part counts, first we have to show that a relationship exists between the part count and DCPR weight. By using the data set which was provided by the aerospace company we can see that there is an increasing curve which shows a direct proportional relationship between part counts and DCPR weight. A significant correlation was found to exist, and the R^2 value, adjusted R^2 value, P-value, F-test and the number of elements (n) are shown in Figure 20, and Table 28.

Table 28 : Identified Relationships between Part Counts and DCPR Weight

R^2	Adjusted-R^2	P-value	F-Test	# of n
0.83	0.81	<0.0001	42.7528	11

The power relationship between the part count and DCPR weight is given as:

$$Part\ count = 55.517\ (DCPRwt)^{\wedge 0.5821} \tag{23}$$

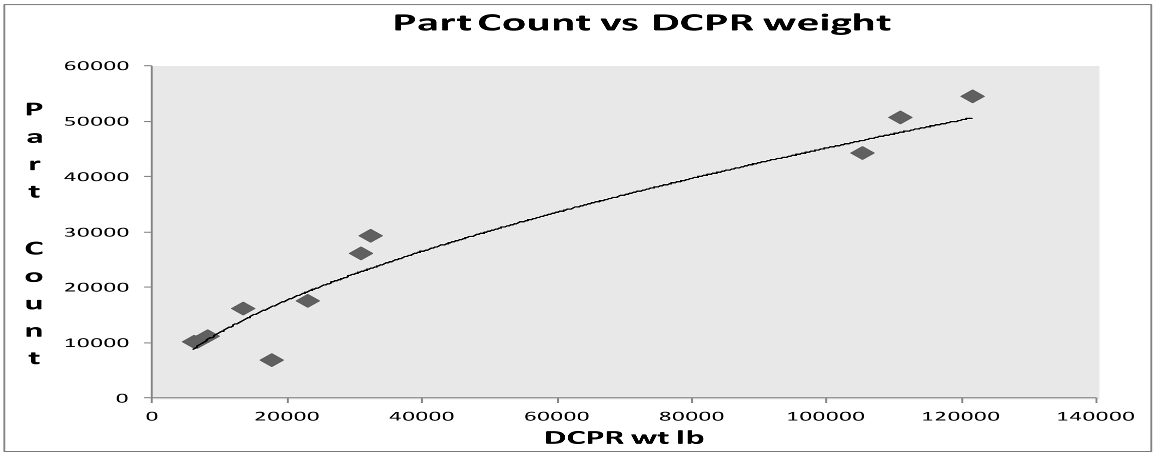


Figure 20 : Part Count vs. DCPR Weight

Next, we have to show that a relationship exists between the DCPR and empty weight. By using the data set which was provided by the Aerospace Company, we found that there is an increasing curve which shows a direct proportional relationship between DCPR weight and the empty weight. A significant correlation was found to exist, and the R^2 value, adjusted R^2 value, P-value, F-test and the number of elements (n) for these power relationship as shown in Figure 20, and in Table 29.

Table 29 : Identified Relationships between DCPR Weight and Empty Weight

R^2	Adjusted-R^2	P-value	F-Test	# of n
0.95	0.95	<0.0001	432.72	23

The power relationship between the DCPR weight and empty weight is given as:

$$DCPR\ wt = 1.568\ (EW)\ ^{\wedge 0.9019} \qquad (24)$$

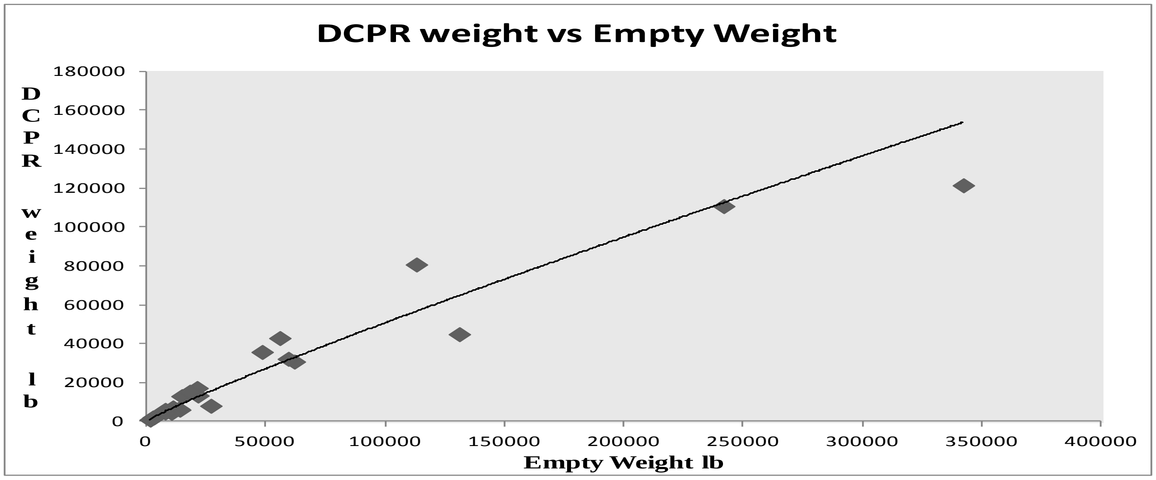


Figure 21 : DCPR weight vs. Empty Weight

The point on the right hand side is an original point which is part of the data set data relating to large-scale advanced composite parts; it is not possible to remove the point from the graph. This data point can be overly influential in the data set and driving the regression results. Also, we examine this possibility by removing this data point and observing the change on the whole regression results. The regression result of this process illustrated that while the data point strengthen the regression results, it is not influential because the overall regression results stayed statistically significant.

Then we have to show that a relationship exists between the touch labor hours and empty weight. By using a power function again, we build increasing curves which show direct proportional relationships between our variables of interest and empty weight which shows a highly correlated relationship as shown in Figure 22 and the R^2 values, adjusted R^2 values, P-values, F-test and the number of elements (n) for these power relationships shown in Table 30.

Table 30 : Identified Relationships between Touch Labor Hours and Empty Weight

Discipline Elements	R^2	Adjusted R^2	P-Value	F-Test	n
Design Hours	0.85	0.85	<0.0001	105.07	20
Design Support Hours	0.70	0.69	<0.0001	43.00	20
Testing Hours	0.62	0.60	<0.0001	29.10	20
Tooling Hours	0.74	0.73	<0.0001	51.89	20
Manufacturing Labor Hours	0.92	0.95	<0.0001	110.97	11
Quality Assurance Hours	0.84	0.82	<0.0001	46.25	11

As shown in Table 30, the adjusted R^2 values for the design hours, tooling hours, manufacturing labor hours, and quality assurance hours are relatively high and the p-values are very low. We can then say that the relationships are statistically significant. The design support hours and testing hours have low adjusted R^2 values and the p-values are less than 0.05. This indicates that the power model does represent a statistically significant relationship; however, there may be other factors that could help explain more of the variation in our data. Given the relationship is statically significant, we will continue to include these factors in our analysis.

The quantified power relationships between our variables of interest and the empty weight are given below:

$$Design\ Hours = 7.0191\ (EW)^{\wedge 1.117} \quad (25)$$

$$\textit{Design Support Hours} = 15.104\ (EW)^{\wedge 1.0056} \quad (26)$$

$$\textit{Testing Hours} = 296.43\ (EW)^{\wedge 0.7920} \quad (27)$$

$$\textit{Tooling Hours} = 0.3022\ (EW)^{\wedge 1.4075} \quad (28)$$

$$\textit{Manufacturing Labor Hours} = 309.91\ (EW)^{\wedge 0.7587} \quad (29)$$

$$\textit{Quality Assurance Hours} = 5.9327\ (EW)^{\wedge 0.9178} \quad (30)$$

The discipline variables of touch labor hour show that the heavy empty weight had more hours (refer to Figure 22). This demonstrates that the relationship does exist between empty weight and design hours, design support hours, testing hours, tooling hours, manufacturing labor hours, and quality assurance hours. In fact, these variables increase as the empty weight is increasing.

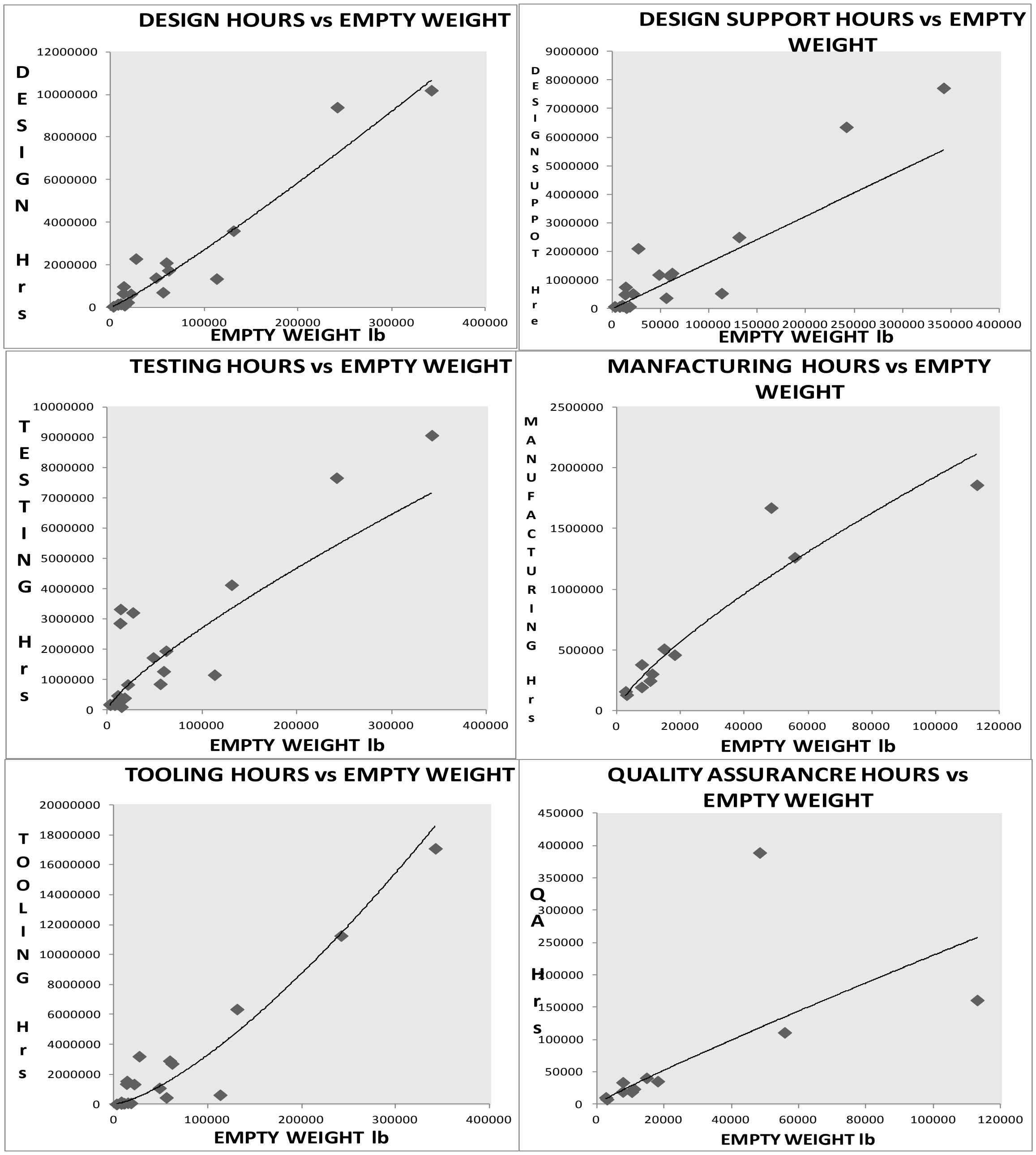


Figure 22 : Touch Labor Hours vs. Empty Weight

As the limitation of the data set and the lack of data relating to large-scale advanced composite parts, it is not possible to remove the original data points on the top and on the right side of the graphs. These original data points can be overly influential in the data set and driving the regression results. We examine this possibility by removing these original data points and observing the change on the whole regression results. The regression result of this process illustrated that while the data points strengthen the regression results, they are not influential because the overall regression results stayed statistically significant.

Then we have to show that a relationship exists between the average touch labor hours and average part sizes. By using formulas (25), (26), (27), (28), (29), and (30), we calculate the missing data for touch labor hours and by using formulas (23) and (24), we calculate the missing part counts. Then we calculate the ratio of the touch labor hours by dividing the touch labor hours by the empty weight and then calculate the average part sizes by dividing the empty weight by part counts for the new models of military and civilian aircraft as shown in Table 31.

Table 31 : Average Part Sizes and Average Touch Labor Hours

Model ID	Average PartSize (lbs EW/part)	Design (hrs/lb EW)	Design Support (hrs/lb EW)	Testing (hrs/lbs EW)	Tooling (hrs/lb EW)	Mfg (hrs/lb EW)	Quality Assurance (hrs/lb EW)
X1	2.79	17.08	15.76	61.00	6.69	49.51	3.18
X2	2.80	17.27	15.77	59.80	6.96	48.38	3.15
X3	2.80	17.27	15.77	59.80	6.96	48.38	3.15
X4	2.81	17.41	15.77	58.98	7.14	47.62	3.13
X5	3.15	22.21	15.96	38.23	16.71	28.80	2.64
X6	3.17	22.50	15.97	37.37	17.47	28.05	2.62
X7	3.22	23.38	16.00	34.90	19.98	25.90	2.55
X8	3.23	23.40	16.00	34.85	20.03	25.86	2.55
X9	3.30	24.48	16.03	32.17	23.43	23.57	2.47
X10	3.36	25.46	16.06	30.00	26.87	21.73	2.40
X11	3.43	26.63	16.10	27.70	31.42	19.81	2.32
X12	3.54	28.48	16.15	24.58	39.70	17.25	2.22
X13	3.64	30.18	16.20	22.17	48.59	15.30	2.13
X14	3.68	30.93	16.22	21.23	52.92	14.55	2.09
X15	3.74	5.90	20.86	77.19	17.89	26.82	2.97
X16	3.81	33.36	16.27	18.56	68.85	12.45	1.98
X17	4.80	5.80	12.13	41.15	6.70	25.92	4.38
X18	5.51	4.47	10.25	44.78	21.54	19.83	1.58
X19	11.10	6.73	4.40	16.55	2.78	2.13	1.21
X20	19.44	0.06	5.02	1.52	0.09	1.61	0.37

The data shown in Figure 23 reinforce the inversely proportional relationships between our variables of interest and average part sizes. The corresponding R^2 values, adjusted R^2 values, P-values, F-test and the number of element (n) for these power relationships are shown in Table 32.

Table 32 : Identified the Relationships between Touch Labor Hours and Part Size

Discipline Elements	R2	Adjusted R2	P-Value	F-Test	# of n
Design Hours	0.73	0.72	<0.0001	49.09	20
Design Support Hours	0.86	0.85	<0.0001	107.15	20
Testing Hours	0.67	0.65	<0.0001	36.24	20
Tooling Hours	0.53	0.50	<0.0001	20.02	20
Manufacturing Labor Hours	0.86	0.85	<0.0001	107.60	20
Quality Assurance Hours	0.77	0.76	<0.0001	61.14	20

As shown in Table 32, the adjusted R^2 values for the design hours, design support hours, testing hours, manufacturing labor hours, and quality assurance hours are relatively high, and the p-values are very low. Therefore, the relationships are statistically significant. The tooling hours has a low adjusted R^2 value, however, again since the p-value is less than 0.05, we still can say the relationship is statistically significant and will use it for the rest of our analysis.

The quantified power relationships between our variables of interest and average part sizes are shown in the following formulas:

$$\text{Design Hours} = 401.02\ (\text{Average Part Sizes})\ ^{\wedge -2.4851} \quad (31)$$

$$\text{Design Support Hours} = 38.64\ (\text{Average Part Sizes})\ \wedge^{-0.7454} \tag{32}$$

$$\text{Testing Hours} = 204.61\ (\text{Average Part Sizes})\ \wedge^{-1.3836} \tag{33}$$

$$\text{Tooling Hours} = 255.197\ (\text{Average Part Sizes})\ \wedge^{-2.1535} \tag{34}$$

$$\text{Manufacturing Labor Hours} = 207.23(\text{Average Part Sizes})\wedge^{-1.7126} \tag{35}$$

$$\text{Quality Assurance Hours} = 7.855\ (\text{Average Part Sizes})\wedge^{-0.9072} \tag{36}$$

The cost variable elements show that larger average part sizes have fewer hours per pound, and advanced composite materials have additional advantages over materials for design and manufacturing large part sizes. Figure 23 shows uniformly reducing cost slope trends. These touch labor hours fall as the quantity of the average part sizes increase.

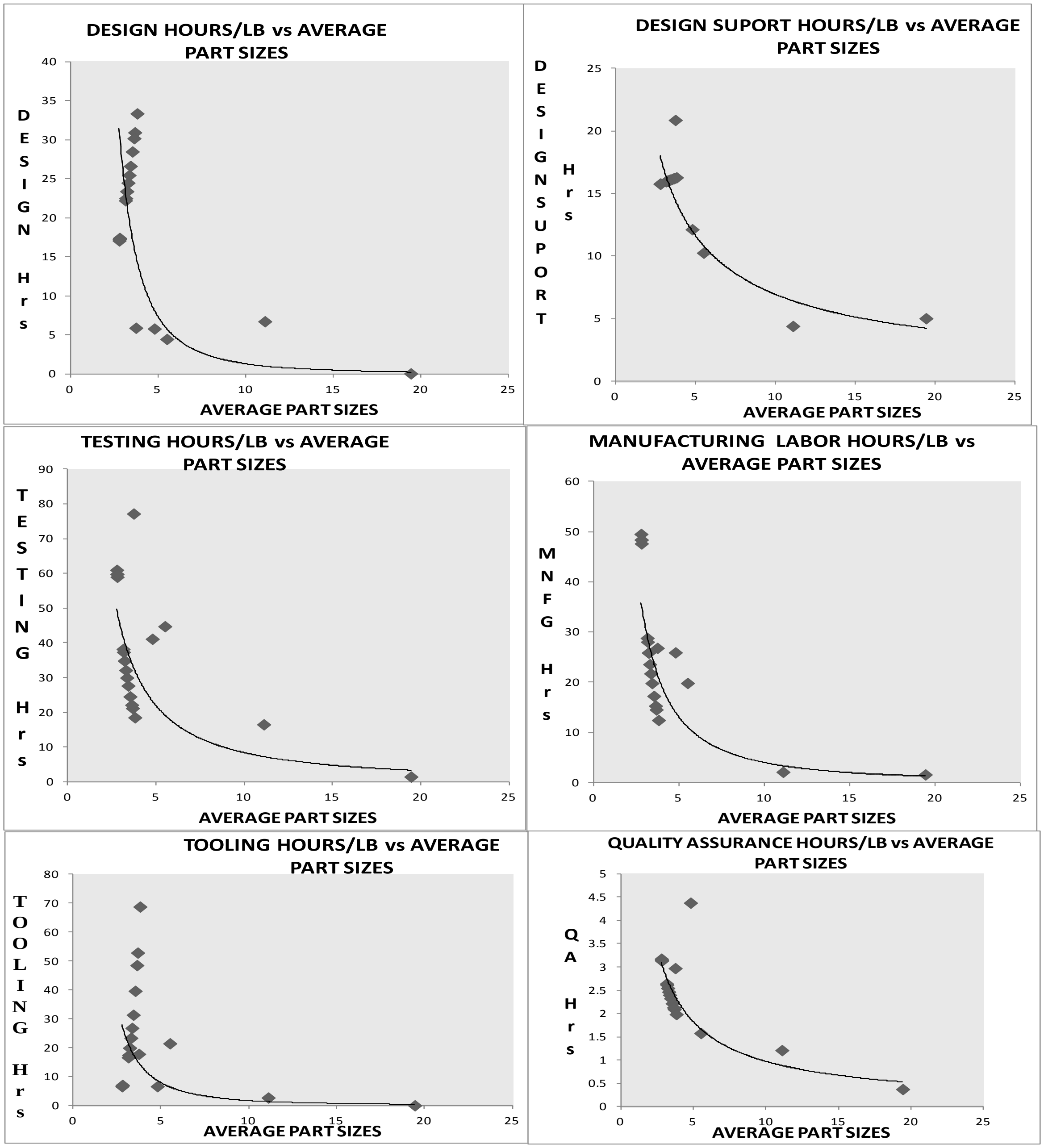


Figure 23 : Average Touch Labor Hours vs. Average Part Size

Again as the limitation of the data set and the lack of data relating to large-scale advanced composite parts, it is not possible to remove the data points on the top and on the left side of the graphs. These data points can be overly influential in the data set and driving the regression results. We examine this possibility by removing these data points and observing the change on the whole regression results. The regression result of this process illustrated that while the data points strengthen the regression results, they are not influential because the overall regression results stayed statistically significant.

We use formulas (23) and (24) and by multiplying formula (23) with the estimated percentage of the part count. Then we calculate the new average part size by dividing the empty weight by the new part count. By using formulas (30), (31), (32), (33), (34), and (35), we calculate the new touch labor hours of our desired variables. After that, we calculate the adjusted ratio of the cost reduction of our desired variables by dividing the new calculated touch labor hours by the old ones. To determine how these equations work, we can use the empty weight of ACCA, 21,080 lb, and calculate the value in Table 33 and from that we generate curves for the relationships between the cost discipline variables and the average part counts as shown in Figure 24. We see that there are increasing curves which show a direct proportional relationship between percentages of cost variables and percentages of average part counts as shown in Figure 24.

As shown in Figure 24, the data curves are more realistic if they are linear or polynomial, but they appear as power relationships. The cost discipline variable data curve shapes are not the same, the design hours and quality assurance hours having the steepest slope and appearing almost linear. On the other hand, design hours and quality assurance hours will increase as the part size increase, due to the number of parts, whether larger or smaller. However, we still confirm that the design support hours, testing hours, tooling hours, and manufacturing labor hours have a power relationship. There also will be an optimal point in the part size reduction at which the design support hours, testing hours, tooling hours, and manufacturing labor hours will start to decrease, but not in the same way as do the design hours and quality assurance hours.

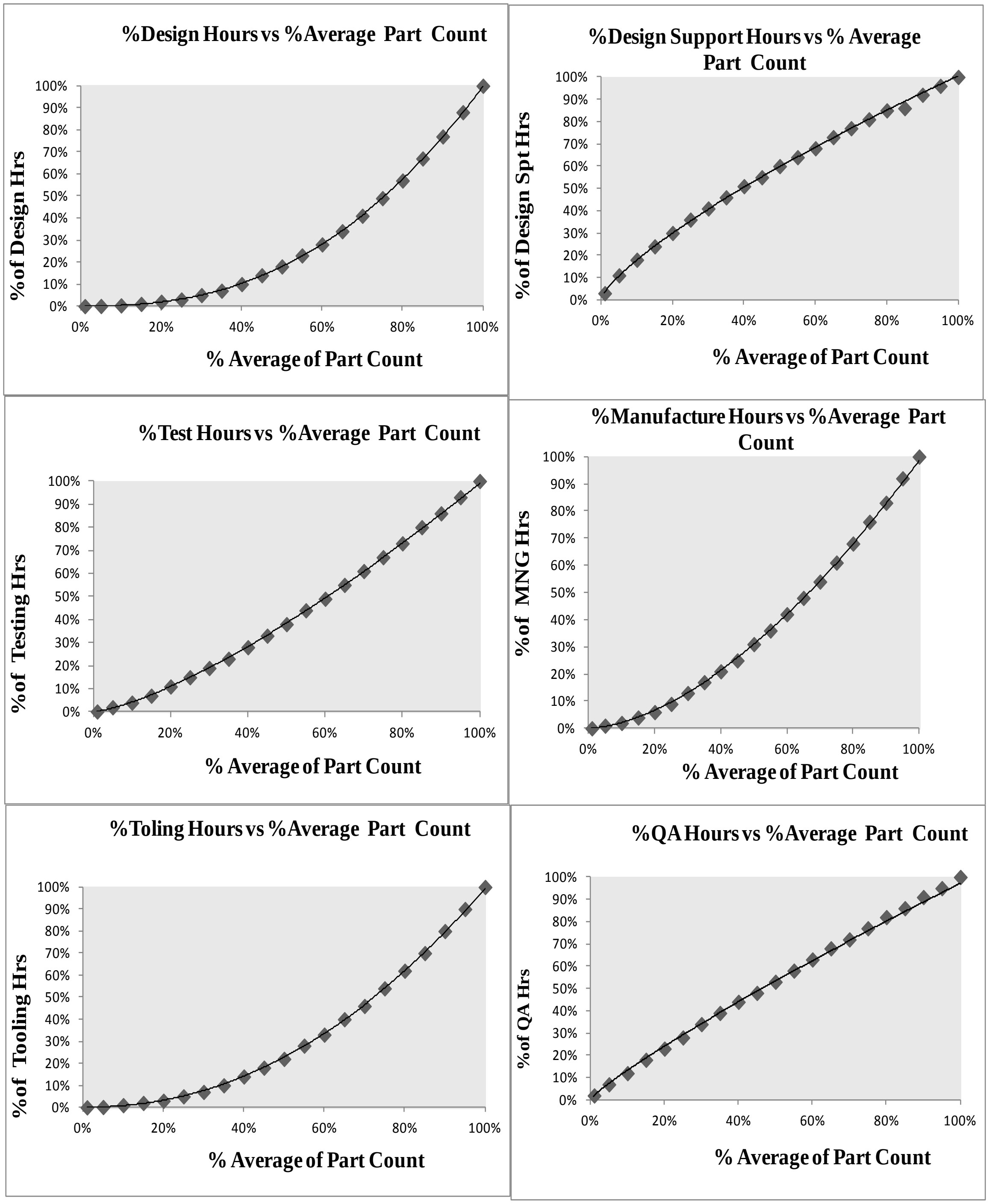


Figure 24 : Percentage Touch Labor Hours vs. Percentage Average Part Count

Table 33 : Adjusted Ratios of Touch Labor Hours and Part Counts

% Part Count	% Design Hours	%Design Support Hours	% Testing Hours	%MFG Labor Hours	% Tooling Hours	%Quality Assurance Hours
100%	100%	100%	100%	100%	100%	100%
95%	88%	96%	93%	92%	90%	95%
90%	77%	92%	86%	83%	80%	91%
85%	67%	86%	80%	76%	70%	86%
80%	57%	85%	73%	68%	62%	82%
75%	49%	81%	67%	61%	54%	77%
70%	41%	77%	61%	54%	46%	72%
65%	34%	73%	55%	48%	40%	68%
60%	28%	68%	49%	42%	33%	63%
55%	23%	64%	44%	36%	28%	58%
50%	18%	60%	38%	31%	22%	53%
45%	14%	55%	33%	25%	18%	48%
40%	10%	51%	28%	21%	14%	44%
35%	7%	46%	23%	17%	10%	39%
30%	5%	41%	19%	13%	7%	34%
25%	3%	36%	15%	9%	5%	28%
20%	2%	30%	11%	6%	3%	23%
15%	1%	24%	7%	4%	2%	18%
10%	0.33%	18%	4%	2%	1%	12%
5%	0.06%	11%	2%	1%	0.16%	7%
1%	0.002%	3%	0.17%	0.04%	0.01%	2%

Classify the Relationship

So the highest reduction in hours per pound occurs at the higher right side of the graphs. We conclude that the relationships that could be quantified with a reduction in the part counts would follow a reduction in the touch labor hours of our interested variables.

Quantify the Relationship

We can quantify these relationships by the fit of the lines. The fit of the lines is as follows:

For design support hours (cost) or non-recurring engineering hours:

Part Count Percentage Reduction for Design Support Hours (H_{NREDS} %):

$$H_{NREDS}\% = a * PCPR^{\wedge b} \tag{37}$$

For tooling hours (cost) or non-recurring and recurring tooling hours:

Part Count Percentage Reduction for Tooling Hours (H_{NRRTL} %):

$$H_{NRRTL}\ \% = c * PCPR^{\wedge d} \tag{38}$$

For testing hours (cost) or non-recurring testing hours:

Part Count Percentage Reduction for Testing Hours (H_{NRT} %):

$$H_{NRT}\ \% = e * PCPR^{\wedge f} \tag{39}$$

For design hours (cost) or recurring engineering hours:

Part Count Percentage Reduction for Design hours (H_{RED} %):

$$H_{RED}\ \% = g * PCPR^{\wedge h} \tag{40}$$

For manufacturing labor hours (cost) or recurring manufacturing labor hours:

Part Count Percentage Reduction for Manufacturing Labor Hours (H_{RML} %):

$$H_{RML}\ \% = i * PCPR^{\wedge j} \tag{41}$$

For Quality Assurance hours (cost) or recurring Quality Assurance hours:

Part Count Percentage Reduction for Quality Assurance Hours (H_{RQA} %):

$$H_{RQA}\,\% = k * PCPR^{\wedge l} \quad (42)$$

Where the variables *(a-l)* represent the coefficients of the line, and PCPR is the variable created to represent the part count percentage reduction.

Conclusions

The primary objectives of this paper were to determine and investigate the relationships between the part counts and the design, design support, tooling, testing, manufacturing labor, and quality assurance touch labor hour for the development and production of the LCC. The relationships were found and proven by first identifying the relationship between the part counts DCPR weight, then between DCPR weight and empty weight, next between touch labor hours and empty weight, then between average touch labor hours and average pat size. This allows us to relate touch labor hour percentage reductions and part count percentage reductions. We then quantified, and classified these relationships accordingly.

Future Research

This work is in progress and additional results will be provided in forthcoming publications. The next publication will show how we will implement the relationships between the part counts and the design, design support, tooling, testing, manufacturing labor, and quality assurance touch labor hour costs for the development and production of the LCC in RAND CERs and update the CERs. In addition, we will examine the effects of these relationships and also the impact the learning curve (LC) on the LCC.

VI. Model Development

Introduction

The purpose of this research is to investigate and improve the methods for evaluating the use of advanced composite materials in airframe structures. Chapter V classified and quantified the relationships between the part counts and the touch labor hours (design hours, design support hours, testing, tooling, manufacturing labor hours, and quality assurance hours) [2]. This chapter develops and proposes cost estimation relationships (CERs) that could be useful in predicting the touch labor hours. These relationships are incorporated into the AFRL LCC model and sensitivity analyses are performed for several scenarios. Finally, learning curve (LC) impacts are applied to the LCC model using new scenarios designed for the new model and a sensitivity analysis for LC performed.

Updating the Cost Estimation Relationships (CERs)

First, the RAND CER formulas are examined (1),(2),(4),(5),(6),(7), and (9) [8, 23, 26, 27, 33, 34, and 47]. Then the material factor formulas (11), (12), (13), (14), (15), and (16) [47] are implemented by using the quantified relationship formulas (37), (38), (39), (40), (41), and (42) [2] and added to the original RAND's CER formulas. Next, the current methodology for calculating the costs of non-recurring engineering, non-recurring tooling, non-recurring testing, recurring engineering, recurring tooling, recurring manufacturing labor, and recurring quality assurance are verified and integrated into the updated CERs.

Non-Recurring Engineering (Design Support) CER

Figure 25 illustrates the inputs that comprise the cost estimation relationship of the non-recurring engineering (CER_{NREDS}). From formula (1), the empty weight (EW) and maximum speed (MS) are the two main cost drivers in the RAND CERs. Formula (11) is the material cost factor NREDS which is correlated to aircraft using large-scale advanced composite materials. The cost relationship is illustrated in Figure 25, where C_{NREDS} is calculated by multiplying H_{NREDS}% from formula (37) by the respective labor rate (LR). H_{NREDS}% reflects the part count percentage reduction for non-recurring engineering hours and C_{NREDS} represents the cost of non-recurring engineering. The new H_{NREDS}% is an additional factor to the existing RAND CERs. Once the parametric values are determined, the suggested changes can be made. The enhanced CER cost element for the non-recurring engineering (design support) is:

$$CER_{NREDS} = 0.0168 * (EW)^{\wedge 0.747} * (MS)^{\wedge 0.800} * NREDS * C_{NREDS} \qquad (43)$$

Where:

$$C_{NREDS} = H_{NREDS}\% * LR_{NREDS} \qquad (44)$$

Figure 25 : Cost Estimation Relationship of the Non-Recurring Engineering

Non-Recurring Tooling CER

Figure 26 illustrates the inputs that comprise the cost estimation relationship of the non-recurring tooling (CER_{NRTL}). From formula (2), the empty weight (EW) and maximum speed (MS) are the two main cost drivers in the RAND CERs. Formula (13) is the material cost factor NRTL which is correlated to aircraft using large-scale advanced composite materials. The cost relationship is illustrated in Figure 26, where C_{NRTL} is calculated by multiplying H_{NRRTL}% from formula (38) by the respective labor rate (LR). H_{NRRTL}% reflects the part count percentage reduction for non-recurring and recurring tooling hours and C_{NRTL} represents the cost of non-recurring and recurring tooling. The new H_{NRRTL}% is an additional factor to the existing RAND CERs. Once the parametric values are determined, the suggested changes can be made. The suggested enhanced CER cost element for the non-recurring tooling is:

$$CER_{NRTL} = 0.0186 * (EW)^{\wedge 0.810} * (MS)^{\wedge 0.579} * NRTL * C_{NRTL} \qquad (45)$$

Where:

$$C_{NRTL} = H_{NRRTL}\% * LR_{NRTL} \qquad (46)$$

Figure 26 : Cost Estimation Relationship of the Non-Recurring Tooling

Non-Recurring Testing CER

Figure 27 illustrates the inputs that comprise the cost estimation relationship of the non-recurring tooling (CER_{NRTL}) non-recurring testing (CER_{NRT}). From formula (4), the empty weight (EW) and maximum speed (MS) are the two main cost drivers in the RAND CERs. TEST is the cost driver related to the number of flight test aircraft using large-scale advanced composite materials. The cost relationship is illustrated in Figure 27, where C_{NRT} is calculated by multiplying H_{NRT}% from formula (39) by the respective labor rate (LR). H_{NRT}% reflects the part count percentage reduction for non-recurring testing hours and C_{NRT} represents the cost of non-recurring testing. The new H_{NRT}% is an additional factor to the existing RAND CERs. Once the parametric values are determined, the suggested changes can be made. The suggested enhanced CER cost element for the non-recurring testing is:

$$CER_{NRT} = 1.81 * (EW)^{\wedge 0.325} * (MS)^{\wedge 0.822} * (TEST)^{\wedge 0.1.21} * C_{NRT} \quad (47)$$

Where:

$$C_{NRT} = H_{NRT}\% * LR_{NRT} \quad (48)$$

Figure 27 : Cost Estimation Relationship of the Non-Recurring Testing

Recurring Engineering (Design) CER

Figure 28 illustrates the inputs that comprise the cost estimation relationship of the recurring engineering (CER_{RED}). From formula **(**5), the empty weight (EW) and maximum speed (MS) are the two main cost drivers in the RAND CERs. Formula (12) is the material cost factor RED which is correlated to aircraft using large-scale advanced composite materials. The cost relationship is illustrated in Figure 28, where C_{RED} is calculated by multiplying H_{RED}% from formula (40) by the respective labor rate (LR). H_{RED}% reflects the part count percentage reduction for recurring engineering hours and C_{RED} represents the cost of non-recurring engineering. The new H_{RED}% is an additional factor to the existing RAND CERs. Once the parametric values are determined, the suggested changes can be made. The suggested enhanced CER cost element for the recurring engineering (design) is:

$$CER_{RED(100)} = 0.000306 * (EW)^{\wedge 880} * (MS)^{\wedge 0.1.12} * RED * C_{RED} \quad (49)$$

Where:

$$C_{RED} = H_{RED}\% * LR_{RED} \quad (50)$$

Figure 28 : Cost Estimation Relationship of the Recurring Engineering

Recurring Tooling CER

Figure 29 illustrates the inputs that comprise the cost estimation relationship of the recurring tooling (CER_{RTL}). From formula (6), the empty weight (EW) and maximum speed (MS) are the two main cost drivers in the RAND CERs. Formula (14) is the material cost factor RTL which is correlated to aircraft using large-scale advanced composite materials. The cost relationship is illustrated in Figure 29, where C_{NREDS} is calculated by multiplying H_{NRRTL}% from formula (38) by the respective labor rate (LR). H_{NRRTL}% reflects the part count percentage reduction for recurring tooling hours and C_{RTL} represents the cost of recurring tooling. The new H_{NRRTL}% is an additional factor to the existing RAND CERs. Once the parametric values are determined, the suggested changes can be made. The suggested enhanced CER cost element for the recurring tooling is:

$$CER_{RTL(100)} = 0.00787 * (EW)^{\wedge 0.707} * (MS)^{\wedge 0.813} * RTL * C_{RTL} \quad (51)$$

Where:

$$C_{RTL} = H_{RTL}\% * LR_{RTL} \quad (52)$$

Figure 29 : Cost Estimation Relationship of the Recurring Tooling

Recurring Manufacturing Labor CER

Figure 30 illustrates the inputs that comprise the cost estimation relationship of the recurring manufacturing labor (CER_{RML}). From formula (7), the empty weight (EW) and maximum speed (MS) are the two main cost drivers in the RAND CERs. Formula (15) is the material cost factor RML which is correlated to aircraft using large-scale advanced composite materials. The cost relationship is illustrated in Figure 30, where C_{NREDS} is calculated by multiplying H_{NREDS}% from formula (41) by the respective labor rate (LR). H_{RML}% reflects the part count percentage reduction for recurring manufacturing labor hours and C_{RML} represents the cost of recurring manufacturing labor. The new H_{RML}% is an additional factor to the existing RAND CERs. Once the parametric values are determined, the suggested changes can be made. The suggested enhanced CER cost element for the recurring manufacturing labor is:

$$CER_{RML(100)} = 0.141 * (EW)^{\wedge 0.820} * (MS)^{\wedge 0.484} * RML * C_{RML} \quad (53)$$

Where:

$$C_{RML} = H_{RML}\% * LR_{RML} \quad (54)$$

Figure 30 : Cost Estimation Relationship of the Recurring Manufacturing Labor

Recurring Quality Assurance CER

Figure 31 illustrates the inputs that comprise the cost estimation relationship of the recurring quality assurance (CER_{RQA}). From formula (9), the empty weight (EW) and maximum speed (MS) are the two main cost drivers in the RAND CERs. Formula (16) is the material cost factor RQA which is correlated to aircraft using large-scale advanced composite materials. The cost relationship is illustrated in Figure 31, where C_{RQA} is calculated by multiplying H_{RQA}% from formula (42) by the respective labor rate (LR). H_{RQA}% reflects the part count percentage reduction for recurring quality assurance hours and C_{RQA} represents the cost of recurring quality assurance. The new H_{RQA}% is an additional factor to the existing RAND CERs. Once the parametric values are determined, the suggested changes can be made.

The suggested enhanced CER cost element for the recurring quality assurance is:

$$CER_{RQA(100)(Cargo)} = 0.076 * (CER_{RML(100)}) * RQA * C_{RQA} \quad (55)$$

Where:

$$C_{RQA} = H_{RQA}\% * LR_{RQA} \quad (56)$$

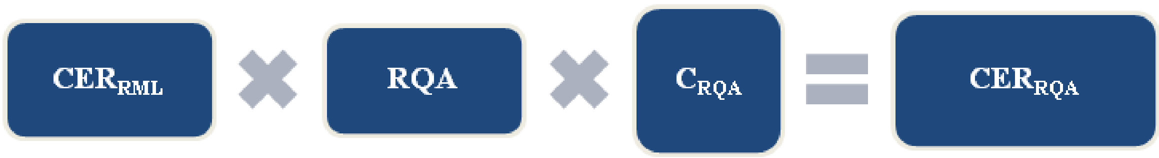


Figure 31 : Cost Estimation Relationship of the Recurring Quality Assurance

As shown in Figure 25 to Figure 31, RAND uses empty weight (EW) and maximum speed (MS) as two cost drivers of the baseline of CERs for calculating the cost of metal aircraft structures. The material cost factors are correlated into RAND CERs as a penalty for using large-scale advanced composite aircrafts. However, the new touch labor hours cost factors are additional factors to the existing RAND CERs to calculate the cost of advanced composite aircraft structures.

Employ the Relationship

Figure 24 and Table 33 [2] conclusively show that the reduction percentage in design support hours, a piece-based process, is affected the most by the reduction percentage of part counts. Reduction percentage in quality assurance hours is next since fewer parts need to be checked. Testing, most likely, will also be strongly affected by the reduction percentage of part counts since fewer parts reduce both the sheer number of parts and the number of different types of parts that need to be tested. Reductions percentage in total manufacturing hours is also affected by the reductions percentage of part counts, but not as significantly. It is not realistic to think that a vehicle made of one single part would necessarily have the largest manufacturing labor hour reduction. Similarly, the number of parts may lessen tooling requirements. However, complexity increases with part counts, thereby mitigating some of the likely labor hour reductions that come with fewer parts. Design of the vehicle in total is necessary regardless of the number of parts used; however, there is likely some kind of part count effect. Evaluation of the preliminary results appears to support this conclusion.

The relationship between the touch labor hours and part counts, as illustrated by the fit line (see Figure 24) has a universal positive slope. For part counts percentage reductions, 100% of the established value falls at the upper right of the figure. Hence, the minimum reductions take place at the opposite corner or at the bottom left of the figure because of the zero labor hours used. Thus, the relationship appears to have some quantifiable percentage reduction in touch labor hours because of the respective reduction in total part count that is not used. However, clearly, if all parts are eliminated, then there is no cost for LCC.

This research has determined that there is a quantifiable relationship between percentage reductions in part counts and percentage reductions in touch labor hours [2]. The effect of part count percentage reductions permeates the development and production phases of the aircraft LCC. The next step is to incorporate these relationships into the AFRL LCC model.

AFRL LCC

The current AFRL LCC model has notional static values integrated into the model for non-recurring engineering hours (design support hours), non-recurring tooling hours, non-recurring testing hours (contractor test), recurring engineering hours (design hours), recurring tooling hours, recurring manufacturing labor hours, and recurring quality assurance. This research proposes to replace the static values for all touch labor hours with calculated values based on collected data and the updated CERs.

Part count reductions or part count reduction factors are not currently taken into consideration in the AFRL LCC model. Since the reduction in part counts is not factored into the cost elements, it has no effect on the final LCC estimate. Based on the relationship demonstrated by this research between part counts and touch labor hours cost elements, it is reasonable to assert that as part counts decrease, the touch labor hours costs will also decrease.

Integrating the updated CERs into the AFRL LCC model is straightforward for touch labor hours since the static factors are in the model; the new updated CERs are simply substituted for the static factors. With these new CERs for touch labor hours integrated into the model, the effect that part count reductions have on the AFRL LCC model can be determined. This is achieved by generating a LCC estimate that uses the new updated CERs values and comparing the output to a LCC estimate which did not incorporate reduction percentage in part counts.

AFRL LCC Model Assumptions

The AFRL LCC model, built with Microsoft EXCEL ®, incorporates some of the cost estimation relationships (CERs) for military aircraft. The aircraft estimate is broken into three major components: airframe, engines, and avionics. The airframe CERs, for both development and production, were initially developed for the Air Force by RAND [34]. The simplified Operation and Support (O&S) costs are from Raymer's work [33]. The materials cost factors are from [47]. The basic ACCA data is from [48].The base year (BY) for labor rates (LR) (in dollars) in the AFRL LCC model is 2006. An inflation index is included to facilitate changing to a different base year. This model also adds development and production costs for engines and avionics. There are separate Microsoft EXCEL ® spreadsheets for development, production, O&S, other costs, and LCC. All of the verification scenarios assume that the aircraft is being made from largely composite materials in order to achieve a large part count decrease.

AFRL LCC Model Scenarios

First Scenario

The first scenario is a simple scenario based on an existing LCC estimation with the current RAND CERs. The current methodology for determining the cost of the elements of interest for touch labor hours is analyzed and resulting recommended changes are integrated into the current RAND CERs to produce new CERs. The scenario is for a 100-unit fleet of drones with an expected 25-year life cycle. For the scenario, a largely composite aircraft 97% (with 80% graphite/epoxy, and 17% other (taken as carbon-epoxy)) was selected to highlight the impacts of reduced part counts. All dollars are in BY 2014. A zero percent part count reduction for ACCA was chosen for this scenario. Integrating a zero percent part count reduction into the LCC model, the part counts percentage reductions (PCPR*)* CERs gives a value of 0% for H_{NRES}%, 0% for H_{NRRTL}%, 0% for H_{NRT}%, 0% for H_{RED}%, 0% for H_{RML}%, and 0% for H_{RQA}%. This scenario does not necessarily reflect reality; rather, it provides a numerical value base for comparison. Note that the values are related only in their relative magnitude. In this scenario, not every input labor element cost in the LCC model is discussed, only enough of the significant inputs to make this scenario clear to the reader.

The analysis of the AFRL LCC model starts with a brief perspective on the cost drivers for the total LCC. Figure 32 represents the relative costs within the total LCC model. The acquisition cost for development and procurement represents almost 61% (15.61% Development and 45.50% Productions) of the total LCC model. Development and procurement are the two elements of interest for this research. The model development shows how the new CERs affect these two cost elements.

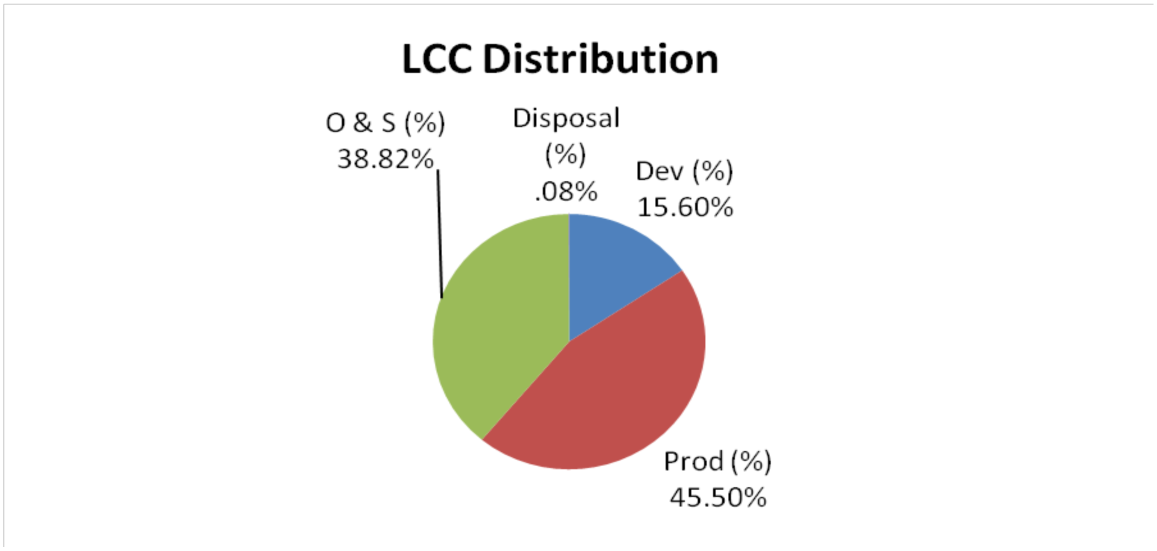


Figure 32 : Life Cycle Cost Distribution

This research analyzed the costs of the touch labor hours for both the development and production phases, using the first scenario. As mentioned before, non-recurring engineering hours (or design support hours), non-recurring tooling hours, and testing hours occur during the development phase of the LCC model. Recurring engineering hours (or design hours), tooling hours, manufacturing labor hours, and quality assurance hours occur during the production phase. In total, these touch labor hours elements represent approximately 24% of the total LCC model's projected costs. In particular, non-recurring engineering hours (design support hours), non-recurring tooling hours, and testing hours cover approximately 5%, 1%, and 1% of the total LCC model's projected costs respectively. Also, recurring engineering hours (design hours), tooling hours, manufacturing labor hours, and quality assurance represent approximately

4%, 2%, 10%, and 1% of the total LCC model's projected costs respectively. Figure 33 shows the relationship of the cost elements in the LCC model. The highlighted (purple) elements within the figure are the elements of interest to this research.

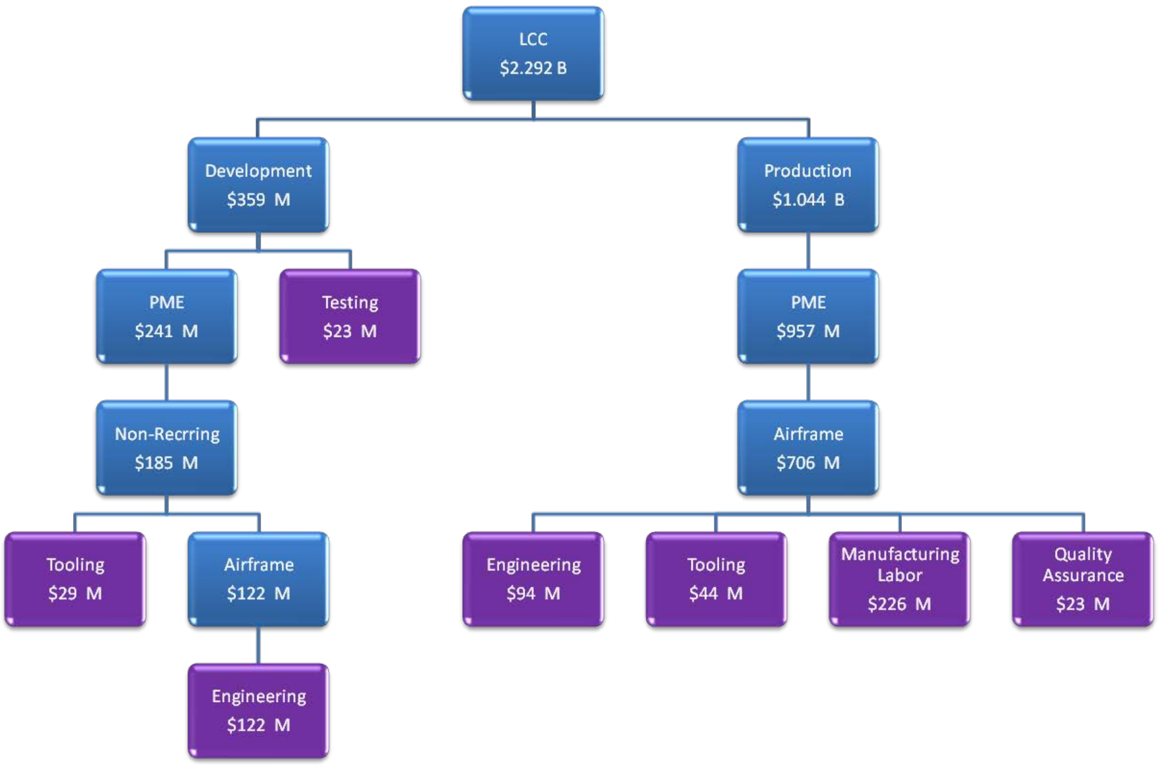


Figure 33 : Cost Elements Life Cycle Cost Series

Only those elements of interest indicated in Figure 33 are presented, these elements (highlighted cells) are followed through the entire LCC model.

Second Scenario:

The effect that the new CERs have on the LCC model cost estimates for the indicated scenario is examined. As was mentioned earlier, it is assumed for this scenario that the aircraft will be made from largely composite materials in order to achieve a large part count decrease. This scenario is based on the first scenario but with a 50% part count reduction for ACCA. Integrating a 50% part count reduction into the LCC model, the part counts percentage reductions (PCPR*)* CERs gives an approximate value of 60% for H_{NRES}%, 22% for H_{NRRTL}%, 38% for H_{NRT}%, 18% for H_{RED}%, 31% for H_{RML}%, and 53% for H_{RQA}%.

The effect that the new CERs have on the LCC projected costs for our scenario is now analyzed. As illustrated above, non-recurring engineering (design support) decreased from $122M to $75M; or 49% in saving from the original value. Similarly, non-recurring tooling decreased from $29M to $7M; non-recurring testing decreased from $23M to $9M; recurring engineering (design) decreased from $94M to $17M; recurring tooling decreased from $44M to $10M; recurring manufacturing labor decreased from $226M to $70M; and quality assurance decreased from $23M to $1M. The reduction in part counts has a direct effect on the variables of interest and the saving percentage as shown in the Table 34.

Table 34 : Life Cycle Cost Differences

Cost Estimation Relationships (CERs)	Non-Recurring Engineering Design Support	Non-Recurring Tool	Non-Recurring Test	Recurring Engineering Design	Recurring Tool	Recurring MFG Labor	Recurring Q A
Original CERs	$122 M	$29 M	$23 M	$94 M	$44 M	$226 M	$23 M
Updated CERs	$73 M	$7 M	$9 M	$17 M	$10 M	$70 M	$1 M
Differences $	$49 M	$22 M	$14 M	$77 M	$34 M	$156 M	$22 M
Differences %	40%	76%	61%	82%	77%	69%	96%

The results from implementing the relationships in the LCC model are striking. The effect of these decreases is seen throughout the LCC model and represents significant cost savings. Figure 34 is identical to Figure 33, but reflects the new updated CERs values.

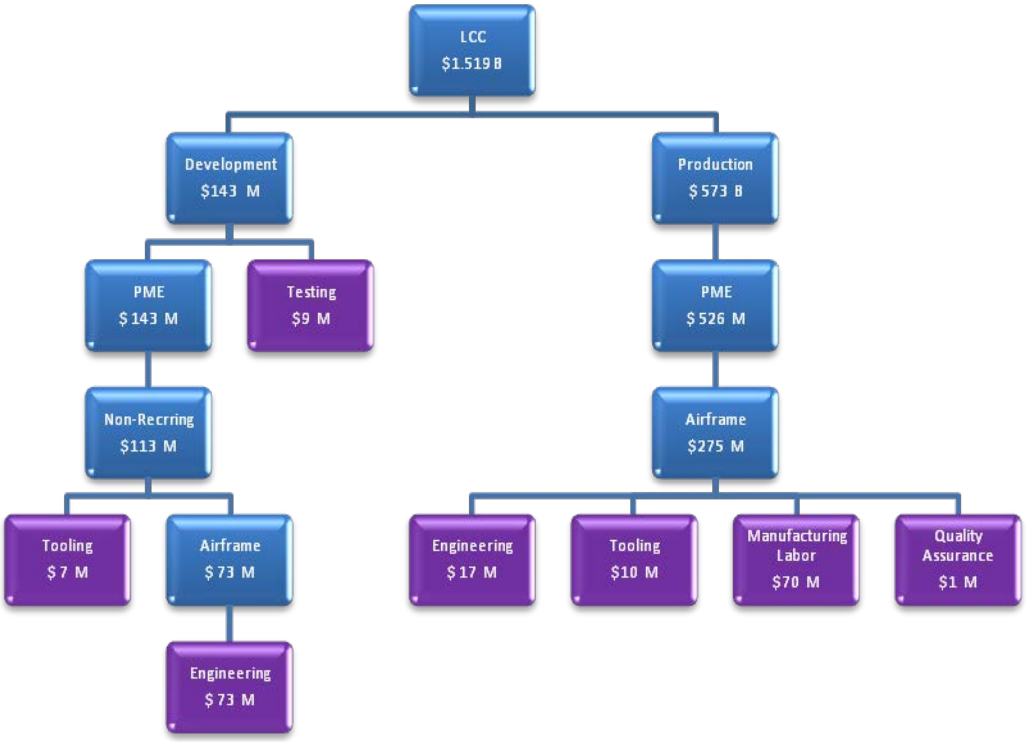


Figure 34 : Applied Cost Elements Life Cycle Cost Model

The cost differences indicated in Figure 33 and Figure 34 are truly remarkable, and continue to grow in magnitude as one progresses through the complete LCC model of the given scenario. A PCPR of 50% for all the touch labor hour, costs elements leads to an initial cost reduction of $375M out of $561M or 67%. However, due to the related relationships throughout the LCC model, the acquisition cost for development and procurement represents almost 53.50% (15.66% Development and 37.85% Productions) of the total LCC model.

The projected development cost decreased $120M; the procurement cost decreased $469M; and the acquisition (development and procurement) cost decreased $589M or a 42% decrease. There is a total decrease in LCC of $775M or 34% of the projected LCC for the given scenario as shown in Figure 35 below.

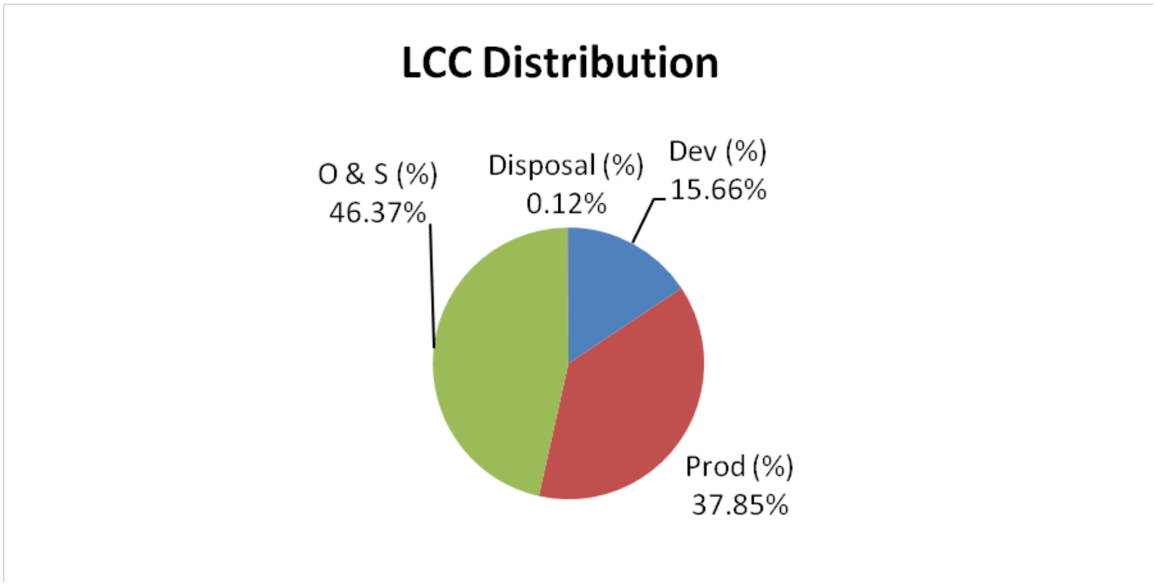


Figure 35 : Life Cycle Cost Distribution

Life Cycle Cost (LCC) Sensitivity analysis

A sensitivity analysis was used to investigate the strength of the LCC estimation model. This was achieved by varying the part count percentage reduction of the touch labor hours of our variables of interest and the LCC periods. The quantities used in the analysis reflect the proposed ACCA program numbers. The LCC periods, which are presented in Table 35, are per the scenarios that reflect the LCC. The PCPR, which are represented in Table 35, are per the scenarios that reflect a PCPR.

Table 35 : LCC Sensitivity Analysis

Life Cycle Cost	Part Count Percentage Reduction						
	0%	25%	50%	75%	80%	90%	95%
10 Years LCC	$ 176 M	$ 139 M	$ 110 M	$ 85 M	$ 81 M	$ 72 M	$ 67 M
15 Years LCC	$ 130 M	$ 103 M	$ 83 M	$ 65 M	$ 62 M	$ 56 M	$ 52 M
20 Years LCC	$ 106 M	$ 86 M	$ 69 M	$ 55 M	$ 52 M	$ 47 M	$ 45 M
25 Years LCC	$ 92 M	$ 75 M	$ 61 M	$ 49 M	$ 47 M	$ 43 M	$ 40 M

As shown in Table 35 above, as the LCC period increases the unit cost of the ACCA aircraft decreases. In addition, as the PCPR increases, considerable unit savings is achieved, especially at the higher LCC periods. The selection of a LCC period, as well as the aircraft PCPR, has a significant impact on the ACCA touch labor hours cost estimate. The aerospace industry standard recommendation for choosing the LCC period is 25 years and PCPR is 80%. Comparing to the original price of ACCA; the cost of RAND without any part count percentage reductions is $ 92 M where the actual cost is $50 million [35]; our chosen estimated price, $47 million, we confirm that we are within the range.

Figure 36 shows the relationship between the LCC and the PCPR. The relationship is not linear, but it approximates an inversely exponentially relationship. From the graph, one can determine that the plotted data declines by a fixed percentage. Also, one can see that the gap between each LCC curve decreases as PCPR increases.

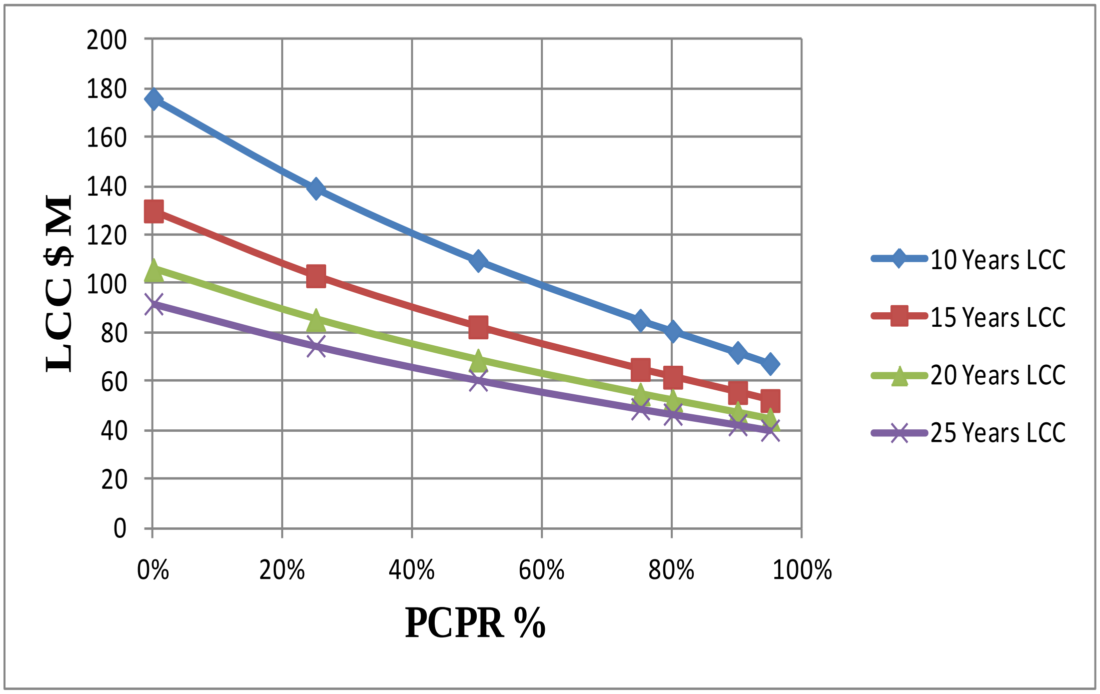


Figure 36 : Sensitivity Analysis for LCC and PCPR Scatter

Figure 37 shows the cost comparison between the LCC periods and the PCPR. As seen from the chart, from 0% to 95% PCPR there is a sharp drop in cost as the number of years goes from 10 to 25. As the PCPR increases, the life span of the aircraft has less effect than when the PCPR is small. There is still a significant reduction in costs as the number of year increases with each PCPR having a different rate of decay.

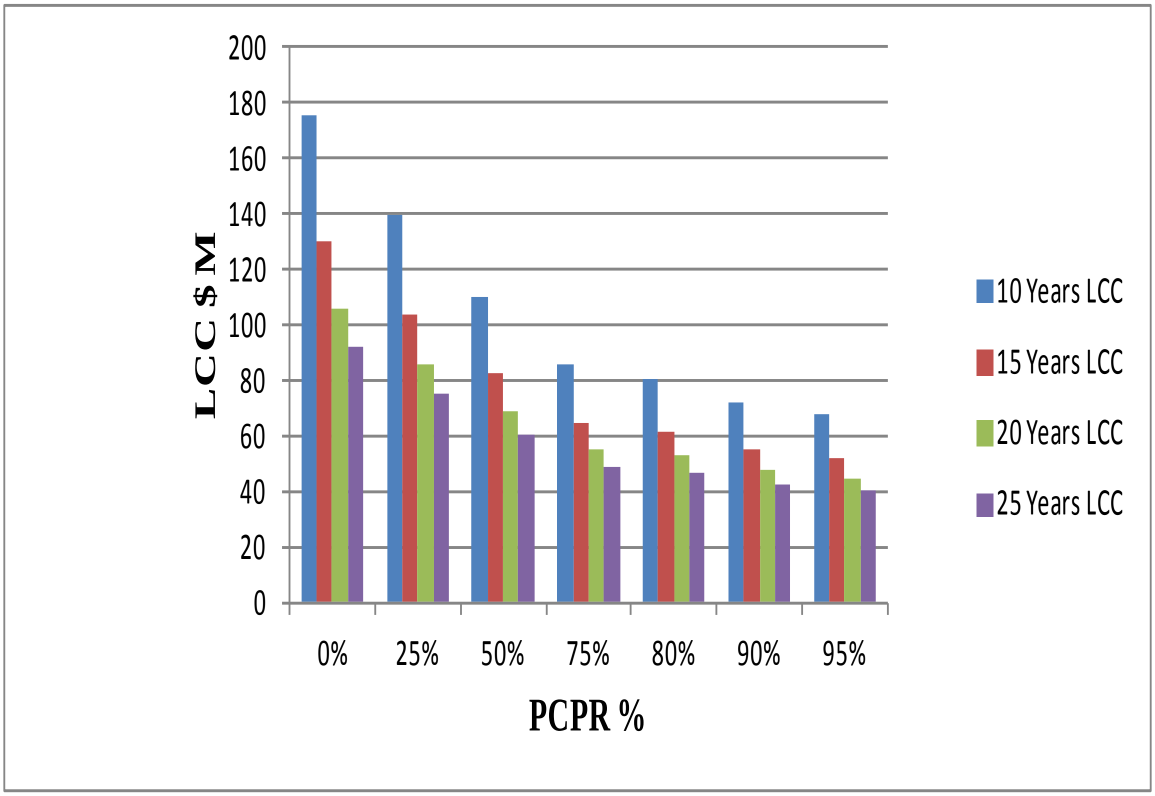


Figure 37 : Sensitivity Analysis for LCC and PCPR Column Chart

Learning Curve (LC)

Using the updated CERs and LCC model developed in the previous sections, the direct touch labor hours cost for the first unit of the ACCA prototype airframe has been estimated. This estimate is then transformed through the use of the prime mission equipment (PME) to the production for the first unit and then to the LCC model as shown in Figure 38.

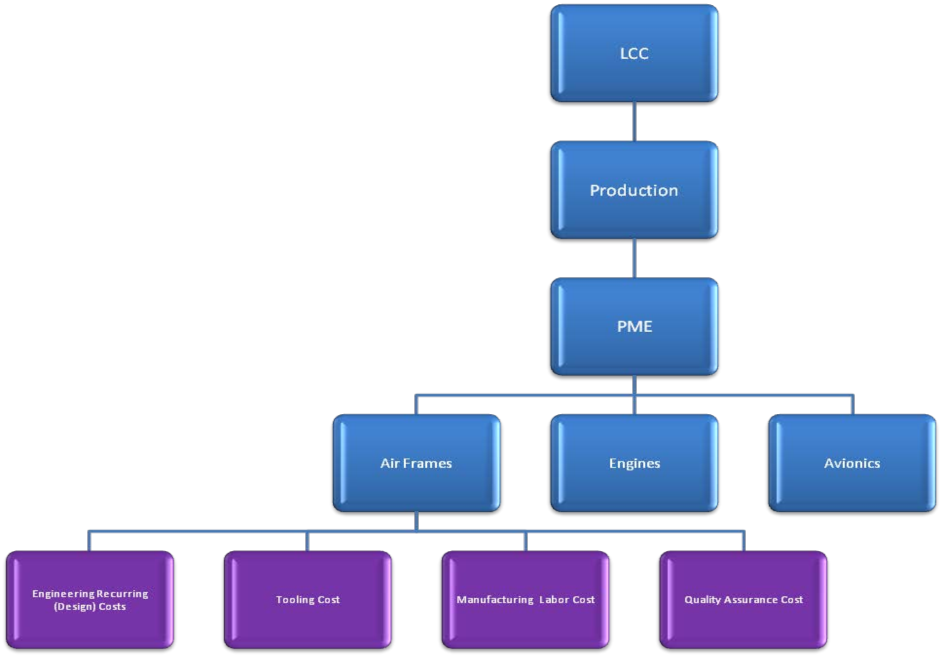


Figure 38 : Applied Production Cost Elements Life Cycle Cost Model

Then, the LC is applied to the LCC model according to the scenarios defined above. This research uses the cumulative average LC formulation **(**18**)**, described in Chapter II. The full production LCC is estimated from the cost of the first LCC unit using equation (57). The aerospace industry standard recommendation for the LCC period is 25 years and PCPR is 80%; the industrial standard for LC rates for aerospace sectors is 85% [42].

$$\mathrm{Cum}_{\mathrm{LCC}} = \sum_{x=1}^{n} T_1 x^b = T_1\,(1^b + 2^b + 3^b + \cdots + n^b) \qquad (57)$$

$\mathrm{Cum}_{\mathrm{LCC}}$ = Cumulative cost per aircraft LCC unit

T_1 = 1$^{\mathrm{ST}}$ aircraft total LCC

x = Aircraft unit

Where:

$$b = \log(\text{learning curve})/\log 2 \tag{58}$$

n = Total number of aircraft

Equation (57) requires input of the quantity of prototype aircraft (ACCA) to be manufactured and the LC expected during the production of the prototype phase.

To calculate the average unit LCC, the cumulative LCC is divided by the ACCA production quantity. This yields equation (59)

$$AVG_{\text{LCC}} = Cum_{\text{LCC}} / QTY_{\text{LCC}} \tag{59}$$

Where:

AVG_{LCC} = Average unit aircraft LCC

QTY_{LCC} = A aircraft production quantity

Learning Curve (LC) Analysis

As shown in Figure 39, for an 85% LC rate, as the average aircraft production unit's LCC increases, the LCC unit price decreases at a faster rate. Significant unit savings can be achieved when production units increase.

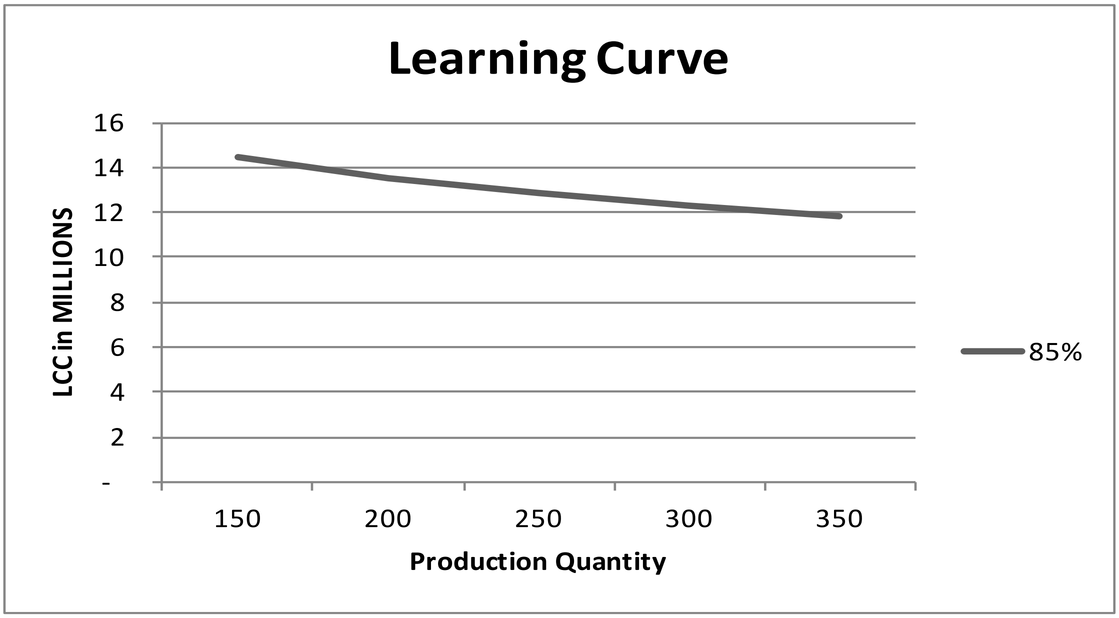


Figure 39 : 85% Learning Curve

Learning Curve (LC) Sensitivity Analysis

A sensitivity analysis is performed to verify the stability of the estimate. This is accomplished by varying the ACCA quantity of production aircraft and the applied LC. The production quantities that are utilized in this analysis reflect the proposed ACCA production numbers. The LC is representative of the aerospace industry standard. The results are presented in Table 36.

Table 36 : LC Sensitivity Analysis

Learning Curve	Average Aircraft Life Cycle Cost production unit				
	150	200	250	300	350
80%	$ 9 M	$ 9 M	$ 8 M	$ 7 M	$ 7 M
82.5%	$ 12 M	$ 11 M	$ 10 M	$ 10 M	$ 9 M
85%	$ 14 M	$ 14 M	$ 13 M	$ 12 M	$ 12 M
87.5%	$ 18 M	$17 M	$ 16 M	$ 16 M	$ 15 M
90%	$22 M	$ 21 M	$ 20 M	$ 20 M	$ 19 M
92.5%	$27 M	$ 26 M	$ 25 M	$ 25 M	$ 24 M
95%	$ 32 M	$ 32 M	$ 31 M	$ 31 M	$30 M
97.5%	$ 39 M	$ 38 M	$ 38 M	$ 38 M	$ 38 M
100%	$ 47 M	$ 47 M	$ 47 M	$ 47 M	$ 47 M

As shown in Table 36, as the LC increases, the average aircraft production unit's LCC increases at a faster rate. Also, as the number of produced ACCA aircraft increases, significant unit savings can be achieved, especially at the lower LCs. The selection of the expected LC, as well as the quantity of produced ACCA aircraft, can have a significant impact on the final average aircraft unit cost estimate.

Figure 40 shows the cost comparisons for various LC percentages and the production quantities. As seen in the chart for an LC rate of 80%, there is a rise in learning and a significant cost impact as the number of production aircraft increases from 150 to 350. As the rates of the LC increase to 100%, there is less and less learning and a corresponding decrease in cost impact.

The industrial standard for LC rates for aerospace sectors is 85% [42]. As shown in Figure 40, and Table 36, LC rates of 85% and below generate a significant reduction in the production aircraft's predicted LCC. While LC rates above 85% do not generate significant reductions in the average production aircraft's predicted LCC. It is interesting that as the production numbers of ACCA aircraft increase with the lower LC rates, the average aircraft production cost actually increases slightly.

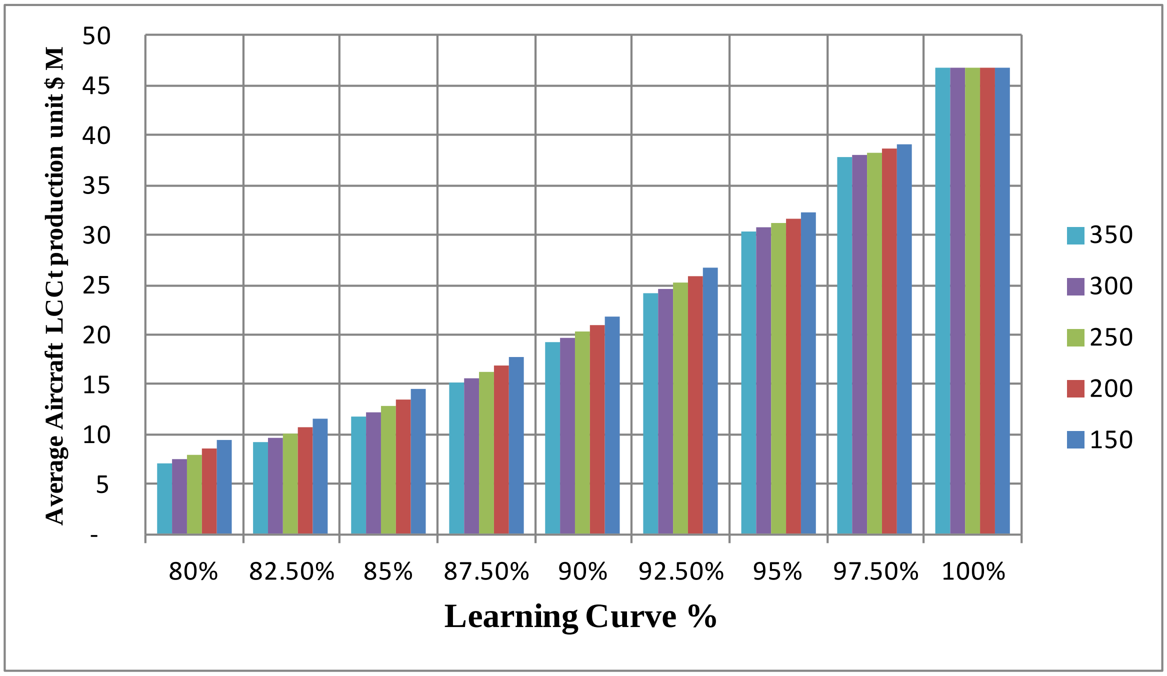


Figure 40 : Learning Curve Sensitivity Analysis

This research relied on the cost model provided by AFRL with updated CERs. There are significant differences between first unit prototype and first unit production aircraft. The LCC cost estimation model is primarily intended for production scenarios, and not for prototype ones. Furthermore, ACCA was not an entire aircraft design or production. Thus, incorporating the LC method into the LCC might be inaccurate, or give false results. Additional research with actual production aircraft is needed.

VII. Summary and Conclusion

Summary

The two objectives of this dissertation are (1) to understand the effects of Z-pin reinforcement in advanced composite material manufacturing processes for aircraft applications, and (2) to develop a more accurate life cycle cost (LCC) estimating model for aircraft for which advanced composite materials comprise a significant portion of the airframe structure.

Chapters III and IV analyze Z-pinned laminated composite fatigue test data by using Monte Carlo simulation techniques to better understand the fatigue response of composite materials in the presence of Z-pins. In addition, they provide a baseline for incorporating the cost implications of using Z-pins in the LCC estimating model. This research understands the effects of Z-pin reinforcement in preventing the delamination by predicting the reliability of tested advanced composite material with and without Z-pinning.

Chapter V investigates and verifies the prototype and production aircraft data for advanced composite and combined advanced composite with metal aircraft structures. This research determines the existence of a relationship between the part count percentage reductions and touch labor hour percentage reductions for the development and production of aircraft. Also these relationships were identified, quantified, and classified.

Chapter VI builds upon the relationships established in chapter five. The chapter uses the relationships of chapter five to propose enhancements to the LCC estimating model. By identifying, quantifying, and classifying these relationships, the chapter updates the RAND cost estimation relationships (CERs) and provides the rational for updating the AFRL LCC estimating model. We determined the effect of the LC on the LCC estimating model. Finally, sensitivity analyses results are described for the enhanced LCC and learning curve (LC) in several scenarios.

Conclusion

This research concludes that the impact of using part counts and large-scale advanced composite materials on touch labor hours in the LCC for aircraft structures was significantly large.

Current RAND CERs account for increase in cost of manufacturing using advanced composite materials. It does not account for reduction in part counts due to large-size of parts manufacturing with advanced composite materials. This research determinates that touch labor hours are related to part counts and that a reduction in part counts will result in a reduction in LCC new updated CERs from this research account for this cost reduction.

Areas of Future Research

An understanding of the effect of using large-part advanced composite materials in aircraft production is still in its initial stage. There is no known cost estimating models for computing the LCC for aircraft built using significant amounts of advanced composite materials. This lack provides abundant opportunities for additional investigation in this field. Also, there is a need for continued research in how using Z-pinning affects the cost of both manufacturing and maintenance. Future research should also examine the cost implications of using Z-pins in advanced composite airframe structures.

Additional research is required to determine if a LC is present when Z-pins are used in advanced composite aircraft structures, together with its implications for LCC estimate models.

Finally, this dissertation determines the short-comings of the LCC estimate methodologies for metallic material aircraft when applied to advanced composite aircraft. These efforts will lead decision makers to a stronger and more accurate LCC estimate model and help decision makers in determining the numerous trade-offs necessary when purchasing aircraft.

This author believes this field of research contains many critically important topics. Approaches are needed to reduce the touch labor hours while keeping the level of reduction in part count percentage. One way to achieve this is through the application and extension of the current LCC estimating model.

Appendix A

2012 International Conference on Industrial Engineering and Operations Management Conference Proceedings Reliability Aspects in Z-Pinned Laminated Composites

S. R. Soni, M. Al-Romaihi, J. R. Wirthlin, and A. B. Badiru

Air Force Institute of Technology, Wright Patterson AFB, OH 45432, USA

Stephen Clay,

AFRL/RB, Wright Patterson AFB OH 45433, USA

Abstract

Composites are finding extensive use in aerospace, sports, auto and medical industries. There are various benefits of using these materials if used with complete understanding of their performance capabilities. One of the most feared modes of failure in composites is delamination. Composites Affordability Initiative by US Air Force has identified joining and co-curing of composites as an important problem area of interest. Delamination is common in such composites and z-pinning provides through-the-thickness reinforcements, to improve structural damage tolerance. Being a relatively new application for joint design, estimating the reliability of z-pinned composite components is quite a complex process and requires knowledge of the uncertainties that occur at various scales. Numerous tests are conducted using different z-fiber diameters and

loading conditions to determine the fatigue life of composite laminates. Appropriate models are used to predict the reliability of tested composites. Commonly used laminate, quasi isotropic, has been considered with and/or without z-pins. The material used was IM7/977-3 prepreg. A set of specimens has been tested to understand the effect of cyclic loading on the response of laminates with/without z-pins. Other parameters considered are stress risers, % ultimate loads, cycle dependent damage and z-pin diameter and volume fraction. All these parameters influence the lifecycle cost of the system.

Table 37 : Example Data for Nine Specimens Tested at Different Loads

Sample ID	Max Stress (ksi)	% Ultimate	Cycles N_a	Damage Area a (%)	Cycles N_b	Damage Area b (%)	Cycles N_c	Damage Area c (%)
5-1	92	80	8,907	100		100		
5-2	92	80	20,453	44	21,453	100		
5-3	92	80	18,404	100		100		
5-4	80.5	70	188,636	64	253,931	90	267,122	100
5-5	80.5	70	187,376	65	202,224	61		
5-6	80.5	70	242,378	62	251,428	61	296,450	100
5-7	69	60	328,026	53	407,688	60		
5-8	69	60	121,710	37	246,552	61	311,000	100
5-9	69	60	242,165	47	325,148	63	400,000	100

Appendix B

2013 American Society for Composites 28th Technical Conference Proceedings

Advanced Composite Air Frame Life Cycle Cost Estimating Model

M. Al-Romaihi, S. R. Soni , J. R. Wirthlin, A. B. Badiru, J. D. Weir
Air Force Institute of Technology,
Barth Shenk
AFRL/RB
Wright Patterson AFB, OH 45433

Abstract

While composite materials have been used in aircraft manufacturing for numerous years, interest in estimating costs for aircraft using large composite structures is still in its infancy and there are no commonly accepted cost models for composite aircrafts. This lack of a universally agreed upon LCC model provides ample opportunities for further research into this area. As research continues in the area of composite aircraft, an area that requires additional research is the effects of automation on cost. Fiber placement machines are frequently being integrated into the manufacturing process to improve the efficiency of composite manufacturing in production scenarios.

Further research is required to determine if a learning curve is present with the incorporation of fiber placement machines as well as improved damage tolerance methods, such as z-pinning, stitching and braiding. Other research that is needed concerns the material cost factors currently used in cost models concerning composites.

These material cost factors were developed by RAND in the early 1990's and have not been updated since that time. Advancements concerning damage tolerance by avoiding delamination will considerably improve the LCC of the aircraft structure. These efforts will lead to a more vigorous and accurate cost model that can aid the decision maker in determining the trade-offs in acquiring aircraft systems.

Keywords

Aircraft design, cost models, composites

Research Issue

There are various manufacturing processes and parts counts associated with composites that are not currently incorporated in existing cost models used for procurement of aircraft systems comprising substantial composite materials. The proposed research is to improve the cost estimating models for composite material aircraft in comparison to historic metallic aircraft. Cost implications of developments of innovative techniques to improve the damage tolerance of composites are incorporated.

Research Result

We report on the effect of realistic manufacturing process cost and total material cost on the cost estimates of composite aircraft through an improved method for evaluating life cycle cost of predominately composite material aircraft in comparison to metallic aircraft. We modified components of the current life cycle cost model used by the Air Force community, in order to better characterize the benefits and tradeoffs associated with composite aircraft development and production. The culmination of this effort is the development of a life cycle cost model that narrows uncertainty and better characterizes the benefits / tradeoffs as part of this research associated with composite aircraft design, development and support.

References

1. Al-Romaihi, M., S. Soni, A. Badiru, J. Weir, S. Clay, and B. Shenk."Fatigue Tests and Data Analysis of Z-pinned Composite Laminates," Tech Science Press Journal, Duluth, GA, May, 2013.

2. Al-Romaihi, M., S. Soni, J. Weir, A. Badiru, and B. Shenk." Cost Estimating Relationships between Part Counts and Advanced Composite Aircraft Manufacturing Cost Elements," Tech Science Press Journal, Duluth, GA, May, 2014.

3. Badiru, A. "Half-Life Learning Curve in the Defense Acquisition Life Cycle," Defense ARJ, Vol. 19, no. 3, 2012.

4. Barringer, H., and D. Weber, D. "Life Cycle Cost Tutorial," Process Plant Reliability Conference, Gulf Publishing Company, Houston, TX., 1996.

5. Beer, F., and E. Jr. Johnston. Mechanics of Materials. McGraw-Hill. New York, 1981.

6. Bock, D. Cost Effectiveness of Composites Materials on the F-15 and F-16 Aircraft. MS thesis, AFIT/GFA/LSY/89S-3, School of Logistic, Department of the Air Force, Air Force Institute of Technology, 1989.

7. Boeing Company."About the 787 Family," Boeing 787 Product Information, March 2010.

8. Boren, H. Jr. A Computer Model for Estimating Development and Procurement Cost of Aircraft (DAPCA-III). The RAND Corporation, R-1854-PR, March, 1976.

9. Boren, H. Jr., and H. Campbell, Learning-Curve Tables: Volume I, 55-69 Percent Slopes. The RAND Corporation, RM-6191-PR, April, 1970.

10. Boren, H. Jr., and H. Campbell, Learning-Curve Tables: Volume II, 70-85 Percent Slopes. The RAND Corporation, RM-6191-PR, April, 1970.

11. Boren, H. Jr., and H. Campbell, Learning-Curve Tables: Volume III, 86-99 Percent Slopes. The RAND Corporation, RM-6191-PR, April, 1970.

12. Bowerman, B., R. O'Connell, and A. Koehler. Forecasting, Time Series, and Regression. Brooks/Cole, 2005.

13. Brookfield, B. "Management Accounting-Decision Management," Financial Management Magazine, April, 2005.

14. Butler, B. Composites Affordability Initiative: Phase II Pervasive Technology, Contract F33615-98-3-5106. Northrop Grumman Corp, Seattle, WA, 2002.

15. Castagne, S., R. Curran, A. Rothwell, M. Price, E. Benard, and S. Raghunathan. "A Generic Tool for Cost Estimating in Aircraft Design," Research in Engineering Design, no. 18, pp. 149-162, 2008.

16. Daniel I., and O. Ishai. Engineering Mechanics of Composite Materials. Oxford University Press, New York, 2006.

17. Freels, J. Modeling Fracture in Z-Pinned Composite Co-Cured Laminated Using Smeared Properties and Cohesive Elements in DYNA3D. MS thesis, AFIT/GMS/ENY/06-S01, School of Engineering and Management, Air Force Institute of Technology, 2006.

18. Griffin, C., and E. Dunning. Development of An Advanced Composite Aileron for the L-1011 Transport Aircraft, NASA Contractor Report 3517, 1982.

19. Hull, D. and T. Clyne. An Introduction to Composite Materials. Cambridge University Press. New York, 1996.

20. Isom, J. A Guide for Consideration of Composite Material Impacts on Airframe Cost. M. S. Thesis, Air Force Institute of Technology, 1991.

21. Kapoor H., j. Blackshire, and S. Soni." Damage Detection in Z-Fiber Reinforced, Co-Cured Composite Pi-Joint Using Pitch-Catch Ultrasonic Analysis and Scanning Laser Vibrometry", Tech Science Press. SL., Vol. 3, no. 3, pp. 221-238, 2010.

22. Kilic, H., S. Soni, R. Patel, and J. Freels. "Effect of Z-Fiber Percentage on the Fracture Behavior of DCB Specimens in Mode I," ICCES, Vol. 1, no. 1, pp. 1-5, 2007.

23. Klumpp, J. Parametric Cost Estimation Applied to Composite Helicopter Airframes. M. S. Thesis, Naval Postgraduate School, 1994.

24. Koury, J. "Composite Affordability Initiative," Proceedings of the Science and Technology Affordability Conference, 1998.

25. Kutner, M., C. Nachtsheim, J. Neter, and W. Li. Applied Linear Statistical Models. McGraw-Hill, New York, 2005.

26. Lambert, D. Composite Aircraft Life Cycle Cost Estimating Model. M.S. Thesis, AFIT/GFA/ENV/11-M02, School of Engineering and Management, Air Force Institute of Technology, 2011.

27. Lemke, A. Part Count: Monolithic Part Effects on Manufacturing Labor Cost, an Aircraft Applied Model. M.S. Thesis, AFIT/GFA/ENV/10-M02, School of Engineering and Management, Air Force Institute of Technology, 2010.

28. Liao, S. The learning curve: Wright's model vs. Crawford's model," Accounting Education, 1988.

29. Liu, H-Y, Mai, and Y-W. "Effect of Z-pin Reinforcement on Interlaminar Mode I Delamination," Composite Materials Conference, ICCM13, 2001.

30. Marc, M., A. Lin, Y. Seki, P. Chen, B. Kad, and S. Bodde. “Structural Biological Composites: An Overview,” JOM, no. 7, pp. 35-36, 2006.

31. Myers, R., D. Montgomery, and C. Anderson-Cook. Response Surface Methodology. Wiley, New Jersey, 2009.

32. Neumeier, P., S. Engelstad, B. Koon, and R. Schmidt. Air Vehicle Technology Integrated Program (AVTIP), Palmdale, CA, 2009.

33. Raymer, Daniel. Aircraft Design. A Conceptual Approach, AIAA Education Series, New York, 2006.

34. Resetar S., J. Rogers, and R. Hess. Advanced Airframe Structural Materials: A Primer and Cost Estimating Methodology, Contract F49620-91C-0003. RAND Project Air Force (R-4016-AF), Santa Monica, CA, 1991.

35. Russell, J. “Advanced Composites Cargo Aircraft prove large structure practicality,” Composites World Magazine, 2010.

36. Russell, J. “Composites Affordability Initiative, Part II,” Composites World Magazine, 2007.

37. Russell, J. “Composites Affordability Initiative: Transitioning Advanced Aerospace Technologies through Cost and Risk Reduction,” AMMTIAC Quarterly, no. 1, pp. 3-6, 2006.

38. Russell, J. “Composites Affordability Initiative, Part I,” Composites World Magazine, 2007.

39. Soni, S., M. Al-Romaihi, J. Wirthlin, A. Badiru, and S. Clay. “Reliability Aspects in Z-Pinned Composites,” IEOM-2012, Istanbul, Turkey, 2012.

40. Soni, S., M. Al-Romaihi, J. Wirthlin, A. Badiru, J. Weir, and S. Clay. "Analysis of Z-pinned Laminated Composite Fatigue Data,” ICAM-2012, BHU, India, 2012.

41. Soni, S., j. Freels, and j. Kuhn. "Failure in Z-Pinned Co-cured Laminated Composites," SAMPE, Memphis, TN, 2008.

42. Stewart, R., and R. Wyskida. Cost Estimation's Reference Manual. Wiley, New York, 1987.

43. Strong, B. Fundamentals of composites manufacturing: materials, methods and applications. Society of Manufacturing Engineers, Michigan, 2008.

44. The Air Force Systems Command Cost Estimating Hand Book Series. Reading MA (no date).

45. Walz, M. "The Dream of Composites," R&D Magazine, 2006.

46. Wright, T. "Factors Affecting the Cost of Airplanes", Aeronautical Sciences Journal, Vol.3, no.2, 1936.

47. Younossi O., M. Kennedy, and J. Graser. Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes1700 Main Street, P.O. Box 2138, Santa Monica, Ca , 2001.

48. Zelinski, P. "Advanced Composite Cargo Aircraft Proves Large Structure Practicality," High Performance Composites, 2010.

49. Zenith Aviation. "Dornier 328J," 6 June 2010. www.zenithaviation.com/0410/pdf/tech_spec_328jet

50. http://rsb.info.nih.gov/ij/download.html

REPORT DOCUMENTATION PAGE				*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
19-06-2014	PhD Dissertation	Sep 2010 – June 2014

TITLE AND SUBTITLE ADVANCED COMPOSITE AIR FRAME LIFE CYCLE COST ESTIMATING	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Mohamed M. AlRomaihi, Colonel, Bahrain Defense Force	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology, Graduate School of Engineering and Management (AFIT/ENY), 2950 Hobson Way, Building 640, WPAFB OH 45433-8865	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT-ENS-DS-14-J-19
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Intentionally left blank	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved For Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Because of their versatility, advanced composite materials are being used at an increasing rate in the manufacturing of aircraft, as well as other products, such as autos, sporting goods, and medical products. Airframe structure materials used throughout aerospace manufacturing processes consist of significantly greater percentages of advanced composite materials. However, these manufacturing processes and the associated reduction in part counts are not considered in the aircraft procurement and life cycle cost (LCC) management processes in the United States Air Force (USAF) community or the Department of Defense (DoD). This situation led the leaders of USAF and DoD to restudy the LCC models that estimate the cost for most weapon systems. Most of the present LCC models and procurement processes were developed and established when the metals were used in airframe structures. Over the last three decades, a series of composite affordability initiatives (CAI) has culminated in a better quantifying system for calculating the influence of advanced composite materials in airframe structures. This research finds that significant relationships exist between part counts, touch labor hours of development, and production cost. The reduction in the part counts led to corresponding reductions in touch labor hours. This research effort was undertaken to update the cost estimating relationships (CERs) for airframes by including the part count percentage reduction (PCPR) cost factors of the above mentioned relationships. The results suggest that the reduction in part counts forces a related percentage reduction in touch labor hours cost categories. The output of this research is the recommendation that the present LCC estimation models for advanced composite aircraft be upgraded.

15. SUBJECT TERMS
Operation Research

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Dr. Jeffery Weir , AFIT/ENS
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	160	**19b. TELEPHONE NUMBER** (937) 255-6565, 4532:mohamed.al-romaihi@afit.edu

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18