The Effects of Design, Manufacturing Processes, and Operations Management on the Assembly of Aircraft Composite Structure

by

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Submitted to the Sloan School of Management and
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ABSTRACT

Composite materials have many characteristics well-suited for aerospace applications. Advanced graphite/epoxy composites are especially favored due to their high stiffness, strength-to-weight ratios, and resistance to fatigue and corrosion. Research emphasis to date has been on the design and fabrication of composite detail parts, with considerably less attention given to the cost and quality issues in their subsequent assembly. For aircraft structures made of advanced composite materials, estimates of the percentage of total manufacturing cost attributable to assembly range from 25% to 50%. This topic is of particular interest to the Boeing Commercial Aircraft Group, which intends to feature composite primary structures on their next-generation airliner, the 777. The central question of this study is "what are the underlying causes of assembly productivity issues for advanced composite structures?" During a Leaders for Manufacturing sponsored internship at Boeing, the following data and information were obtained relating to composite structure assembly: (1) quantitative measures, including percent labor allocated to each assembly task, rework percentages of total direct labor, scheduled assembly flowtimes, and parts availability; and (2) qualitative information from interviews, discussions, and observations with Boeing manufacturing and design personnel.

Through an analysis of these data and information, three categories of aircraft composite structure assembly cost and quality issues are identified. *Ease-of-assembly of composite structures* is affected by material properties and design practices unique to composites, and detail part and fitting dimensional variability. *Parts supply shortages* are caused by production variability in the fabrication shops, resulting in process bottlenecks upstream from assembly. How these shortages directly affect assembly shop productivity, manifest in highly varying per unit labor expenditures and the resulting retention of excess shop capacity, is described. Other *process attributes* which impact assembly productivity are the large schedule and inventory buffers, and the significant worker idle time resulting from the quality assurance process. The effects on productivity of the buffers and quality assurance process are discussed. Finally, recommendations addressing the composite assembly issues identified in this study are presented in the context of engineering design, manufacturing process technology, and operations management practices.

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PREFACE

The research presented in this thesis was performed under the auspices of the MIT Leaders for Manufacturing program, a partnership between MIT and eleven major U.S. manufacturing companies. I am grateful to the LFM program for the support and resources provided during my two years at MIT.

I wish to thank the Boeing Commercial Aircraft Group for their sponsorship of the Leaders for Manufacturing program, and for their support of this research project. Boeing should be commended for permitting student interns to examine manufacturing operations within the company, and to publish the results in a public document. It should be noted that the purpose of the internship is to investigate relevant manufacturing issues, for the purpose of developing recommendations for improvements. Thus, more attention is naturally placed on company practices which bear improvement. If the purpose of the research project was to document every area in which Boeing excels in the design and manufacture of commercial transport aircraft, many more volumes would be required.

I wish to also thank all those in Boeing's MR&D - Advanced Composite Structures group in Auburn, Washington for making my internship a great educational experience as well as a lot of fun. Special thanks are due my company advisors, Peter Doman and Tom May, for their considerable time, interest, and involvement in my internship project.

Finally, I wish to thank my faculty thesis advisors, Professor Stephen Graves and Professor Paul Lagace, for their numerous suggestions, encouragement, and overall guidance throughout this project.

CONTENTS

1.0 Introduction

1.1 Background on Aircraft Composite Structure

Composite materials have many characteristics well-suited for use in aerospace applications. Graphite/epoxy composites are especially favored due to their high stiffness, strength-to-weight ratios, and resistance to fatigue and corrosion. The application of composite materials in aircraft structure is steadily increasing, providing significant reduction in operational life-cycle costs from fuel savings in combination with reduced maintenance costs due to improved corrosion resistance versus metals.[1] The current generation of commercial aircraft uses advanced composites extensively for secondary structure components such as ailerons, elevators, rudders, spoilers, fairings, and engine nacelles. Various sources place the weight savings attained by the use of advanced composite structure in place of aluminum structure at 15% to 30% on individual secondary structure components. The Boeing 757 and 767 contain approximately 1900 and 2860 pounds of graphite and Kevlar composites, respectively, with each amount representing 3% of the aircraft's total structural weight. Newer generation commercial aircraft, such as the Airbus A320, have up to 15% composite materials by weight.[2] Composites also possess potentially negative material characteristics, in terms of aerospace structures, such as low interlaminar strength, low impact damage resistance, and relative brittleness compared to metals. But the primary reason the anticipated shift from metals to advanced composites in commercial aircraft has taken longer than expected is the relatively high cost of composites. The aerospace industry, particularly the commercial side in the increasingly competitive global market, has become increasingly cost-driven in addition

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[1] Hadcock, R.N., "Design of advanced composite aircraft structures", *International Journal of Vehicle Design, Special Publication SP6*, 1986, p.292.

[2] Pilling, Mark, "The Leading Edge", *Aerospace Composites and Materials*, Winter 1988-1989, pp.48-50.

to performance-driven. Advanced composites simply have not yet proven they can achieve cost-reduction objectives in manufacturing.[1]

1.2 Problem Definition

In general, assembly costs are a significant portion of the total manufacturing cost of today's commercial aircraft. Specific to composite structure, estimates of the total manufacturing cost attributable to assembly range from 25% to 50%.[2] Research and development emphasis to date has been on the fabrication of composite detail parts, with considerably less attention given to the cost and quality issues in the subsequent assembly process. This topic is of particular interest to the Boeing Commercial Aircraft Group (BCAG), which intends to include primary composite structure on their next-generation airliner, the 777. Furthermore, Boeing and several other major aerospace companies are now considering future aircraft structural designs consisting almost entirely of advanced composite materials. This study seeks to analyze the effects of design, manufacturing process technology, and operations management practices on the productivity issues related to the assembly of aircraft composite structures.

1.3 Thesis Objectives and Methodology

The central question of this study is "what are the underlying causes of assembly productivity issues for aircraft composite structures?" During a Leaders for Manufacturing sponsored internship at Boeing, the following data and information were obtained relating to composite structure assembly: (1) quantitative measures, including percent labor allocated to each assembly task, rework percentages of total direct labor, scheduled assembly flowtimes, and parts availability; and (2) qualitative information

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[1] Hilton, Peter D., and Kopf, Peter W.,"Aerospace Market for Composites Poised to Take Off", *Research and Development*, Feb 89, p.95.

[2] "Manufacturers Seek Reduced Costs Through New Fabrication Techniques", *Aviation Week & Space Technology*, July 21, 1986, pp. 73-77. Also, an unpublished Boeing internal study, Oct 89.

from interviews, discussions, and observations with Boeing manufacturing and design personnel. The objective of this thesis, through analysis of these inputs, is to identify and describe the leading sources of composite assembly productivity issues, and to propose solutions to these issues in the context of engineering design, manufacturing processes, and operations management.

The results of a literature search are presented in Chapter 2. A review of composite structure applications in transport aircraft is presented in the first section. The second reviews previous studies in the literature which address composites assembly operations.

A description of the composites manufacturing process at the BCAG Fabrication Division is presented in Chapter 3. This includes a brief description of the aircraft components (assemblies) studied, and a thorough discussion of the composites manufacturing process flow, with particular attention given to assembly.

In Chapter 4, the quantitative data and qualitative information and observations acquired during the internship project are presented. The qualitative information is based on the results of numerous interviews and discussions with Boeing personnel representing the many functional disciplines involved in composites manufacturing. These sources include personnel from Design Engineering, Tooling, Manufacturing Engineering, Manufacturing Research and Development (MR&D), Quality Assurance, and the A3410 Composites Assembly shop[1].

In Chapter 5, an analysis of the information presented in the previous chapters leads to a discussion of the sources of composites assembly productivity issues. The purpose of the analysis is to illuminate those characteristics of the aircraft composite structure design-manufacturing

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[1] "A3410" is BCAG Fabrication Division nomenclature for the composites assembly production shop. This shop served as the focus of the on-site manufacturing process studies.

process, both internal and external to the composites assembly shop, which contribute to production inefficiencies and quality issues.

In Chapter 6, recommendations addressing the composite assembly issues identified in this study are presented in the context of engineering design, manufacturing processes, and operations management.

A thesis summary and recommendations for future research in the field of aircraft composite structure assembly, and composite structure design and manufacturing in general, are presented in Chapter 7.

2.0 Literature Survey

The purpose of this chapter is to provide a literature summary in the field of aircraft composites structure assembly. A review of composite structure applications in transport aircraft is presented in the first section.

2.1 Current Applications of Composites in Transport Aircraft

The use of composite materials for aircraft structure has steadily increased since their introduction in the late 1950's. However, the rate of advance of composite applications has been much greater in high-performance military aircraft, the latest generation of business aircraft, i.e., the Beech Starship, and experimental aircraft, than in large commercial transport aircraft. This disparity is due to several reasons, including the higher emphasis on performance versus manufacturing cost in military and experimental aircraft, as well as the conservatism in large commercial aircraft manufacturers towards new materials, design methods, and manufacturing technologies, due to the perceived and real costs of failure in the commercial aircraft industry. Today, there are many examples of the use of composite materials in the primary (or, flight critical) structure of military aircraft, particularly fighters and attack aircraft. In comparison, the majority of composite applications on large commercial transports are in secondary structure such as flight control surfaces.

Several NASA-funded experimental applications of composite primary structure on commerial aircraft occurred in the late 1970s and early 1980s, such as ten composite 737 horizontal stabilizer semi-span panels put into service beginning in 1984. This was Boeing's first use of composite primary load-bearing structure. However, these were generally limited in scope to a few structural components on a few airplanes. In the mid-1980s, applications of composites was extended to entire primary structure subassemblies on commercial jet transports. In 1985, Airbus introduced the composite vertical stabilizer on the A310-300, followed shortly thereafter by the vertical stabilizer on the A300-600R. The A320 was then introduced in 1987 with both a composite vertical and horizontal stabilizer. The 150-

seat, twin-engine A320 is Airbus' most modern jet transport, achieving first flight in 1988 and first commercial service in 1989. The essentially all-composite A320 horizontal stabilizer, built by Construcciones Aeronauticas, S.A. (CASA) near Madrid, Spain has achieved a reported 15% weight savings versus conventional aluminum construction. It has been reported that CASA is using innovative manufacturing techniques which consistently produce high quality components, and is confident that carbon fiber/epoxy materials will continue to be used on primary structure for commercial aircraft.[1] Fabrication of the composite detail parts for the A320 horizontal stabilizer include the relatively standard one stage autoclave molding process for solid laminate ribs and honeycomb sandwich leading edge sections and cover panels. More advanced processes are used for co-curing the integrally stiffened skins and spars, which requires the closely controlled location of the stiffener elements before and during cure, and the generation of sufficient pressure to compact all laminates. Conventional mechanical assembly of the stiffened skins to the spar and rib webs is accomplished using titanium fasteners.

Another example of a recent application of composites to commercial aircraft primary structure is the Aerospatiale/Aeritalia ATR72 turbo-prop driven 70-seat commuter airliner, which first flew in October 1988 and entered commercial service in mid-1989.[2] The ATR72 outer wing structure consists of carbon fiber reinforced plastic (CFRP) skin panels and with a sub-structure of two CFRP spars and eighteen aluminum alloy ribs. (Composite ribs would have been more expensive with negligible weight savings). Metal fasteners are used to mate all the components together. Bonding is avoided due to limited confidence in its use on primary structures. Despite the success for Aerospatiale's design team with the ATR72 composite wing, there is concern for the risk of producing a composite wing for a larger aircraft. "With the higher loads such a large primary structure would encounter, Aerospatiale would be moving into

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[1] Cardaba, Lence, and Gomez, "Design and Fabrication of the Carbon Fiber/Epoxy A-320 Horizontal Tailplane", *SAMPE Journal*, Jan/Feb 1990, p.9-13.

[2] Pilling, Mark, "The Leading Edge", *Aerospace Composites and Materials*, Winter 1988-1989, pp.48-50.

unchartered territory if it chose composites."[1] Thus, the current philosophy at Aerospatiale is that the new A330/340 large transport jets will utilize composites in well-understood secondary and non-structural applications, and will not use composites in primary structure such as the wings. Thus, it is anticipated that composite usage on these next-generation Airbus jetliners will remain at the current level of 15-20% of empty weight.

While the use of composite materials in aircraft structural applications are increasing, Hilton and Kopf identify three reasons for what they consider to be the slower than expected penetration of composite materials into the overall aerospace market:[2]

1. the extreme consequences of failure and resulting conservativeness in introducing new materials and technology
2. the need to develop new design technology for composites
3. the labor-intensive and expensive methods of manufacturing

In this source's view, this last reason is the biggest remaining issue for composites. Advanced composite design capability has improved enormously with experience over the past 15 to 20 years and confidence in use of composites has increased accordingly. Thus, achieving the projected growth for aircraft composites applications depends largely on improved manufacturing technology that will increase efficiency, reduce costs, and offer greater quality consistency. Given this need for an improved understanding of composites manufacturing issues, this study seeks to explore those issues relating specifically to composites assembly operations.

2.2 Previous Studies on Composites Assembly

A review of the literature revealed that the vast majority of documentation on composites relates to design methodologies and part fabrication techniques. There are relatively few studies which specifically address

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[1] Ibid., p.50.

[2] Hilton, Peter D., and Kopf, Peter W.,"Aerospace Market for Composites Poised to Take Off", *Research and Development*, Feb 89, p.98.

assembly operations or assembly issues overall. In this section, a review is presented of the few studies which were found regarding composite structure assembly.

Lambert[1] addresses one of the major composites assembly issues in a 1987 article focusing on the unique problems of drilling and countersinking holes in composites for mechanical fasteners. While drilling through graphite/epoxy and aluminum stack-ups are relatively compatible, the requirements for drilling through graphite/epoxy and titanium are almost at opposite ends of the spectrum. Lambert describes a test series conducted by General Dynamics on drilling graphite/epoxy-titanium. The previous method required two types of drills and two separate drilling operations. Based on the test data, a predictive model was developed to determine optimum drilling conditions, in terms of drill material, drill bit geometry, and drill speed and feed rates. The article describes in detail the test parameters, methodology, and results. Results of the study showed that higher drill speeds decrease tool (drill bit) life exponentially. Higher drill feed rates also decrease tool life, but with less impact than does speed. Also, it was determined that increasing drill point angles resulted in longer tool life. Ultimately, a predictive model was developed consisting of independent and dependent variables, a cost equation objective function, and constraints. The minimum-cost drilling conditions generated by the model resulted in an 80% cost reduction and 76% cycle time reduction, when compared to the previous method of drilling graphite/epoxy-titanium. In summary, this study by Lambert was one of the most specifically focused on improving technology which has a direct impact on composite structure assembly.

In a report on carbon fiber composites applications in the military aircraft industry, Anderson[2] asserts that research is needed in the area of bonded joints and their adhesives. Advances in this area would serve to reduce the number of fasteners required in composite structure, and the associated

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[1] Lambert, Brian K., "Find Low-Cost Methodology When Machining Composites", *Cutting Tool Engineering*, December 1987, p.20.

[2] Anderson, B.W., "The impact of carbon fibre composites on a military aircraft establishment", *J.Phys. D: Appl. Phys 20* (1987) pp. 311-314.

stress concentration effects of fastener holes. This reflects a recognition for the importance of both assembly and design efficiency in future composite aircraft structure applications.

Very little composites manufacturing cost information is available in the public literature. This is understandable given that composites are still a cutting edge technology where cost reduction offers great competitive advantage, resulting in individual companies considering cost related information highly proprietary. One leading trade magazine, however, cited studies performed by Grumman Corporation that indicated assembly constitutes 40-50% of the total cost associated with composites manufacturing. This 1986 article also published the following composites manufacturing direct labor cost breakdown, although no source for these figures was cited:[1]

Skins fabrication	13%
Substructure fabrication	43%
Structural assembly	44%

Table 2.1: *Composite Manufacturing Direct Labor Cost*

Assuming the source was valid, this cost breakdown of the overall composite manufacturing process reinforces the importance of assembly as a major cost component. A further breakdown was also provided of the structural assembly direct labor cost component:

Load	6%
Fit-up/shim	30%
Drill/fasten	52%
Inspect/rework	12%

Table 2.2: *Assembly Direct Labor Cost*

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[1] Kandebo, Stanley W.,"Manufacturers Seek Reduced Costs Through New Fabrication Techniques", *Aviation Week & Space Technology*, July 21, 1986, pp. 73-77.

This allocation of direct labor in composites assembly provides an indication of how labor cost is consumed. This article also summarizes the assembly problems encountered with composites compared with metals: increased shimming requirements, use of costly precision fasteners instead of inexpensive rivets, the need for higher-tolerance holes for the precision fasteners, material breakout and delamination, increased inspection, and increased drill and tool wear.

However, this and other studies stop short of identifying the underlying causes of why certain assembly operations are more time-consuming, in which operations are there the greatest opportunities for improvement, and most importantly, how potential improvements can be realized and implemented. The intended contribution of this study is to provide a comprehensive analysis of composites assembly operations, and to determine at least some of the answers to the above questions.

3.0 Composites Manufacturing at the Boeing Fabrication Division

A brief overview of composites manufacturing at the Boeing Commericial Aircraft Group (BCAG) Fabrication Division in Auburn, Washington is presented in this chapter. After a general description of the composite aircraft structures studied during this project, the top-level manufacturing process flow is discussed. This serves to illustrate the "supplier-customer" relationships between the various production shops most closely involved with composites assembly. Following this is a detailed review of the A3410 composites assembly shop, its process flow, and descriptions of the major assembly operations conducted there.

3.1 Composite Assemblies Studied

The primary focus of the on-site research project at the Fabrication Division was the graphite/epoxy structures assembled by the A3410 shop. Of the several dozen components assembled there, the following were studied in depth:

a) 757 rudder
b) 757 elevator
c) 757 aileron
d) 737 elevator
e) 747-400 winglet

The structural components of an aircraft are categorized according to their flight criticality. The fuselage, wings, vertical stabilizer, and horizontal stabilizer, for example, are critical for the safe, controlled flight of an aircraft, and are therefore considered primary structure. Other structures such as flight control surfaces, fairings, and small access panels are not flight critical and are considered secondary structure. The rudder, elevators, and aileron are all flight control surfaces, and are therefore classified as secondary structure. The 747-400 winglet is not considered flight critical, but it does share similar design characteristics of primary structure. For example, the winglet has relatively thick gage structural components, characteristic of primary airfoil structure such as wings.

For current generation airliners, the five composite assemblies studied are the largest and most significant graphite/epoxy composite components manufactured by BCAG. For the purpose of studying assembly issues, these structures are the most interesting due to their production volume, size, and relative cost.

A brief description of each of these assemblies is provided:

757 Rudder

> The 757 rudder was originally designed as a graphite/epoxy structure, in the 1978-81 timeframe. It is the largest graphite/epoxy structure made at Auburn. The completed rudder assembly weighs approximately 320 lbs, and is approximately 700 square feet in area. It is constructed using a conventional spar, rib, skin design (reference Figure 3.1 for illustration). The rudder has a front and mid spar, six internal ribs, two end ribs, and four separate skin panels (upper and lower panels for both the left and right sides). This assembly requires over 2,000 fasteners to assemble each unit.
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> Production rate = 7 per month (1 every 3 manufacturing days).

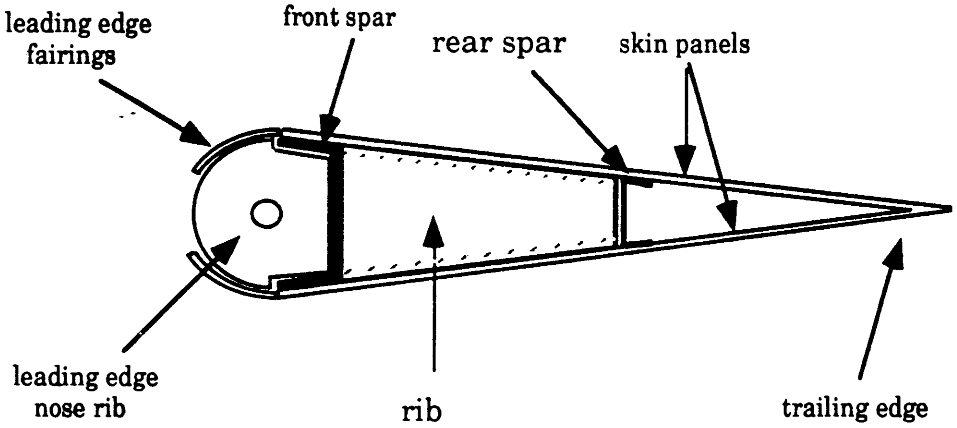

Figure 3.1: *Cross-section of a typical spar, rib, skin panel design, also known as a panelized rib design.*

757 Elevator

The 757 elevator was also originally designed as a graphite/epoxy structure. It is the second-largest graphite/epoxy structure manufactured at Auburn, and is made of conventional spar, rib, panelized skin construction. The elevator has a front spar only (no mid spar), and only three internal ribs, two closeout ribs, and two skin panels (left and right). It too was designed in the 1978-81 timeframe.

Production rate = 7 shipsets per month,[1] (1 every 3 manufacturing days).

757 Aileron

The 757 aileron is a unique design, utilizing a full-depth honeycomb core bonded construction rather than the panelized rib construction of the other assemblies studied in this project. For a schematic illustration of a bonded honeycomb core construction, see Figure 3.2. The aileron is virtually entirely manufactured in the A3430 fabrication shop.[2] The aileron is almost entirely bonded together rather than mechanically fastened. As a result, during fabrication the aileron undergoes three separate autoclave cure cycles . The A3410 assembly shop only installs the aileron's actuator and hinge fittings. As with the other 757 aircraft components, the aileron was originally designed in the 1978-81 timeframe.

Production rate = 7 shipsets per month, (1 every 3 manufacturing days).

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[1] A shipset consists of one left and one right elevator, aileron, or winglet.

[2] The separate functions and relationship of the A3430 and A3410 shops will be discussed in detail in the subsequent section, 3.2.

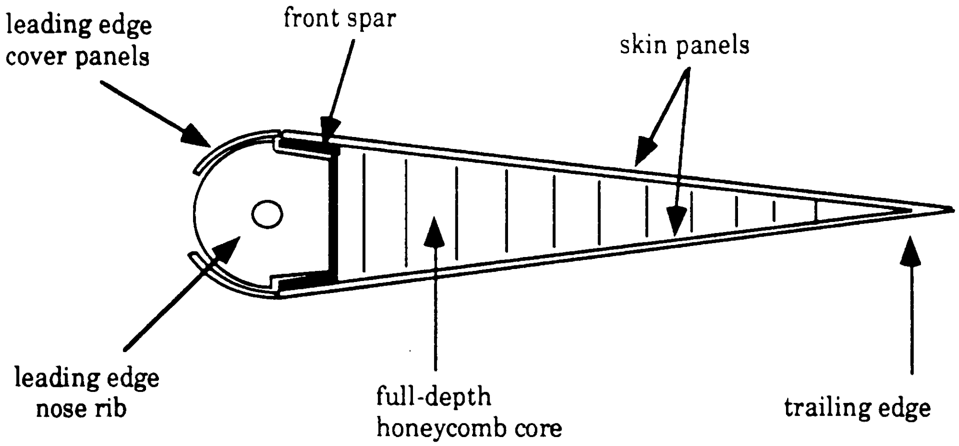

Figure 3.2: *Cross-section of a typical full-depth honeycomb core composite airfoil, similar in construction to the 757 aileron. The skin panels are bonded to the honeycomb core, reducing the need for the mechanical fasteners of panelized-rib designs.*

737 Elevator

This graphite/epoxy structure was designed in the early 1980's to replace the original aluminum 737 elevator design. It is a good example of a design which simply substitutes composite detail parts for aluminum, known colloquially as a "black aluminum" design. Although relatively small in size compared to the other components studied, the 737 elevator has the highest part count and the highest rejection tag rate per unit.[1] The 737 elevator has the highest production volume of any component studied.

Production rate = 17 shipsets per month, increased to 21 per month in December of 1990, (1 every manufacturing day).

747-400 Winglet

The winglet is the most recent composite structure design, with production having begun in 1987. The main understructure components are two machined titanium fittings for attachment to the wing, and a graphite/epoxy front spar which provides the primary

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[1] A3410 shop Quality Assurance rejection tag data.

support to the two skin panels. The winglet assembly also includes composite fairings for the leading edge and the interface with the wing.

Production rate = 5 shipsets per month, (1 every 4 manufacturing days).

3.2 Manufacturing Process

The overall composites manufacturing process flow and the assembly process flow are described in the next two subsections.

3.2.1 Composites Manufacturing - General Description

Figure 3.3 "Composites Manufacturing Process Flow" shows a simplified process flow diagram for the entire composites manufacturing process at the Fabrication Division.

The A3430 shop fabricates the various individual detail parts such as spars, ribs, skin panels, leading edge covers, etc. Graphite/epoxy composite laminates are fabricated from tape or fabric material which is composed of graphite fibers pre-impregnated with epoxy resin. The graphite/epoxy material is cut into specified shapes, kitted, layed-up on a molding tool (lay-up mandrel), vacuum bagged and compacted, and cured in an autoclave under heat and pressure. After curing, composite parts are trimmed to final net shape and inspected. The detail parts are then transported to inventory storage and eventually to A3410 for assembly into the various aircraft structures described in section 3.1.

The A3250 shop is the Fabrication Division machine shop. This shop takes aluminum and titanium precision cast-forgings supplied by vendors and machines them into hinges, flight control actuator fittings, and other metal components. These fittings are installed into the graphite/epoxy front spars of the rudders, elevators, and ailerons in the A3410 shop.

Once assembly, paint, and inspection are completed in A3410, the assembled structures are shipped to one of Boeing's aircraft final assembly plants, at Renton or Everett. These plants are referred to as the Prime Divisions.

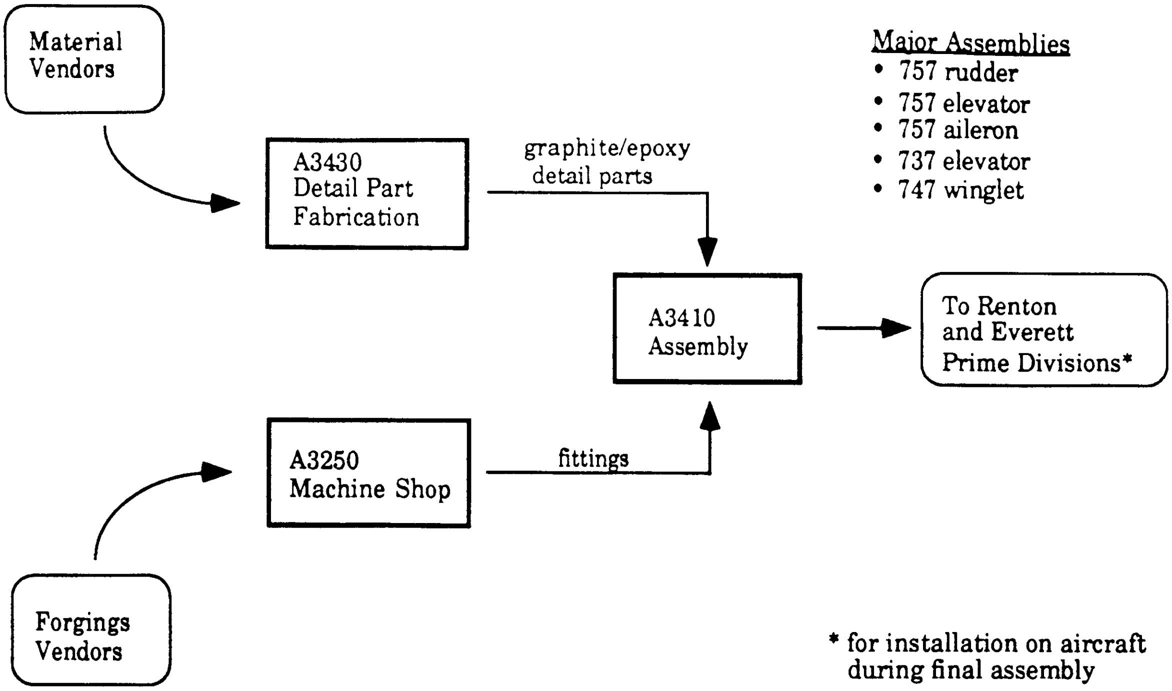
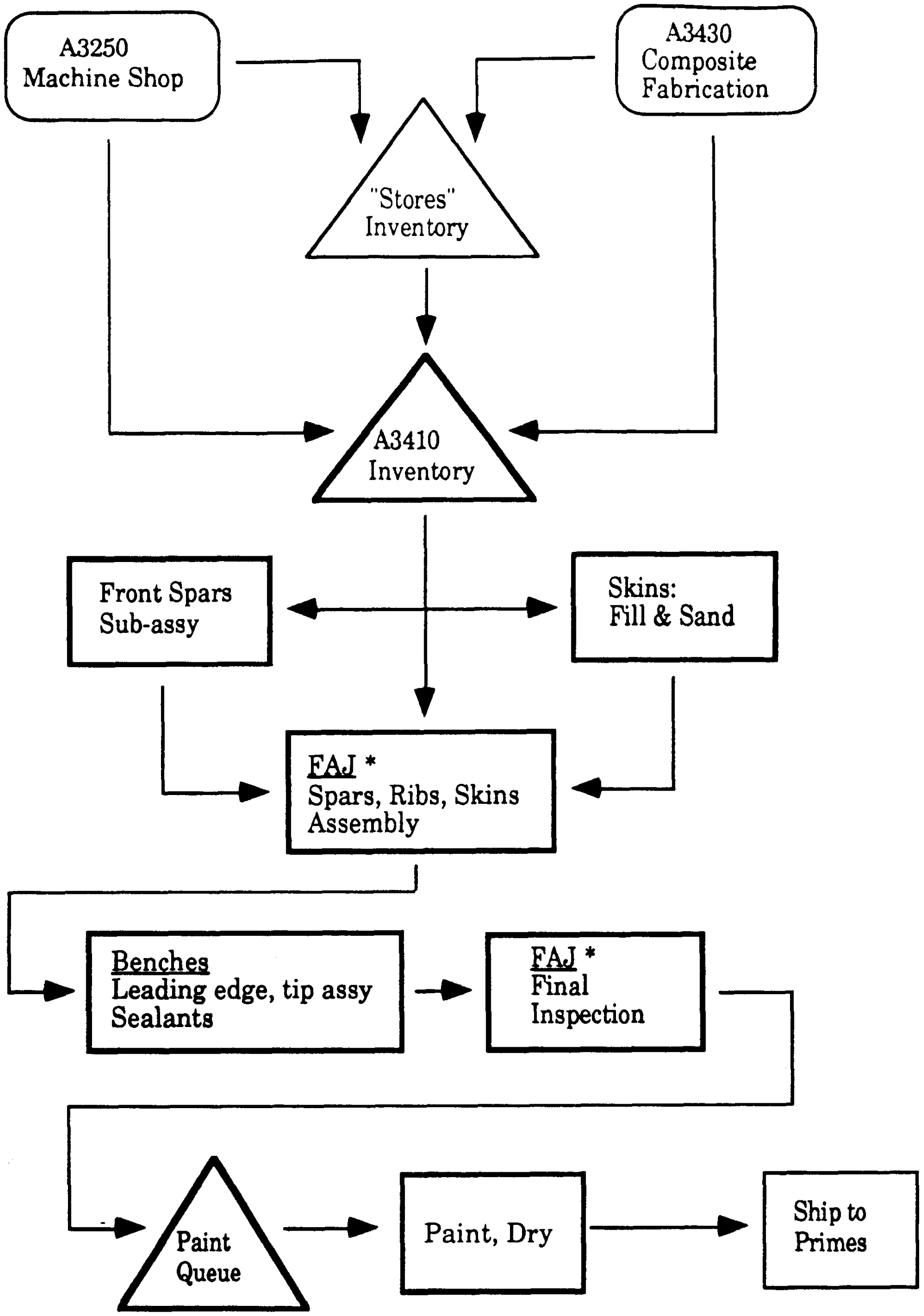


Figure 3.3: *Composites Manufacturing Process Flow at Boeing's Fabrication Division.*

3.2.2 A3410 Composites Assembly Process Flow

Figure 3.4 is a detailed process flow diagram showing the assembly process steps within the A3410 shop. This particular process flow is for the 757 rudder, but it is representative of the basic process steps common to the other composite assemblies studied.



* FAJ = Floor Assembly Jig

Figure 3.4: *A3410 Assembly Process Flow. The stations and processes located within the A3410 shop are outlined in bold black*

The major assembly operations are conducted at the following three stations in the process flow: (1) front spar sub-assembly, (2) floor (or final) assembly jig (FAJ) assembly, and (3) bench assembly. The operations at each of these stations are, in chronological order:

- part fit-up and indexing (assembly jig-loading)
- shimming
- drilling, reaming, and countersinking holes for fasteners
- fastener installation
- sealing
- QA inspection
- rework

Following are brief descriptions of each of these operations:

a) part fit-up and indexing, (assembly jig-loading)

> The devices used to precisely locate and hold in place detail parts and fittings during assembly are called floor (or final) assembly jigs (FAJs). These tools are made of very rigid steel support structures onto which are mounted carefully machined headers and locating plates. Part fit-up involves the loading of the individual detail parts into the FAJ. Indexing means precisely locating the parts relative to the FAJ and relative to each other. This is accomplished by butting parts up against components of the assembly jig, called "headers", or aligning parts and fittings with tooling alignment holes (called "K-holes") and pins.

b) shimming

> Shimming is a critical task in the assembly of aircraft structures because even small gaps between mating surfaces lead to improper loading of the composite laminates, which can lead to delaminations and structural failure. Once parts are loaded into the FAJ, a prescribed clamping load is applied, either by spring-loaded temporary fasteners or weighted bags of buckshot. Pre-loading of the detail parts is typically limited to approximately 10 pounds/foot. Any

remaining gaps between mating surfaces greater than a specified maximum size (generally ≥ 0.009") requires the insertion of a shim to fill the gap.[1] These gaps are measured by the shop mechanics using feeler gages. A polyimide laminated material known as "Kapton" is used to create customized shims to fill the gaps between mating surfaces. Layers 0.003" thick can be peeled off the shim stock to obtained the required thickness shim. Shims can be from 0.006" to 0.060" maximum. Gaps larger than 0.060" are not permitted to be shimmed, and become a rejectable condition in assembly.

c) drilling, reaming, and countersinking holes for fasteners

Once composite detail parts are indexed and shimmed properly, holes in each of the mating surfaces must be drilled, reamed, and countersunk in preparation for the installation of fasteners. Typical mating surfaces are rib to spar, skin panel to spar, skin panel to rib, and leading edge cover panel to front spar. Graphite composites are especially difficult to drill, requiring more time, a higher degree of operator skill, and special carbide-tipped drills, reamers, and countersinks.

d) fastener installation

Following hole preparation and inspection, fasteners are installed. Unlike metal structure, rivets or other interference fit fasteners are not used in composites assembly due to particular characteristics of composite materials.[2] Most fastener types consist of a pin (bolt), washer, and collar (nut). In general, composites' fasteners are designed to be locked in place by the collar deforming around the pin as it is installed. To minimize galvanic corrosion problems between aluminum and graphite composite material, titanium fastener components are used in place of aluminum fasteners. Titanium

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[1] The clamping pre-load and gap allowables are discussed and explained in Chapter 4.

[2] The material properties of composites which require the use of non-interference fasteners are discussed in Chapter 4.

fastener components are also used in place of steel fastener components in order to save weight.

e) sealing

Once a structure has been assembled, sealants are applied at joints to achieve a smooth aerodynamic surface. In contrast to the assembly mechanics who are assigned to specific stations, designated employees, known as sealers, roam the entire shop applying sealants to each assembly as required.

f) QA inspection

At numerous steps in the assembly process, Quality Assurance inspections are required. Two purposes are served: one, to check the quality of the workmanship; and two, to insure that each operation specified on the manufacturing plan has been accomplished. Out-of-tolerance conditions or improper procedures result in the documentation of these “discrepancies” on rejection tags (if a major problem) or “pick-up” forms (if minor).

g) rework

Once a discrepancy has been identified and documented, the paperwork is routed through a series of organizations who must decide whether the discrepancy requires major rework, minor rework, scrapping of the part, or if the part or assembly can be used as is (UAI). If minor rework is required (i.e., ≤ four hours estimated) the shop floor mechanics perform the rework as direct labor hours. If major rework is required (i.e., ≥ four hours estimated) the rework is performed under a separate labor hour category, known as “control code 4”. As such, control code 4 (CC4) is synonomous with major rework. The only difference between direct labor hours and CC4 rework hours is that they are tracked separately by the Fabrication Division’s internal accounting system.

3.2.3 A3410 Composites Assembly Shop Workforce

The workforce in the A3410 composites assembly shop consists of direct labor, indirect labor, and supervisory employees. The direct labor is provided by mechanics and lead mechanics. Each composite structure has at least one lead mechanic for each shift. Lead mechanics are determined by seniority, which is determined by both time with the company and time within the assembly shop. Operations are primarily conducted over two shifts per day, with limited activity during the third shift overnight. On the first shift, each type of structure has one to two mechanics working at two (757 rudder) to eight (737 elevator) assembly jigs. Additional mechanics work at benches (flat tables) on those assemblies nearing completion. The second shift has about one-half the manning levels of the first shift.

As described above in the assembly operations discussion, one of the primary skills required of the mechanics involves proficiency with power drilling, countersinking, and routing tools. Another skill which mechanics develop with experience, which some consider more of an art, is the custom shaping and installation of shims into gaps between mating surfaces of components being assembled. Part fit-up, pre-loading within limits, fastener installation, and application of sealants are other skills acquired with experience in the assembly shop. In general, each mechanic is capable of and expected to perform each type of operation required in composite structure assembly, although less skilled or experienced mechanics tend to leave the most difficult drilling or countersinking operations to others.

4.0 Data and Information Presentation

The purpose of this chapter is to present the quantitative data and qualitative information acquired during the author's research project at Boeing. The data and information were obtained through numerous sources, including direct observations of shop processes, shop mechanic surveys, interviews and discussions with design and manufacturing personnel, inquiries of the finance directorate, and various job scheduling and tracking reports. A detailed analysis of the composite structure assembly issues indicated by the data and information is provided in Chapter 5 - "Analysis of Composites Assembly Issues".

4.1 Assembly Shop Data

This section presents the quantitative data acquired during the internship project associated with composites assembly.

4.1.1 A3410 Composites Assembly Productivity Trends

One of the prime motivations of this study is that graphite/epoxy composite aircraft structures are considered to be very expensive relative to their aluminum counterparts. Since the focus of this study is on the assembly of composite structures, labor hour data for the A3410 composites assembly shop was requested from the Boeing Fabrication Division Finance organization. The actual labor hour data is confidential to Boeing, therefore non-dimensionalized per unit labor hour data was provided to the author. The data illustrate the lack of productivity improvements over time in the A3410 shop, and the high variability in labor expended per unit. This data is presented in Figures 4.1.a and 4.1.b. The data shown are for the 757 rudder and the 747-400 left winglet. The other composite structures studied had similar labor per unit histories. The data indicates the direct labor hours expended in assembly, and does not include major rework (control code 4) labor hours or indirect labor.

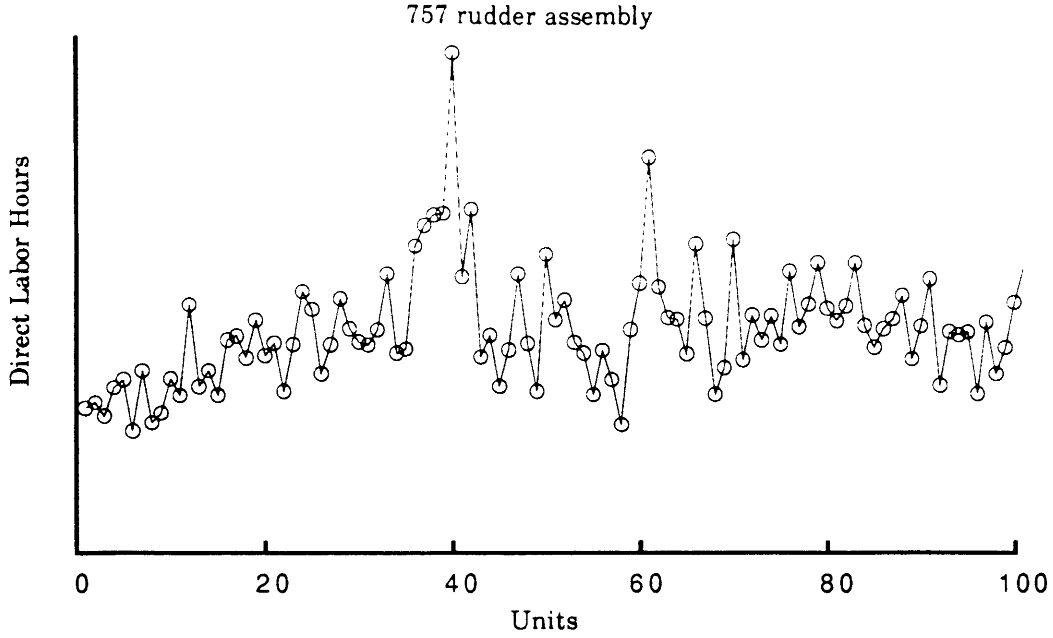


Figure 4.1.a: *757 rudder direct labor (DL) per unit. The time period covers approximately 18 months of production.*

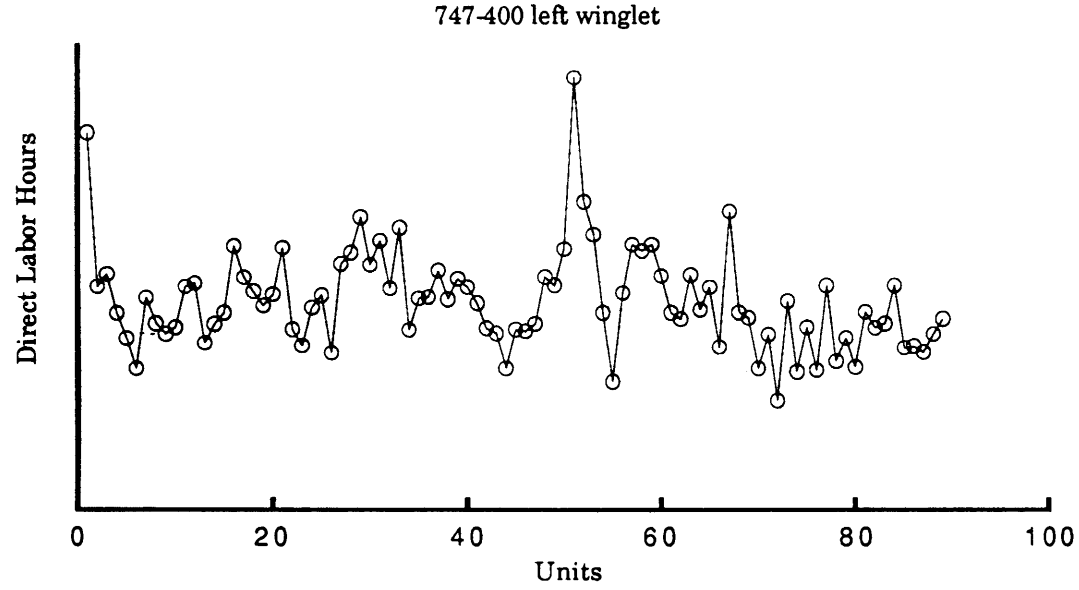


Figure 4.1.b: *747-400 left winglet direct labor (DL) per unit. The time period covers approximately 24 months of production.*

These direct labor per unit data suggest the central question of this study: "what are the underlying causes of assembly productivity issues for advanced composite structures?"

4.1.2 Labor Allocation to Each Assembly Operation

This section presents estimates of the relative percentages of direct labor expended performing the various discrete operations which comprise composite structure assembly in the A3410 shop. Data from any previous quantitative assessments of this scope for composites assembly operations in the Fabrication Division was not available at the time of this study.

Description of Methodology

The first consideration was how to obtain data in the most accurate yet time efficient manner. The most accurate means would be to perform a traditional time study of the A3410 operations. This approach would consist of observing shop activities with a stopwatch and recording the time spent by mechanics on each type of assembly operation, such as part fit-up, shimming, hole drilling and countersinking, etc. However, this would be an extremely time-consuming process for an individual researcher to collect enough data to be statistically useful and from which to draw reliable conclusions.

Due to the above considerations, an alternative method with which to obtain assembly labor allocation data was developed which involved surveying the A3410 mechanics and lead mechanics directly. The author assumed that the mechanics themselves would have the best available knowledge of the time spent on each assembly operation. This method had the advantage of acquiring a substantial amount of the experience available in the shop in a relatively short time. Although there was some concern regarding the precision of the survey, results in the form of relative percentage estimates of total labor effort would be useful in identifying the most time-consuming operations.

After consultation with several MR&D Advanced Composite Structures and MR&D Factory Support personnel, a survey form was developed listing the major assembly operations and other time expenditure categories. The form is reproduced in Figure 4.2. A cover sheet was attached to the survey describing its purpose and providing instructions on how the form should be completed, as shown below.

Purpose

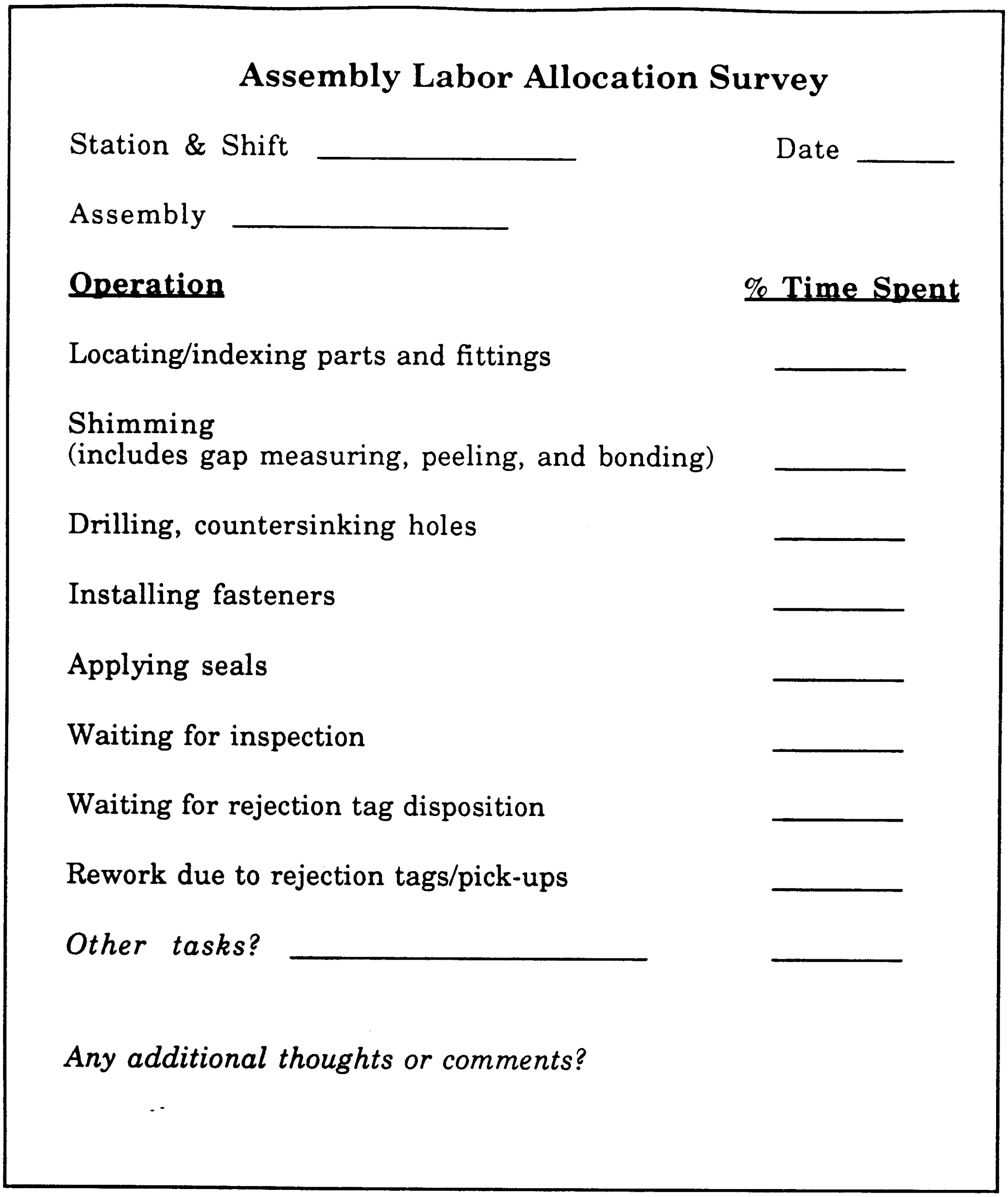
To estimate the average relative percent labor spent in each assembly operation or waiting category, in order to determine those which are most time-consuming.

Instructions

On the attached survey form, please write in the relative percent of time spent on the assembly operations listed. Feel free to write in an operation or other catergory if it is not listed.

A comments section was also provided soliciting any ideas from the shop mechanics on what were the major issues affecting composites assembly or how the process could be improved.

Out of approximately fifty-eight A3410 mechanics and leads assigned to the five composites assemblies studied, twenty-seven survey responses were collected for a response rate of 47%. The aggregate survey results for all five composite assemblies are presented in Table 4.1.



Assembly Labor Allocation Survey

Station & Shift ______________ Date ______

Assembly ______________

Operation	**% Time Spent**
Locating/indexing parts and fittings	________
Shimming (includes gap measuring, peeling, and bonding)	________
Drilling, countersinking holes	________
Installing fasteners	________
Applying seals	________
Waiting for inspection	________
Waiting for rejection tag disposition	________
Rework due to rejection tags/pick-ups	________
Other tasks? ______________	________

Any additional thoughts or comments?

Figure 4.2: *Assembly Labor Allocation Survey Form*

Assembly Operation	Labor Mean	Labor Ranges
part fit-up	11%	7 - 17%
shimming	11%	4 - 20%
hole drilling	15%	8 - 18%
fastening	19%	15 - 31%
sealing	8%	4 - 17%
inspection	6%	3 - 8%
rej. tag disposition	13%	7 - 22%
rework	12%	4 - 18%
other	5%	0 - 8%

Table 4.1: *A3410 Assembly Labor Allocation to each assembly operation, showing mean values and ranges across the composite structures studied. The operations are listed in sequential order.*

The range of labor allocation estimates for several of the operations are fairly wide. However, given the differences in size, number of parts, fittings, and fasteners, part dimensional accuracy, and other process variables, the mean values at least provide a general indication of how labor effort is consumed in this particular composite structure assembly shop.

The survey results indicate that for secondary structure, the largest portion of labor expended in assembly is associated with the mechanical fastening of composite detail parts and fittings. Hole drilling, reaming, and countersinking operations plus fastener installation together account for an estimated 34% of total labor. Part fit-up and shimming is somewhat lower, accounting for about 22% of labor expended.

Rework is estimated to consume approximately 12% of total labor. The survey did not attempt to distinguish between the amount of time expended on "control code 4" (major) rework primarily associated with rejection tags, and the minor rework associated with "pick-ups".

Together, the estimated amount of time spent waiting for Quality Assurance inspection and waiting for rejection tag disposition accounts for about 20% of the mechanics' time. Note that this is time in which not only the mechanics are idle, but the assembly is waiting also. In effect, the process flow is temporarily stopped. Sometime the mechanics can work around the part or operation step with the discrepancy awaiting tag disposition, but more often they cannot.

4.1.3 Detail Part and Fitting Shortages

A result which appeared repeatedly in the comments section of the survey was that the mechanics often did not have a complete set, or kit, of detail parts and fittings to assemble when scheduled to, or that if they did have parts, they did not fit together well . During subsequent follow-up interviews, the A3410 mechanics were asked to estimate the percentage of assemblies which did not have the required detail parts and fittings available when needed. The shop mechanics were also asked to estimate how long they had to wait, on average, for the late details or fittings to be delivered. The results of these follow-up interviews are presented in the Part and Fitting Shortage/Delays Estimates shown in Table 4.2. "Percent Units with Parts Stock-outs" refers to the percentage of assembly units for which complete parts kits were not available on the scheduled assembly start date. "Average Delay" refers to the average number of manufacturing days beyond the scheduled assembly start date that it takes for all the required parts to be delivered.

While the information summarized in Table 4.2 are rough estimates based on the shop mechanics experience and recollections, it nevertheless served as the first clear indication of a random, highly variable supply of incoming parts from the fabrication shops to the assembly shops.

Assembly	Percent Units with Parts Stock-outs	Average Delay (days)
757 rudder	10%	2
757 elevator	50-100%	5-10
757 aileron	50-90%	1-2
747-400 winglet	25%	2-3
737 elevator	50%	1

Table 4.2: *Part and Fitting Shortage/Delay Estimates, as estimated by shop mechanics*

The results of this survey generated interest in additional data pertaining to the A3410 assembly process. The types of data which existed and were acquired during this study are (1) control code 4 rework hours as a percentage of total labor hours according to the Fabrication Division financial accounting database, (2) scheduled assembly flowtimes as defined by Fabrication Division production schedules, and (3) records of actual detail part availability and assembly completion dates versus scheduled dates, according to Industrial Engineering - Shop Load "critical hardware" charts reviewed in weekly management meetings. This information is presented in the following sections.

4.1.4 Rework as a Percentage of Total Direct Labor

Based on Fabrication Division accounting system data, the percentage of units requiring control code 4 (major) rework and the total amount required on the 757 rudder and elevator, the 737 elevator, and the 747-400 winglet, expressed as a percentage of the total labor hours expended, is presented in Table 4.3. These results were provided by Industrial Engineering Estimating/Finance personnel. Total control code 4 rework hours charged were compared to total direct labor hours for the indicated sample size of units. The rework percentage is the quotient resulting from dividing the control code 4 hours by the total labor hours expended (direct labor + CC4 rework).

$$\text{Rework \%} = \frac{\text{CC4 rework hours}}{\text{Total hours}}, \quad \text{where Total = direct labor hours + rework hours}$$

Assembly	Sample size (no. of units)	Percent units reworked	CC4 rework, as percent of total labor for all units
757 rudder	101	35%	3%
757 elevator	232	12%	2%
737 elevator	978	15%	2%
747 winglet	182	14%	2%

Table 4.3: *A3410 percent of units reworked, and control code 4 rework as percent of total labor for all units*

Note that the rework percentage based on the accounting system data is substantially less than that estimated by the shop mechanics. This discrepancy will be discussed in Chapter 5 - "Analysis of Composites Assembly Issues".

4.1.5 Assembly Flowtimes

The scheduled assembly flowtimes for two of the composite structures studied are shown in Figure 4.3. The numbers within each schedule bar represent the manufacturing days (work days) between each milestone. Beginning with the center of each bar, the grey area represents a given unit's assembly start and complete dates as scheduled by the Fabrication Division. The "Corp. Start" and "Corp. Comp." milestones stand for corporate start and corporate complete dates, respectively. These milestones have little meaning to the A3410 shop, and simply denote the scheduled period for the assembly activity as tracked by Boeing's corporate production schedule management system. The "Parts Available" milestone is the day all the detail parts are supposed to be drawn out of what is referred to as "stores". "Stores" is the inventory storage system where material, parts, and subassemblies are kept in between production process stages. On the "parts available" date, the kits containing all the required parts and fittings are brought to the inventory racks at the various

A3410 assembly stations (refer to Figure 3.2 - *A3410 Assembly Process Flow*). The last milestone on each bar is the date the unit is scheduled to be installed at the aircraft final assembly plant, known as the "prime" division. This date is also known as the "jig-load" date at the prime.

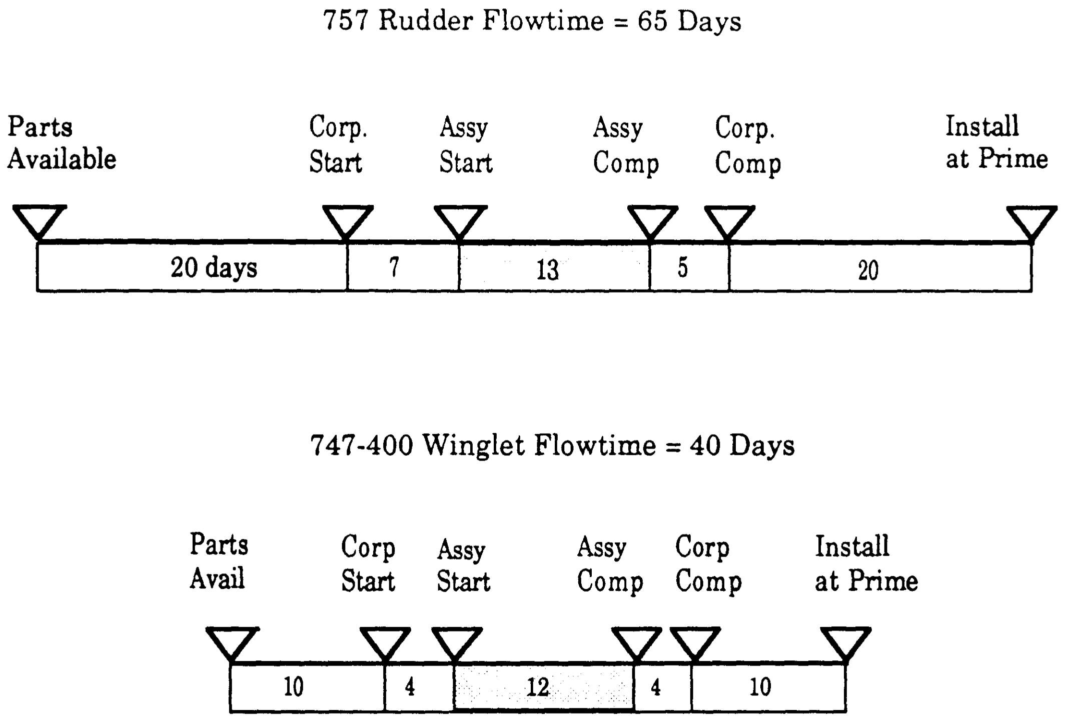


Figure 4.3: *Assembly Flowtimes, showing the period scheduled for actual assembly activity (grey) and the overall allocated flowtime period.*

The allocated flowtime is three and one-half to five times the scheduled assembly period. The flowtimes and actual assembly schedules for the other composite structures studied are equivalent. According to the A3410 IE - Shop Load manager, the large schedule buffers in the flowtimes serve the purpose of providing schedule protection. In his opinion, reducing these schedule buffers represents an outstanding opportunity for making the composites manufacturing process more efficient. At present, the schedule and associated inventory buffers have become somewhat institutionalized, as everyone knows the size of the available time buffer. Therefore, the upstream fabrication shops tend to work toward the scheduled assembly start dates, and rarely if ever meet the earlier milestones. This view was concurred with by an A3410 Production Control - Expediting clerk who stated that "in effect, we (the Fabrication Division) don't work to our published completion schedules; we work to our downstream customer's load (start) dates. If our suppliers, the A3430 and A3250 shops, worked to completion schedules, then production flow would be much smoother with less contingencies, expediting, and tracking of short parts."[1]

4.1.6 Parts Availability versus Schedule

Actual dates of parts availability, assembly start, completion, and shipment to primes are tracked by the A3410 IE Shop Load group for every composite structure unit. This information is recorded on what are referred to as "Critical Hardware" charts. These charts are reviewed in weekly meetings attended by the shop management team in order to highlight those detail parts and fittings which are required for ongoing assemblies yet are unavailable, and are therefore "critical". The chart reproduced in Figure 4.4 is typical for the 757 rudder, elevator, and aileron, 737 elevator, and the 747-400 winglet. Note that complete sets of parts are not usually available until the day assembly is to start, and often are not available until several days and sometimes weeks later. Parts and work starts are chronically late, usually at least consuming the ten-fifteen day buffer before scheduled assembly start, and many times not arriving until well after that. In some cases, assembly actually starts before all the parts are available, but the start date is still considerably delayed.

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[1] A3410 Production Control - Expediting personnel

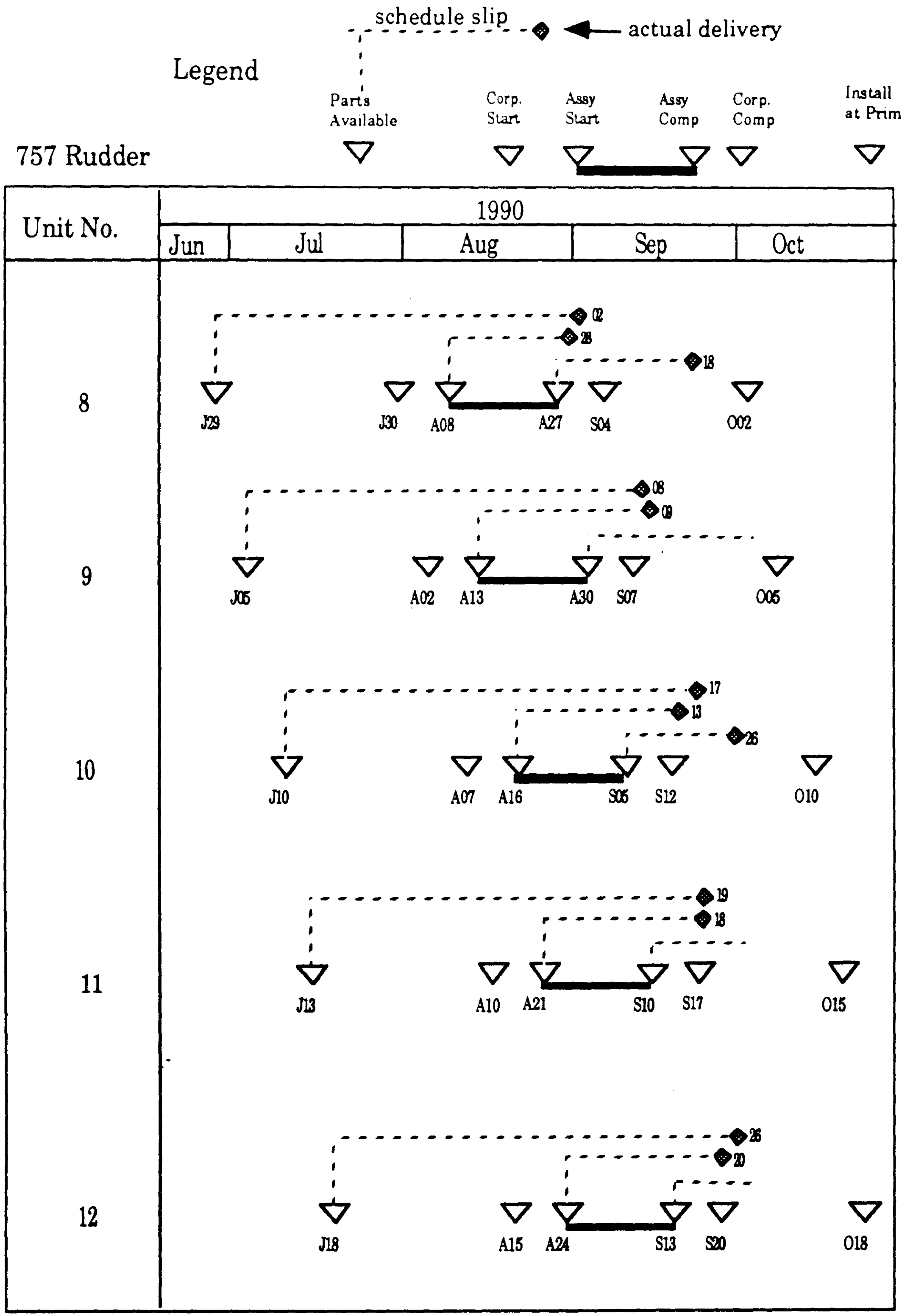

Figure 4.4: *Typical Parts Availability vs. Scheduled Dates. Source: A3410 Critical Hardware chart.*

4.2 Factors Influencing Assembly

In this section, the qualitative information which was obtained through numerous interviews and discussions with Boeing personnel, as well as observations by the author, are documented. The information is organized along general topic areas relating to composites design, tooling, assembly operations, and other factors which impact assembly productivity.

4.2.1 Material properties and design practices

The information presented in this section, unless otherwise noted, was primarily obtained from the MR&D Advanced Structural Composites group and the 777 Composite Empennage engineering organization. Discussions with these engineers focused on the material properties and engineering design practices which impact the assembly of composite structures.

Graphite/epoxy composite material properties

One of the advantages of graphite/epoxy and other filamentary composite materials over metals is the tailorability of laminate designs so that maximum strength, offered by the reinforcing fibers, is coincident with the greatest load and stress paths. Thus, composite materials are highly anisotropic, exhibiting relatively high strength and stiffness in the plane of the laminate, but relatively low interlaminar (z-direction, out-of-plane) strength and stiffness (see Figure 4.5).

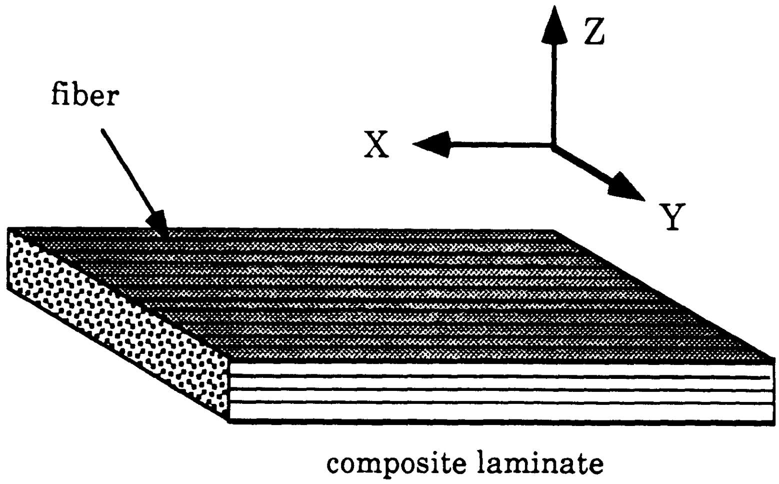

Figure 4.5: *Composite material coordinate axes, showing the x-y plane and z out-of-plane (interlaminar) direction.*

As a result, composite laminates generally do not resist out-of-plane loads nearly as well as in-plane loads. Out-of-plane loads are imparted on a laminate when it is assembled to another laminate by mechanical fasteners, as shown in Figure 4.6. If fastener pull-up loads are too great, the composite material will experience delaminations and possible loss of structural integrity.

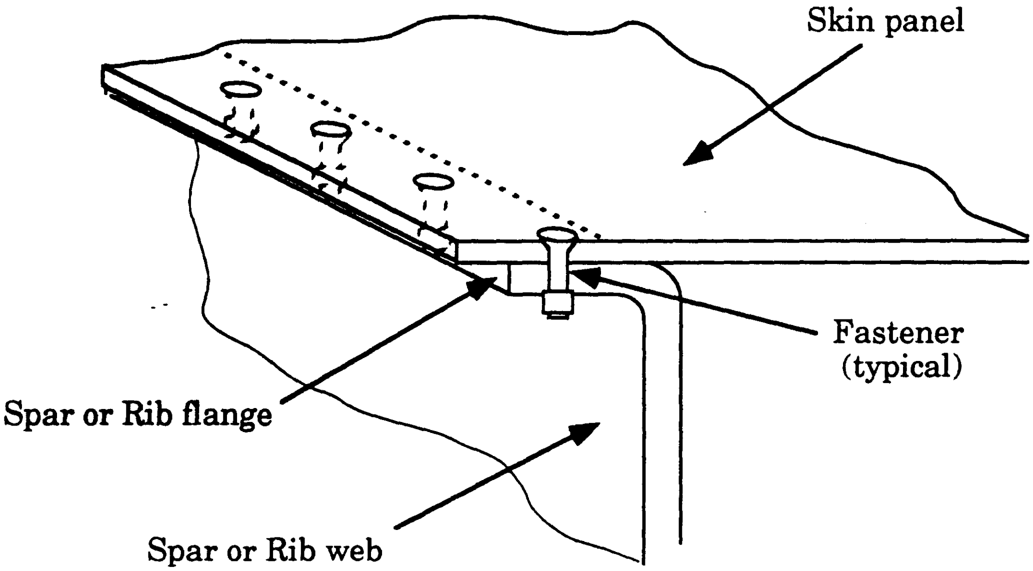

Figure 4.6: *Typical spar-skin panel or rib-skin panel mechanically fastened joint. Note how the fastener pull-up load acts in the z-direction of both laminates.*

Using mechanical fasteners to assemble composite laminates can offset the strength and stiffness advantages of composites. The hole required for a fastener can reduce the localized load-carrying capacity of the laminate material by approximately 40%[1]. This characteristic gives rise to criticism of traditional spar-rib-skin panel composite structures as black aluminum designs. The implication is that these types of designs merely substitute one material for the other, without taking full advantage of the unique anisotropic properties characteristic of composite laminates.

Ply thickness variability

The graphite/epoxy uni-directional tape and woven fabric material used to lay up composite structures exhibits an average ply thickness variance of approximately ± 7%. This variance can lead to composite laminates varying in thickness by ± 7%, which for thicker gage parts in particular, leads to inherent shimming requirements during assembly. Composite designers must take this variability into account when determining part tolerances. The Boeing Materiel Division is currently working with its suppliers to reduce this ply thickness variation.

Ply drops

Ply drop-offs in composite laminates can occur due to partial plies in a laminate design (not extending the full dimensions of the laminate) or due to lap-splices of two adjacent ply sections.

partial plies

Through carefully detailed load analysis, designers are able to design composite structures with custom-tailored ply shapes and sizes within the laminate. The objective is to minimize the amount of material required, thereby saving weight. The result is composite parts which have multiple ply-drops, often along the mating surface where the part is joined to another. Given the nominal ply thickness of .0074", plus the variability in

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[1] Hadcock, R.N., "Design of advanced composite aircraft structures", *International Journal of Vehicle Design, Special Publication SP6*, 1986, p.283.

the ply thickness and fabrication processes, the presence of ply-drops results in an increased probability of shimming requirements during assembly.

lap-splices vs. butt splices

The other design practice which results in ply-drops in composite fabric laminates is the requirement to overlap adjacent plies in the same layer of a laminate rather than allow them to be butted up against each other. A fabric ply splice is often necessary in a laminate due to the part size, geometry, and ply orientations, and due to finite fabric pre-preg material widths. A schematic illustration of a ply drop due to a lap-splice is shown in Figure 4.7.

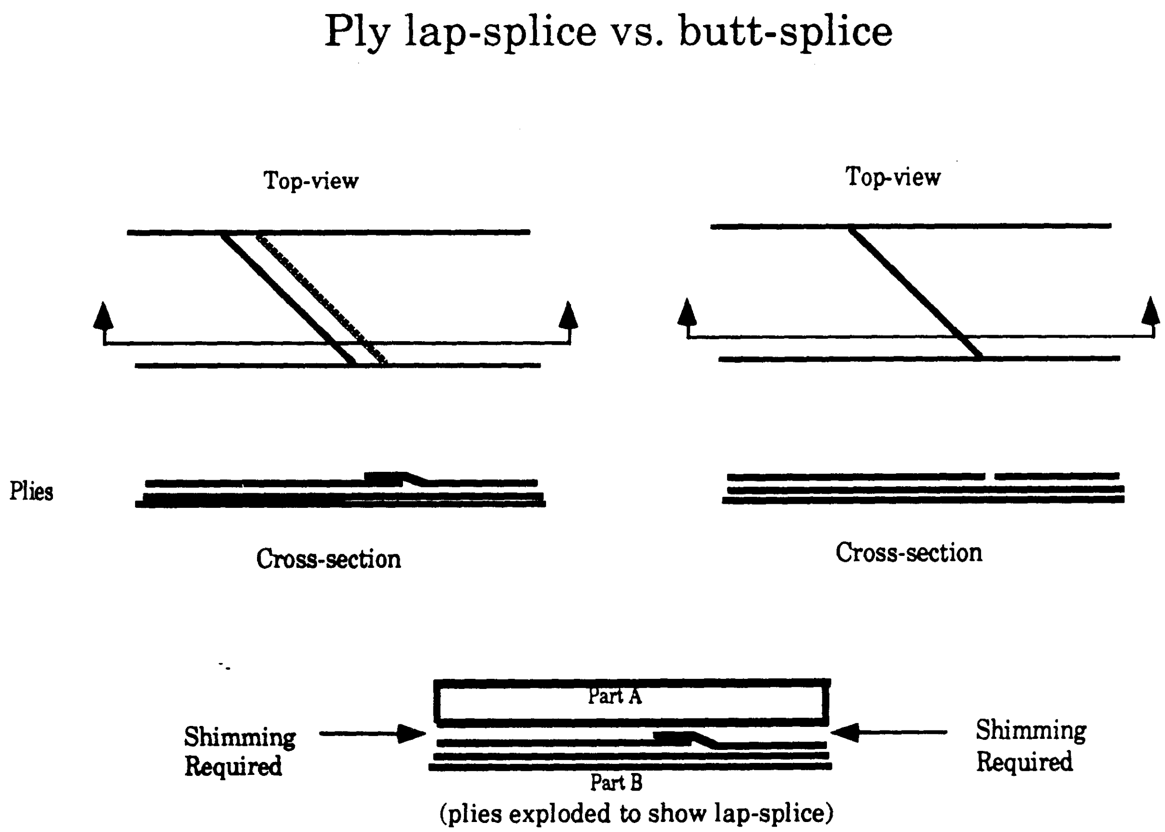

Figure 4.7: *Ply lap-splices vs. butt-splices*

Designers require lap-splices to insure complete load transfer between adjacent co-planar plies. The concern is that simple butt-splices will reduce the load capacity of that particular layer of the laminate, due to the ply discontinuity at a splice. To further insure maximum structural integrity, some designs require laterally separate splices from one laminate layer to another, which also serves to minimize the build-up of lap-splice "bumps" in any one particular location on the surface of the part. Nevertheless, the presence of lap splices under a mating surface can create the need for shimming in assembly, for the same reasons as described previously for partial-ply drop-offs.

Co-curing/co-bonding versus mechanical assembly

From an assembly point of view, improved composite designs could feature fewer detail parts and fewer mechanical fasteners. The generally common practice of stiffening secondary structure skins with bonded honeycomb core is an example of an improved design. The co-bonding of stringers to the skin panels for the 777 composite horizontal stabilizer is another example of such a design improvement. For example, with traditional methods of mechanical fastening, 5,000 and 7,000 fasteners would have been required for the 777 horizontal stabilizer's lower and upper skin panels, respectively. With co-bonding, the number of fasteners required for each panel is reduced to 192.[1]

4.2.2 Fabrication tooling

In the context of composites fabrication and assembly, the term "tooling" has a different meaning than in general public use. In composites, tooling refers to jigs, fixtures, mandrels, molds, templates, form blocks, etc.

Based on experience with A3410 and A3430 composite manufacturing, an MR&D Factory Support engineer stated that tooling is an area where there is much room for improvement. Problems such as parts not being trimmed correctly, holes in the wrong locations, and parts not fitting together correctly can be traced back to tooling design, coordination[2], and

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[1] Boeing 767X Horizontal Stabilizer chart, MR&D Advanced Composites

[2] Tool coordination means the consistency of critical dimensions and reference locations between fabrication lay-up mandrels, sub-assembly tools, and final assembly tools (between Auburn fabrication, assembly, and Renton or Everett prime divisions, for example.)

maintenance. In this engineer's opinion, substantial benefits would be gained by better controlling tolerances. Tolerance build-up of details plus tooling tolerance build-up should be studied before shimming allowance is figured into the design of composite parts.

Fabrication tooling: lay-up mandrels

A Fabrication Division manufacturing engineering supervisor, with former experience in tooling, identified detail part dimensional variation as the biggest issue for assembly. The sources of part variation result from (1) inaccuracies in lay-up mandrel tooling, (2) variation due to the autoclave curing process, or (3) inaccuracies attributable to the hand routing fixtures used to trim and check contours of the parts. In this individual's opinion, the accuracy and consistency of lay-up mandrels is perhaps the most critical factor in the production of consistent, high quality composite detail parts.

The lay-up mandrel material is very important. Lay-up mandrels are made from a variety of materials, such as aluminum, steel, Invar[1], carbon fiber reinforced plastic (CFRP), fiberglass, ceramic, and nickel electroplate. Each has its own advantages and disadvantages. The metal materials are more durable than the CFRP or ceramic, but can have highly differential coefficients of thermal expansion (CTE) from the composite laminates, causing part warpage after cure. Some materials can be fabricated into lay-up mandrels with fewer mold transfers, thus minimizing error in the form of tolerance build-up. Production rate, expected program duration, and anticipated design changes all influence tooling material decision.

Regarding durability, BCAG has traditionally strived for a 600 shipset life-span for tooling. This has been met reasonably well by aluminum and other metal lay-up mandrels, but fiberglass and graphite/epoxy tooling have not proved as durable. These materials have been susceptible to damage from handling, and susceptible to cure-cycle degradation. Thus,

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[1] "Invar" is the registered trade name of the French Societe Cresot-Loire, and refers to the metal's "invariable" dimensional properties as a function of temperature. Invar is a 38% nickel alloy of steel, is very durable, and has a CTE very close to that of graphite/epoxy. Drawbacks include Invar's high cost, weight, and low thermal conductivity.

composite tools have generally lost favor at Boeing on the basis of durability. Boeing is attracted to advanced metal materials such an Invar due to a need for high production rates and minimization of downtime due to damaged tools.[1]

Aluminum lay-up mandrel tools are used extensively in composites fabrication. However, graphite/epoxy and aluminum have significantly different coefficients of thermal expansion. This results in different amounts of expansion and contraction between the laminate and the lay-up mandrel during the autoclave curing process, which creates residual stresses and warping in the cured part. For a graphite/epoxy part built off an aluminum tool, the large difference in CTEs must be compensated for in the machining of the tool surface. Despite one report in the literature that with proper compensation for thermal expansion, aluminum tooling gives the detail part accuracy required for graphite/epoxy parts[2], experience at Boeing has shown that the differential effects have been very difficult to predict. Often, it has taken many series of trials and errors machining and re-machining a lay-up mandrel before the proper compensation for differential thermal expansion is achieved.

Multiple mold transfers lead to tolerance build-up and poor tool coordination between master models, lay-up mandrels, hand-routing fixtures, and assembly jigs. Current tool design and fabrication processes based on multiple mold transfers and optics are considered obsolete, and the 0.010" tolerances achieved are not good enough to provide consistent, high quality detail parts. However, machining costs increase exponentially when trying to achieve tighter machining tolerances, as illustrated schematically in Figure 4.8.

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[1] "Tooling for composites: New materials may solve some old problems", *Advanced Composites*, Jul/Aug 1990, p.51-61.

[2] "Lockheed Aluminum Tool Aids Composite Assembly", Metalworking News, June 29, 1987, p. 8.

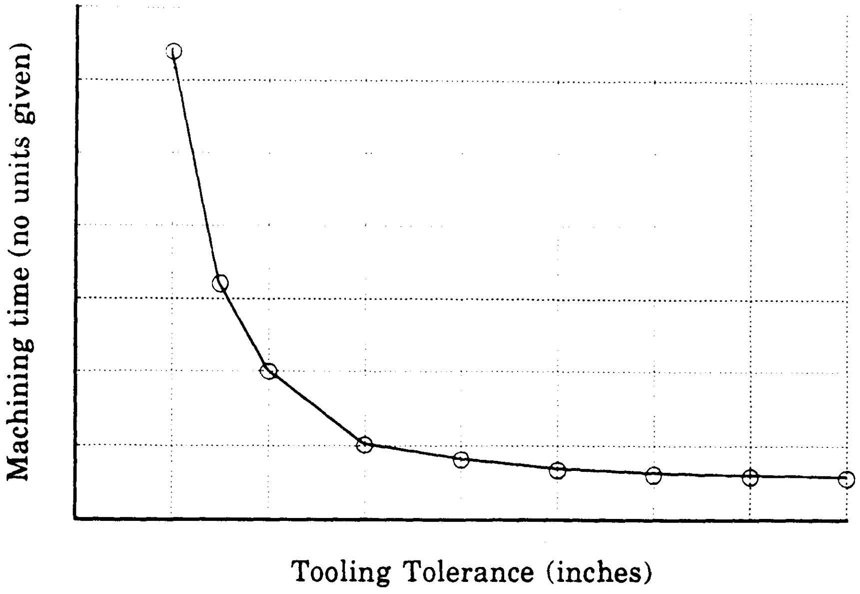

Figure 4.8: *Schematic of required machining time vs. tooling tolerance. Source: Boeing Tool Design Manual*

Dedicated maintenance, or "routining", of lay-up mandrels is an important activity which should be done in a preventative fashion, but which is currently performed only as corrective action when a mandrel starts producing rejectable parts. "Routining", or calibrating, the lay-up mandrel involves checking the face contour of the mandrel, and readjusting it to the correct contour if necessary.

Male versus female lay-up mandrel tooling

According to some MR&D Advanced Composite Structures engineers, the use of female tooling for the fabrication of detail parts would be preferable from an assembly standpoint. Female tooling allows dimensional control of the "outside mold line" (OML) of a part. For spars, ribs, ribchords, and most other components, the OML serves as the mating surface to other details. In order to provide a smooth, dimensionally controlled surface, mating surfaces[1] should be on the tool side of a part when possible. Bag

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[1] Also referred to as "faying surfaces" or "$ surfaces".

side surfaces, which are usually the OML mating surfaces for parts formed on male tools, are uncontrolled, and thus dimensional stability (repeatability) of a male tool-produced part is reduced. See Figure 4.9 for illustration.

Another reason to prefer female over male tooling is that the latter impacts the option for aircraft growth without retooling. Adding more plies to a male tooled composite part to give it higher load carrying capacity will also exceed the designed OML dimensions of that part.[1] Factors which argue against the use of female tooling include its relatively higher cost of fabrication, and uncertain confidence in the integrity of female tooled parts, due to ply bridging and resin starvation or richness in the corner radii.

Fabrication tooling: hand-routing fixtures (HRFs)

A hand routing fixture is used to trim composite detail parts to their final dimensions, after curing. One problem is that hand-routing fixtures are made of fiberglass, a relatively pliant material, yet these are used to check the contour of details after curing, and to guide the hand router during trimming. This leads to inaccuracy since the detail part is fabricated on a comparatively very rigid lay-up mandrel.

Another issue involves the quality assurance inspection of skin panels after trimming on a hand-routing fixture. Part contour is inspected while on the hand-routing fixture, but Boeing specifications allow for ten-pound bags to be placed on the skins at specified intervals along all mating surfaces. However, the pre-load cannot always be applied in assembly since the skin panel is loaded into an assembly jig. As a result, skin panels that pass A3430 quality assurance inspection may appear to be out of contour in assembly. Also, when mounted on the hand-routing fixture, only the gaps along the perimeter of the detail are inspected. Other mating surfaces in the center of a skin panel, for instance, where ribs would be attached, are not inspected.

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[1] In this context, "growth" refers to increasing the gage thickness of the structure in order to carry higher loads for future higher payload versions of the airplane.

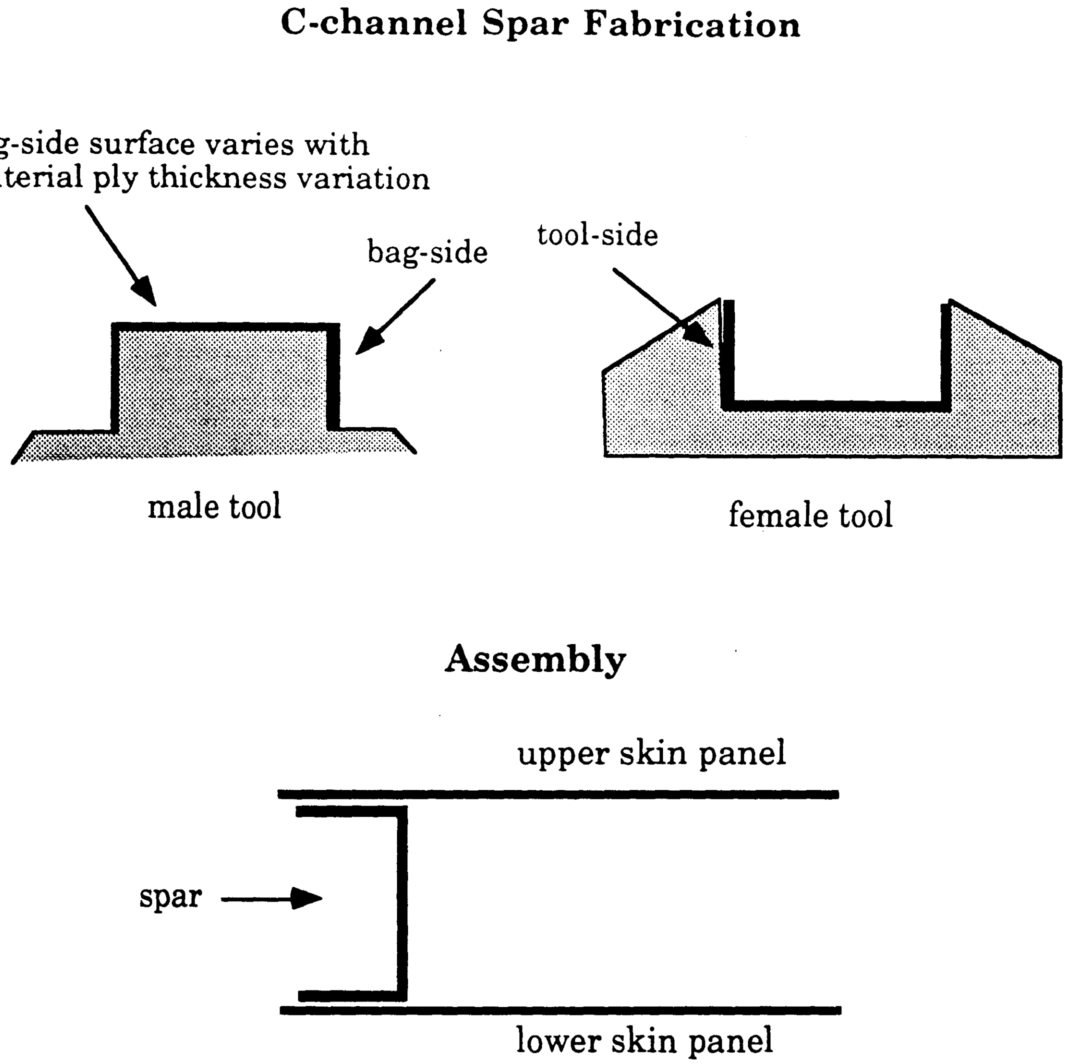

Figure 4.9: *Illustration of the lay up of a C-channel spar on (a) a male tool, and (b) a female tool. Note the tool-side and bag-side surfaces resulting from each method, and how a female tool provides better dimensional control of the spar's OML.*

4.2.3 Autoclave curing process

Autoclave process variability is a factor just beginning to be understood. Differential heat and cool rates have a major effect on the uniform cure of a set of composite laminates within a given autoclave loading. Heat rates for parts vary due to (1) tool size and material, and (2) tool location within the autoclave chamber. New initiatives to better control the autoclaving process include (1) introducing turbulence into the hot air inflow to obtain more uniform heat rates throughout the chamber, (2) grouping of tool/part combinations which share similar prescribed heat rates, and (3) repair and replacement of autoclave "finger racks", which support the lay-up mandrel tools during cure inside the autoclave . Many of these racks no longer evenly support the lay-up mandrels placed on them, leading to deflection of the lay-up mandrels and warpage of the composite laminates during cure.

4.2.4 Assembly tooling

The devices used to precisely locate and hold in place detail parts and fittings during assembly are called final (or floor) assembly jigs (FAJs). These assembly tools are made of very rigid steel support structures onto which are mounted carefully machined headers and locating plates. The headers and plates are used to index details and fittings in the jig. When constructing the final assembly jig, accurately locating the headers and fittings is very difficult and very critical to the quality of the jig. Final assembly jigs are built using optics (theodolites similar to land surveyor's equipment), which have finite accuracy limitations of approximately ±.005"-.010" per twenty feet of distance between the theodolite and the target location on the jig. For large jigs, such as for the 757 rudder, this limitation in optics accuracy can lead to significant error build-up.

An example of how assembly jig tooling problems affect the production flow is provided by the 757 rudder front spar assembly jig. For a certain period, this assembly jig, used to install hinge and actuator fittings in the graphite/epoxy front spar, was out of commission. During installation of the fittings, excessive pre-loading (stresses and deformations) were being created in the front spar. One of the causes has long been known to be inaccurate locating plates on the jig, but only recently had action been taken to make corrections. When the assembly jig went out of service, the supply of rudder front spars was stopped, effectively shutting down 757 rudder production. Another example of a problem with the assembly shop tooling is that there are small but significant differences between the two rudder final assembly jigs. A front spar (with fittings) may fit into one of the jigs, but not in the other.[1]

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[1] Production Control - Expediting personnel

4.3 Information on Assembly Operations

4.3.1 Part fit-up and shimming[1]

The various attributes of composite structure design and manufacturing which lead to part fit-up difficulties and shimming are described in this section.

Dimensional variation in detail parts and fittings

A majority opinion among design engineers, MR&D engineers, manufacturing engineers, and shop mechanics, is that composite detail parts need to be fabricated to closer tolerances in order to reduce the amount of labor-intensive shimming required during assembly. This is especially a concern for relatively thick gage composite structures, which have higher bending stiffnesses and are correspondingly more difficult to pull-up than are thin structures.[2] Shimming requirements for thick composite structures are under careful study at Boeing at this time. For example, during a 777 composite empennage design-build team meeting, representatives of the Boeing Military Airplane (BMA) division stated that shimming was their number one issue, with fasteners a close second. The emphasis on shimming by the BMA personnel is noteworthy when compared to the relatively lesser concern regarding shimming exhibited by the Fabrication Division composites assembly mechanics in the labor allocation survey. The disparity is likely a result of each group's relevant experience with graphite/epoxy composite structure, with BMA's experience being with relatively thick gage airfoil primary structure on military aircraft programs, and the Fabrication Division's experience being with relatively thin gage airfoil secondary structure assembled in the A3410 shop.

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[1] The information presented in the following three sections, unless otherwise noted, was primarily obtained from the MR&D Advanced Structural Composites group. Discussions with these engineers focused on three process areas in composite assembly: shimming requirements, drilling operations, and fastening.

[2] According to an MR&D engineer, the relative terms "thick composite structure" and "thin composite structure" refer to laminate gages greater than 0.200" and less than 0.125", respectively.

In composite structure, shims are generally required to be inserted in gaps between mated parts which are as small as 0.008"-0.009", prior to drilling operations and subsequent fastener installation. These assembly gap tolerances, above which shims are required, are tighter than the tolerances met in fabricating graphite/epoxy parts. As discussed previously, cured detail parts can vary up to 7% from the nominal design thickness due to a 7% thickness variation in the composite pre-preg material plies . This variation contributes to custom fitting and shimming requirements in assembly. Among the MR&D Advanced Structural Composites engineers, detail part dimensional accuracy is considered one of the greatest inhibitors of cost-effective assembly of graphite/epoxy structures.

> "If composites are ever to be produced in a manner cost-competitive with conventional metal, parts fabrication processes will have to be capable of producing detail parts which are consistently dimensionally accurate, eliminating the hand fitting and shimming process currently required. It has been proven through years of experience in metal structures that a basic requirement for cost effective assembly work is dimensionally accurate detail parts."[1]

This is a particular concern for composite primary structure, such as the 777 empennage. Compared to secondary structure such as the composite control surfaces currently manufactured by Boeing, most primary structure has generally greater gage thickness and reduced compliancy for attaining proper fit-up without extensive shimming.

The 747-400 winglet manufacturing engineer concurred, stating that a significant assembly issue is the dimensional variability of composite detail parts. Currently, dimensional accuracy and consistency is very poor. Most designs don't compensate for this, and this creates endless headaches in assembly. Also, trimming of parts, performed by a hand router, has a +/- .030" tolerance, which results in variations from part to part of up to .060".

An example of the impact of detail part variability is in regard to the warpage of the winglet skin panels. This was identified by the winglet manufacturing engineer as a common problem; the panels are virtually

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[1] MR&D Advanced Structural Composites - Assembly

always warped. The problem is due to uni-directional tape in certain areas of the skin panel, which are designed to add additional reinforcement in selective areas. However, expansion/contraction behavior of tape is different from fabric, leading to warpage. The winglet originally had 10 pound/foot pull-up load limits, but engineering now allows up to 60 lb/ft. However, the workers have difficulty indexing parts (moving them into correct positions) with such high loads applied. A possible solution to reduce or eliminate the warpage would be to design a balanced skin panel laminate, where the term "balanced" implies an equal number of $\pm\,\theta$ (theta) plies in the laminate[1].

Similar assessments were heard from the shop mechanics. A 757 elevator mechanic agreed that the assembly operation experiences high variability. Sometimes parts fit together very well, and sometimes they must spend hours trying to get parts to fit together. Sometimes there is no rework required, and sometimes there is a lot required. In the opinion of one of the 747-400 winglet mechanics, the Fabrication Division must improve detail parts quality, and suggested implementing tighter tolerances. For example, for the 747-400 winglet leading edge fairing, the parts rarely fit. There are frequent hole mismatchs between the vendor-supplied navigation light lens cover and the fairings onto which the lens covers are mounted. Also, even after fastening, joints between adjacent parts sometimes are not flush. Another example is that at the Everett final assembly plant for the 747, the wing extension and winglet holes mismatch. Everett mechanics must plug and re-drill the previously drilled holes in the winglet. In this mechanic's opinion, the source of the problem is poor tool coordination.

Another tolerance issue, according to manufacturing engineers, regards a need for machined fittings to be more accurate. It is strongly believed among this group that Boeing must continue efforts towards applying statistical quality control (SQC) to Boeing's internal processes and to their vendors as well. To illustrate the severity of the fittings quality problem, it was mentioned that over a certain period of time, the rejection rate for one

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[1] For composite laminate design purposes, ply directions are referenced as an angle $\pm\theta$ from a given principal axis in the laminate's reference plane.

of the rudder front spar fittings was 84 out of 104. A detailed description of the problem follows: Vendor-supplied forgings have surface pitting in the material. The machine shop has to grind the surfaces to remove this pitting. The machining process grinds away approximately 0.020 - 0.030" or more from the exterior dimensions of the forging. The fitting machined from the forging tolerances are only +/- .020". Finally, bushing holes and attachment holes are machined, but indexed (referenced) to only one side (the bottom) of the fitting. The result is that all the tolerance build-up error collects at the top surface, which must be heavily shimmed to fit-up correctly with the front spar upper flange. This problem has seen some improvement in the past year due to the imposition of tighter tolerances. Nevertheless, the 757 rudder front spar fittings still require lots of shimming, an estimated 25% of total labor. However, the 757 rudder assembly itself does not require much shimming.[1]

Pull-up load limitations

A certain amount of clamp-up (or pre-load) is generally required for assembly. A typical conservative limit is approximately 10 lbs. per linear foot of mating surface. For composite parts, it is particularly critical to control the amount of pre-load placed on laminates due to their relative weakness and brittleness in the out-of-plane or z-direction. This is accomplished by limiting the amount of clamp-up pre-load applied by the use of specially configured, spring-loaded temporary fasteners, and by establishing a maximum gap size above which shims are required. A good rule of thumb is on the order of 0.008"-0.009" maximum, but this can vary depending on the span of a mating surface gap. The controlling parameter is the amount of strain induced in the laminates by installing and torqueing a fastener across a gap. Strain is a function of the gap length, as well as the displacement induced by the fastener clamp-up load. If a gap is very short in width, large stresses and strains will be induced in the laminates, whereas if the gap is relatively long, the laminates will not experience high stresses and strains. In practice, due to poor fit-up of details and fittings, the shop mechanics must shim excessive gaps or reject

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[1] Manufacturing Engineer, 757 rudder and 757 elevator

parts because otherwise they would exceed the gap or pull-up load limitations in order to install fasteners properly.

The concern raised by the MR&D engineers is that the limit generally specified may be too conservative, resulting in more gaps requiring shimming than would exist if greater pull-up loads were allowed. It was not known to what degree analysis or testing had been accomplished to establish the current limit and, given the potential impact on the assembly of composite structure, these engineers agreed that a thorough test/analysis program would be worthwhile. Currently, pull-up load criteria are difficult to establish. The key issue for analysis is how to determine the stresses and strains induced by pull-up loads.

4.3.2 Drilling operations

The following topics affect ease-of-drilling operations and resultant amounts of rework. The phrase "drilling operations" in this document refers to drilling, reaming, countersinking, and deburring, unless otherwise noted.

Drilling, reaming, countersinking

The cost of carbide drills for drilling graphite/epoxy laminates is five times greater than cutters for conventional aluminum material. Also, drill life for these special drills is only ~50% of the usable life of drills used for aluminum structure. Effective countersinking of holes in graphite/epoxy laminates requires a special cutter which costs 7.5 times its aluminum structure counterpart.[1]

Many factors affect the quality and efficiency of composite drilling operations. These include the material being drilled (perhaps the biggest factor) the drill feed rate, drill speed (rpm); and condition of the drill motors. Higher drill rpm speeds allow a mechanic to work faster. However, a higher degree of skill and experience on the part of the mechanic is necessary to utilize higher drill rpm speeds and maintain

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[1] MR&D Cost Study Groundrules, April 90

quality. Reamers provide closer tolerance holes than drills. Reaming is a time-consuming multi-step process, where first a pilot hole is drill, followed by a one or more step reaming operation. Drilling quality is critical in assembly of composites or metal structure, since hole size and perpendicularity affect the mechanical strength and the fatigue life of the fastener/hole system.[1]

Automated drilling machines are not currently utilized in composite secondary structure manufacturing at Boeing. The capital expense of incorporating such automation has not been deemed worthwhile for secondary structure. However, on several military programs involving composite primary structure, automated drilling machines have produced very promising results, such as a rejection rate of only 30 out of 10,000 holes.

Drilling through dissimilar material stackups

Another key concern identified by multiple sources is the difficulty of drilling through dissimilar material stack-ups. Drilling through graphite/epoxy laminates is itself difficult and relatively expensive, requiring special carbide steel tipped drills and countersinks and a good degree of skill and experience by the mechanic. However, when two components of dissimilar material composition, such as a graphite/epoxy spar and a titanium fitting must be fastened together, the drilling operation is especially difficult. The optimum drilling parameters in terms of drill speed (rpm) and feed rate for graphite/epoxy and titanium are entirely different. Thus, either a compromise speed and feed rate is used, or a time-consuming two step drilling operation is utilized. The most common dissimilar material stack-ups found in the A3410 shop are titanium and aluminum hinge or actuator fittings installed onto graphite/epoxy front spars of rudders, elevators, and ailerons.

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[1] MR&D Factory Support engineer

Impact of tape vs. fabric composite pre-preg material

A phenomenon known as "fiber breakout" can occur when drilling composite material, and was identified as an assembly concern in the Auburn assembly shops. During conventional mechanical assembly, holes must be drilled and countersunk in the cured laminates prior to fastener installation. With tape laminates, a condition known as "fiber breakout" occurs at the exterior surfaces, particularly the drill exit side of the laminate if a temporary backing material is not used. This condition is similar in nature to exit hole damage when drilling through plywood, and results in damaged fibers in the vicinity of the drilled hole with associated degradation in strength and appearance. An operation termed "deburring" is required to remove damaged fibers and smooth the hole surface, prior to fastener installation. With fabric laminates, fiber breakout is still a concern, but much less so than for tape laminates. Thus, where mechanical assembly of composite structure is required, laminates comprised of fabric plies are preferred in terms of preserving the laminate's structural integrity and quality.

For composite structure composed of graphite/epoxy tape, the addition of a fabric exterior layer on each side greatly reduces the frequency and the magnitude of fiber breakout. This exterior fabric material can be graphite/epoxy, fiberglass, Kevlar, etc. From a purely structural performance viewpoint, the addition of exterior fabric plies to tape laminates is undesirable because it represents extra weight. However, the MR&D engineers maintained that for graphite/epoxy tape laminates without fabric exterior plies to control fiber breakout, product quality decreases and assembly costs increase due to repair, rework, and scrap. Furthermore, composite design engineers can substitute exterior tape plies with fabric plies in order to minimize or eliminate any extra weight.

4.3.3 Fastening

The fastening of graphite/epoxy structure, and sources of rework pertaining to fasteners, are addressed in this section.

Fasteners for composite structure assembly are generally much more expensive than their conventional metal structure counterparts, with the typical graphite/epoxy fastener costing about $1.00 each while the typical aluminum fastener costs about $.05 each.[1] Although a precise count was not obtainable, a lead mechanic estimated that 2,000 fasteners are required to assemble the 757 rudder. There is a great variety in the types of fasteners currently used, with over 300 different pins (bolts), washers, and collars (nuts) (collectively known as "standards") kept in stock for the assembly of the 757 rudder and 747-400 winglet alone. Most of the variety is due to multiple diameters, grip lengths, material types, and different installation methods due to varying degrees of access to the bolted joint. The cost of special oversized fasteners is high. These unique fasteners are prescribed by liaison engineers for holes which have inadvertently been drilled out-of-tolerance. One of the first-line shop supervisors suggested that a more cost-effective method of dealing with oversize holes would be to simply increase the oversize hole up to the next size standard fastener, if possible.[2] The majority of fasteners used in composite assembly must be installed manually. The exception are the “blind” fasteners used to install the last skin panels to close out a structure, which can be installed using a power tool.

The primary fastener used in commercial aircraft composites assembly is the Hi-lok. This fastener consists of a steel or titanium pin (or bolt) onto which is installed a steel, aluminum, or titanium collar (nut). This collar is torqued down over the pin until the designed clamping load is applied to the structure, at which time a portion of the frangible collar breaks off. The collar is designed to lock in place by deforming around the pin threads as it is installed. Due to the high amount of friction between the pin and collar, this fastener requires a hex key (Allen wrench) to prevent the pin from rotating as the collar is torqued down around the pin. An assembly problem with Hi-Loks involves stripping of the pin's hex key recess, thus preventing the required torque and clamping load from being achieved.

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[1] MR&D Cost Study Groundrules, April 1990

[2] A3410 shop supervisor

Also, the frangible portion of the collar sometimes separates prior to full torqueing. The MR&D engineers cited these reasons as the major factors behind reported estimates that up to 15-20% of all Hi-lok fasteners initially installed in composites require rework in the form of replacement. According to these engineers, Hi-Loks in aluminum structure are installed in interference fit holes, and do not have hex stripping or insufficient torqueing problems nearly as frequently as with Hi-Loks in composites.

A fastener system featuring a free-spinning collar has been identified as a possible replacement for Hi-Loks on commercial aircraft structure. A free-spinning collar is one which only requires torqueing to lock it in place once the collar has spun down the pin to the designed grip length. Thus, the hex recess in the pin is rarely used. Also, the collar is designed so that when the specified torque is achieved to lock the fastener in place, there is no part which breaks away, which must then be removed from the assembly. This free-spinning fastener is currently used throughout the aerospace industry on military programs such as the C-17, ATF, and B-2, but has yet to be certified by Boeing for commercial aircraft. This fastener's reported advantages include being quicker and easier to install due to its free-spinning collar, which translates into reduced assembly labor required. It also is considered to be more reliable in its installation, experiencing a lower rework rate than Hi-Loks, and is easier to inspect. For these reasons, according to MR&D and 777 design engineers, Boeing production mechanics working on the ATF program reported good experience with the free-spinning fastener, and preferred these fasteners over Hi-Loks. The fastener system total weight is reported to be slightly higher than the Hi-Lok; however, it is also reported to cost slightly less. Another issue is its qualification at Boeing for use on commercial aircraft. Some concerns identified are the need to verify pre-load consistency, reliability of the locking mechanism, and the effect of the hand installation tool wear on pre-load and locking. At this writing, a qualification test program is underway for this fastener.

4.3.4 Detail part/fitting supply shortages and quality variability

Among the A3410 shop mechanics, detail part shortages were almost universally identified as one of the leading problems in composites assembly productivity. This finding corresponds well to the parts availability records presented in chapter section 4.1.6. According to the mechanics, for example, the 757 ailerons from A3430 were frequently arriving after the scheduled assembly completion date, and well into the fifteen day schedule buffer ahead of the actual jig-load date at Renton. On almost all assemblies, the mechanics end up waiting for detail parts from the A3430 shop. Many times they can work around, but often they are held up for hours and days at a time. Then, when the part arrives, it disrupts the flow of their work to go back and install it .[1] According to another 757 elevator mechanic, if good detail parts were consistently provided on schedule, they could substantially increase their production rate.

The 757 rudder mechanics also concurred that part availability was a significant problem for the assembly shop. For instance, for a period of several days the 757 rudder crews had no front spars in their inventory racks. As a result, the mechanics stretch out the job and slow down their workpace. At the end of a shift, one rudder mechanic working at the final assembly jig was overheard saying that he "had only drilled twelve holes all day." A 747-400 winglet mechanic had similar thoughts, stating that a significant productivity problem is the lack of detail parts from A3430. "It is very frustrating to not have parts. If we see we are short of parts in our inventory racks, we naturally slow our work rate in order to make the current job last." This mechanic noted that a potential cause for the parts shortages is that A3430 only has two tools (lay-up mandrels) each for the left and right winglet skin panels. If one tool is out of service for rework, routining, or whatever, then there is no way the A3430 shop can keep up the required production rate.

Representatives of the A3250 machine shop identified several issues in the manufacturing process. They stated that their first problem was not being able to get precision forgings from their vendors on schedule. A high rate of rejections in A3410 which required replacement fittings from A3250 only exacerbated the problem. Work orders for the replacements were not released on schedule, and when the work orders were released, the

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[1] A3410 757 elevator mechanics

production schedule was not realistic. For example, an order of fittings which they normally had ten days to accomplish was required in one or two days. Thus, too many scraps and reworked fittings coming back from A3410 created severe disruptions in A3250's scheduling and work process flow.

Consistent producibility of quality detail parts is considered an ongoing challenge in composites manufacturing. At the conclusion of a presentation on this study's preliminary findings the Fabrication Division General Manager commented that, "A big productivity impact in composite structure is due to unproducible designs. There is no way some part designs can be fabricated without getting rejected." He cited the 767 auxiliary power unit (APU) duct as an example. At that particular time, seven 767s were awaiting this part at the Everett, Washington final assembly plant. While this particular example is focused on the fabrication difficulties with a part, these difficulties in turn affect the supply reliability of detail parts to the A3410 assembly shop.

4.3.5 Inventory levels

The following example illustrates the substantial work-in-process (WIP) inventory objectives which exist for detail parts and fittings in the composites manufacturing process. There are approximately 250 details in the 737 front spar alone, a high number of parts. Details for balance panels and tower ribs are built up as subassemblies, then sent to "stores" inventory. When the balance panel subassembly station is ready for the parts, they are drawn out of stores, subassembled, and then sent back to stores. Similarly, when the front spar subassembly station is ready, the units are drawn out of stores, assembled onto the front spars, which are then transfered to stores. Finally, when the floor assembly jig (FAJ) is ready to assemble a complete 737 elevator, the front spars are drawn out of stores and delivered to the FAJ. This is an inefficient process, and is partly caused by the Fabrication Division inventory objective equal to 45 days (or shipsets) worth in stores.[1] An example

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[1] A3410 and A3420 General Supervisor

calculation of the total number of parts which are the objective inventory at any one time follows:

For tower ribs: 5 per balance panel
x 6 balance panels per elevator shipset
30 tower ribs per shipset
x45 days/shipsets of inventory
1,350 tower ribs = inventory objective

Some shop managers realize this large in-process inventory is expensive and impacts production efficiency. As a result, the A3410 General Supervisor is trying to establish a full production line for the 737 elevator. This line would be fully sequential, involving each of the sub-assembly process steps described above, arranged in-line one after the other. The intent is to operate the line in a just-in-time production mode, with parts and subassemblies being produced and delivered only when the next process step requires them, thereby eliminating the need for "stores" inventory.

4.3.6 Shop Loading

One of the measures used by Fabrication Division management to evaluate the performance of the assembly shops is a “realization factor”. A realization factor is the ratio of labor hour standards (calculated based on the operations listed on the manufacturing plan corresponding to each assembly) divided by the average historical actuals labor hours expended. A3410 shop performance reports showed that the “baseline” realization factor for the 757 rudder station was approximately 20%.

In response to an inquiry as to whether the labor standards applied to the 757 rudder assembly were unfairly low, an IE Methods/Standards engineer agreed to observe the operations in the 757 rudder assembly area and independently calculate the nominal labor hours required to complete each unit. The computed hours would be based on standards which specify the amounts of time required to perform basic shop assembly operations such as indexing of parts, drilling holes, installing fasteners, etc..After examining the manufacturing plan, and observing exactly what operations and tasks the mechanics had to perform, the nominal set-up and run times for the 757 rudder assembly operation were determined.

The results of this analysis confirmed the labor hour standards shown on the manufacturing plan. Again, these standards were approximately 20% of the actual average labor hours expended assembling each rudder. This finding raises the question of where is the extra time spent? Why is the 757 rudder realization factor so low? What is being done the other 80% of the time? Why is the 20% value accepted as a baseline? These questions are discussed and analyzed in detail in Chapter 5.

According to the IE Shop Load manager, the planned 757 rudder flowtime is eight manufacturing days, plus five days in paint. A rudder is scheduled to be started every three manufacturing days, alternating between the two final assembly jig's in the rudder assembly station. Therefore, the planned final assembly jig flowtime equals six days. Thus, rudder flowtime requires about two days on the bench tables. Comments made by a 757 rudder mechanic indicate that the scheduled rudder assembly flowtime is significantly more than what is actually required: "When things run smoothly, and we have all our parts, we can get rudders through the final assembly jig in about three days, on tables for two, then over to paint." [1] Thus, the required flowtime through the rudder assembly station, when all parts are available, is five days instead of the scheduled eight days. While this does not explain the 20% realization factor, it does indicate that substantially more labor is *expended* on assembly than is *required*, and that at least part of the reason is the randomness in the supply of detail parts and fittings.

4.3.7 Quality Assurance process

The results of the survey indicated approximately 20% of the mechanics' time was spent waiting for quality assurance (QA) inspection and rejection tag disposition. The mechanics believe there are real inefficiencies in the QA process. For example, even minor discrepancies, such as oblonged

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[1] A3410 757 rudder lead and other mechanics

holes or countersinks which always require an oversized fastener, go through the full rejection tag or pick-up process, including engineering disposition.[1] Several mechanics felt that they should be responsible for their own quality of work, with the station supervisor responsible for final approval. Sometimes the mechanics must wait for QA personnel to finish paperwork or other inspection jobs before they inspect their assemblies. Sometimes they can work around this, but many times they cannot and are idle.

The rejection tag disposition process is also a source of delay and idle time in the assembly shop. It usually takes from one-half to two days to obtain disposition of a rejection tag, which must go through up to seventeen steps of a review and approval process. Sometimes, the mechanics can continue with the job by working around the affected area, but often they cannot. If sufficient urgency is applied, such as for a very late assembly, the tag can be walked through in one-half hour.[2]

An opposing view which gives balance to the debate regarding the QA process was provided by the A3410 general supervisor who stated that he was ambivalent about giving "ownership" of quality to the mechanics. In his opinion, a certain amount of "checks and balances" will always be needed.

4.3.8 Training

The Fabrication Division often assigns new mechanics to work in A3410 composites assembly. These new people often have no experience or basic training with power tools, such as how to adjust countersink height and how to drill at correct angles. Thus, the new people are either afraid to work on the parts, or make many mistakes, or both. While BCAG provides up to two weeks of classroom training for new hires to learn how to read engineering drawings, process specifications, and manufacturing plans, that doesn't prepare people to be a mechanic. Experience has shown that it takes from 3 to 6 months for a new hire or transfer to develop good drilling

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[1] A3410 757 rudder mechanic

[2] A3410 757 rudder mechanics and QA personnel

skills and confidence.[1] One suggestion for productive use of the mechanics' time when detail parts or fitting were not available is to use the time for training. A common concern among the mechanics is that they do not get enough instruction in basic shop mechanic skills and techniques. In other words, at least some of the mechanics would like to have more training.[2]

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[1] A3410 757 rudder mechanic

[2] Production Control - Expediting personnel

5.0 Analysis of Composites Assembly Issues

In this chapter, composites assembly issues are identified through an analysis of the quantitative and qualitative data and information acquired during the internship project and documented in Chapter 3 and Chapter 4. The literature survey of Chapter 2 provides additional background information.

The composites assembly issues identified in this analysis are organized into three categories: (1) the material, design, and manufacturing process attributes which impact the "ease-of-assembly" (or lack thereof) of graphite/epoxy parts, (2) detail part and fitting supply variability, and (3) other operational attributes which impact assembly productivity. Recommendations on methods to address these composites assembly issues through design, manufacturing process technology, and operations management considerations are presented in Chapter 6.

5.1 Ease-of-Assembly of Graphite/Epoxy Parts

Current composite aircraft structures possess several characteristics which make their assembly particularly difficult and labor-intensive. In this section, the material properties, design practices, and manufacturing process attributes which can adversely affect the assembly of graphite/epoxy parts are discussed. The discussion is organized to address the factors impacting the three major assembly operations: (1) part fit-up and shimming, (2) drilling operations, and (3) fastener installation.

5.1.1 Part Fit-up and Shimming

The assembly labor allocation study results shown in Figure 4.3 indicate that for the composite secondary structures assembled in the A3410 shop, part fit-up and shimming combined account for approximately 22% of the labor expended. Note that while the 22% labor estimate for these activities is substantial, it is less than the initial experience with composite structure in military programs such as the B-2, ATF (F-22), and A-6, where part fit-up and shimming accounted for a significantly higher percentage of labor. A possible explanation for this disparity is that for relatively thin-gage structure, such as the control surfaces assembled in A3410, the part bending stiffnesses are low enough to enable fit-up of mating surfaces without exceeding allowable pull-up loads and thereby damaging the graphite/epoxy laminates. Composite airfoil structures such as those in the military programs typically have greater gage thicknesses, and the resulting higher bending stiffnesses make it more difficult to fit-up parts precisely without exceeding allowable pull-up loads. Since extensive shimming was initially experienced with the relatively thick-gage composite structures in the A-6 wing, the B-2, and the ATF programs, a concern exists that the same will happen with the 777 empennage's relatively thick composite structure.[1] The following sections discuss the major sources of shimming requirements in composite structures.

dimensional accuracy and variability

As discussed in Chapter 3, shimming to meet the thousandths of an inch tolerances of aerospace structures is a labor-intensive process requiring a significant amount of skill and experience on the part of the shop mechanic. Many of the sources presented in Chapter 4 held the opinion that the time required for part fit-up (or, indexing) into the floor assembly jigs and the degree of shimming required is directly affected by detail part and fitting dimensional accuracy and variability. Sources of variability in mating surface smoothness include design features such as ply drops due to partial plies and lap-splices. Another frequently identified source of part dimensional inaccuracy and variability in composites assembly is tolerance build-up in tooling and parts.[2] This build-up is an issue because currently, some assembly gap tolerances are specified tighter than the tolerances allowed in the fabrication process for graphite/epoxy parts. Tolerance build-up results from the ± 7% variability in the composite ply material thickness, the variability resulting from uncontrolled (bag-side) mating surfaces during autoclave curing, and from limitations in the accuracy of

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[1] MR&D Advanced Composite Structures - Assembly

[2] A3410 shop supervisor
MR&D Factory Support
Manufacturing Engineering supervisor

tooling in both the fabrication and assembly stages of composites manufacturing. As a result, design engineers must allow for a specified tolerance range when designing parts. Through a multi-step manufacturing process, these tolerances can accumulate. The current method of correcting for tolerance build-up in detail parts and fittings is to shim the resulting gaps when the parts are mated for assembly. Thus, in order to reduce the amount of labor-intensive shimming required during assembly, detail parts and fittings need to be fabricated to closer tolerances, with better accuracy and better control of dimensional variation.

Maximum gap and pull-up load limits

The pull-up, or clamping, load allowables described in Chapter 4 also impact the amount of shimming required for composite structure. The opinion expressed by several engineers was that the allowable loads may be too conservative. Expressing maximum allowables in terms of gap thicknesses and pounds per foot clamp-up loads is somewhat of a simplification. The engineering criteria for preserving the structural integrity of composite laminates are the induced strains in the material, which are a function of the material bending stiffness and the length of the gap, as well as the applied load and gap thickness. However, a high degree of conservatism may be warranted with graphite/epoxy composite material because it is relatively brittle compared to metals, it is relatively weak in the out-of-plane (z) direction, and it tends to fracture rather than undergo stress-relief by yielding, as do metals. Furthermore, one must recognize the practical limitations in a production shop environment of accurately determining material strains due to clamping loads across gaps. This may be the strongest argument for using very conservative and simplified design allowables.

5.1.2 Drilling operations

The assembly labor allocation study results also indicate that approximately 15% of the total labor effort is spent performing drilling, reaming, and countersinking operations. The labor required is a function of the number of holes required for fasteners, the accessability of the part when loaded in the floor assembly jig, drill speed and feed rates, the thickness of the laminates or stack-ups being drilled, the number of drilling operations required per hole (pilot holes, reaming operations, and countersinking), and the amount of deburring that must be performed due to fiber breakout within and at the exit surfaces of each hole. A source of labor intensiveness and rework is the difficulty of drilling through dissimilar material stack-ups such as a graphite/epoxy front spar flange, Kapton shim, and titanium hinge fitting. This was identified as a significant issue by many shop, manufacturing engineering, and MR&D personnel, who agreed that from an assembly point of view, dissimilar stack-ups should be minimized where possible. The total costs related to graphite/epoxy drilling operations, in addition to labor costs, are also functions of the hand drill costs, cutter (drill bit, reamer, countersink) costs, and cutter life before resharpening is required. As described in Chapter 4, these equipment costs are significantly higher than for metal structure. Also noted in Chapter 4 was the opinion that training, skill, and experience are key factors in a mechanic's ability to drill composite material efficiently and with minimal rework, and that greater amounts of mechanic training would be beneficial.

5.1.3 Fastener installation

The results of the survey indicate that the installation of fasteners consumes approximately 20% of the labor expended in the assembly of composite secondary structures in A3410. This large percentage is a function of both the large number of mechanical fasteners required in each composite structure, and the average time required to install each fastener. This average time to install each fastener is relatively high due to the manual installation methods required, and the non-free spinning nature of the fastener collars. In comparison, aluminum structure is assembled by automated riveting machines or other interference fit fasteners, which are generally quicker to install and require less rework than composite structure clearance fit fasteners. Material costs of even standard-size composite fasteners were reported to be higher relative to conventional metal structure fasteners, with the custom-size fasteners required for oversize holes being extremely expensive since they are not purchased in economic quantities.

The application of automation to composites fastener installation operations is less attractive than for aluminum because there are fewer fasteners to install in composite structure. Therefore, manual fastener installation will probably continue to be the norm for composites assembly. However, the use of fasteners featuring free-spinning collars could significantly reduce the labor required in composites assembly. As described in Chapter 4, Boeing is currently investigating the potential application of this type of fastener to their commercial composite structure assemblies, based on successful experiences to date on military aircraft programs. The free-spinning collar type fasteners also have the potential benefit of producing more uniform clamp-up loads than the composite fasteners currently in use, and require substantially less rework.

5.1.4 Results/impacts

The extremely tight fit-up tolerances required with aircraft composite assemblies, on the order of thousandths of an inch, and the high variability in part dimensional accuracy, both lead to significant labor requirements in assembly operations. The labor intensiveness of composites assembly operations is also generally attributable to the large number of fasteners required in mechanically assembled composite structures (compared to co-cured or co-bonded structures), and the exacting standards and manual nature of the drilling and fastening operations. Also, these same composite structure characteristics create substantial potential for detail part or fitting rejection for being out-of-tolerance, and rework due to mistakes in the assembly operations. The shop study results presented in Chapter 4 indicate that rework accounts for, on average, approximately 12% of the mechanics' labor effort. However, the rework percentage of total direct labor hours calculated from the accounting system data, shown in Table 4.2, indicated that control code 4 (or, major) rework only consumed 2-3% of total labor expended. This disparity is discussed next.

If the accounting system data is accurate, then major rework is not very significant, and the overwhelming majority of labor (97%) is expended in the initial direct labor operations, and correcting minor discrepancies (or, "pick-ups"). Although one cannot directly measure minor rework (pick-ups) since it is not tracked separately from direct labor hours, one could conservatively estimate the amount of rework expended for pick-ups to be approximately 1% of total labor hours expended.[1] If this is an accurate interpretation of the accounting system's data, then the biggest target of opportunity may not be in reducing rework, but in reducing the direct labor hours expended in composites assembly. Resources should be devoted to streamlining operations, reducing inefficiencies and idle time, and not necessarily to improving quality, in the sense that "quality" is synonomous with "reducing the amount of rework". However, a qualifier must be added to the above analysis. The labor hour data do not necessarily take into account the disruption and idle time associated with rework, such as waiting for QA inspection and rejection tag disposition. Thus, a second possible interpretation is that the data is somewhat misleading because the accounting system does not fully capture the impact of rework. This alternative explanation is more consistent with the shop experience.

5.2 Detail Parts Supply Variability

Based on the parts availability data and shop personnel commentary presented in Chapter 4, the ability of the upstream fabrication shops to provide a steady, consistent supply of composite detail parts and machined fittings appears to be a significant issue for A3410 composites assembly. In this section, the likely causes of the supply variability and the resulting impact on A3410 assembly shop productivity are analyzed.

5.2.1 Parts production variability

Variable yields in the upstream A3250 machine shop and A3430 composites fabrication shop contribute to detail part and fitting supply variability to the A3410 shop. The sources of dimensional variability described in section 5.1.1, such as composite material ply thickness variation, tooling tolerance build-up, and variation in the curing and trimming processes, can cause parts to fail quality assurance inspections in fabrication and never be

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[1] Source: A3410 Quality Control data. This data indicates pick-ups consume about one-third the labor hours as do CC4 major rework.

shipped to assembly. If and when rejections of a particular part occur frequently enough, in effect a bottleneck in the manufacturing process is formed, and part shortages will occur in the downstream assembly shop.

For a set of parts which comprise a given assembly, if the average fabrication process yield rates fall even slightly below 100%, a significant effect on downstream parts availability will result, due to a certain number of component parts being scrapped and requiring re-fabrication. The probability that all parts for a given assembly will be successfully fabricated on the first try is also a function of the total number of parts in the assembly, as illustrated in Figure 5.1. The plots in this figure are derived using the following equation:

$$\text{Probability (zero parts scrapped for a given assembly)} = Y^n$$

where, n = number of component parts in the assembly
Y = average part fabrication yield for all n parts

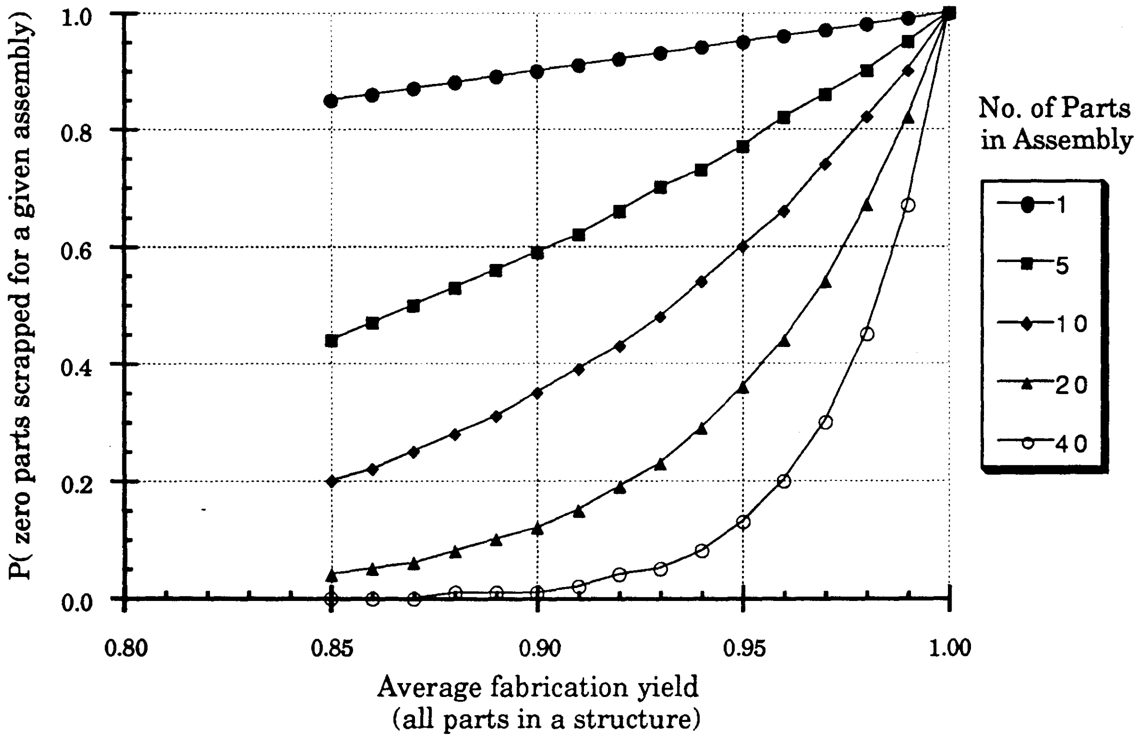

Figure 5.1: *Probability of zero parts scrapped for a given assembly, as a function of the number of parts in the assembly and the average fabrication yield rate.*

This example illustrates the importance of high fabrication process yields for detail parts and fittings to the reliable, on-schedule availability of complete parts kits for the assembly shop.

Part or fitting rejection rates may result partly from random process variability, with no recognizable pattern in supply variability. Rejection rates may also be traced to more determinisitic sources such as tooling degradation or damage, or a particular group of precision forgings of marginal material or dimensional quality, for example.

Another source of disruption in the supply of parts to A3410 is due to scheduled and unscheduled maintenance of lay-up mandrel tooling. This can be especially disrupting if the number of lay-up mandrels for a given part is very low. If, for example, there are only two lay-up mandrels for a given composite skin panel, and one lay-up mandrel requires maintenance, the production capacity of that skin panel has been reduced by 50%.

Another impact to the consistent flow of parts and fittings is from the disruption caused by high rejection rates on other parts which use the same fabrication equipment. In A3430, autoclave space can be taken up by composite parts being expedited to replace rejected parts, at the expense of those parts normally scheduled. Similarly, the machining equipment in A3250 cannot produce the scheduled fittings if it is being used to rework or replace a previous set of rejected fittings.

Thus, less than nominal yields for a certain part type can cause disruption which ripples through the entire process affecting the production of other parts, resulting in expediting of missing details and fittings, delays in subsequent jobs, and a general disruption of the process flow. These effects result in idle time while waiting for parts, and perhaps overtime in order to get back on schedule.

5.2.2 Feedback delays

Feedback processes in the composites manufacturing process have significant delays which exacerbate the part shortage and quality problems. In the example cited in Chapter 4 of the extremely high rejection rate for a group of 757 rudder fittings, a significant part of the problem in replacing the defective fittings was that the machine shop did not know for approximately ten days that A3410 needed replacement fittings. This was the result of information traveling slowly through the various required channels. Another example was where the 757 rudder mechanics once waited two weeks to get a replacement splice plate from the A3430 shop, which reportedly only took one day to fabricate. This illustrates the feedback delays between A3410 and A3430, and the impact of an erratic supply of detail parts as well as the disruption caused by a large number of poor quality or damaged parts that require replacement. Another issue that effectively contributes to feedback delays is the large inventories of parts that are maintained. By the time a problem shows up in A3410, numerous other units with perhaps the same defect have been produced and are in the figurative pipeline, yet they too will be rejected. Generally, the machine shop prefers to run large lot sizes of a given fitting, in order to economize machine set-up times. However, this practice contributes to the inflexibility of the process.

5.2.3 Results/impacts

Meeting the specified production rate and scheduled deliveries to the prime division final assembly plants are the primary performance measures, which in turn drive labor and tooling capacity requirements, at the Fabrication Division and probably at most manufacturing organizations. While this emphasis on meeting rate is not an assembly productivity issue in and of itself, when combined with the apparent supply variability of acceptable detail parts and fittings, and the attendant feedback delays to the fabrication shops, several impacts to A3410 shop productivity result. These impacts are analyzed in the remainder of this section.

flat learning curve

The lack of an appreciable learning curve (or, experience curve) in A3410 is apparent in the direct labor per unit histories for the 757 rudder and 747-400 winglet shown in Figures 4.1.a and 4.1.b. The traditional theories to explain the absence of learning curve are a) skill dilution among the workforce due to turnover, and b) no more learning due to being too far down the learning curve. Skill dilution is a possibility. If the A3410 shop experiences high turnover, and is continually receiving new, inexperienced mechanics while losing their skilled people, then the overall learning curve will be flat. For example, in the summer and fall of 1989, the A3410 shop experienced a noticeable surge in DL/unit. Boeing's Fabrication Division Industrial Engineering/Finance personnel were fairly confident in attributing this decrease in productivity to an influx of Boeing Military Airplane (BMA) new-hires at this time who, while waiting for security clearances, were assigned to Auburn to gain experience assembling composite structures. However, since the fall of 1989, according to the A3410 General Supervisor, the shop workforce has been relatively stable, and skill dilution since the fall of 1989 has not been very significant.

"No more learning" could be the case with the 737 elevator, of which over 1,000 units have been produced since the early 1980's. However, the theory that there is no more learning to benefit from does not explain the high variability in direct labor expended from one unit to the next. Also, the other assemblies studied have had production runs on the order of only a few hundred. In the case of the 747-400 winglet, production only started in late 1987, and the direct labor per unit history shown in Figure 4.1.b is the entire record for the first ninety units. Thus, one can conclude that there should still be some observable learning effects with most of the composite assemblies.

One explanation for the lack of a learning curve in A3410 composites assembly is that continual design and tooling changes cause perturbations in the learning curve, because the mechanics have to constantly deal with changes in the design or changes in the process. Each change is *intended* to be an improvement. However, the changes are made in such continuous and rapid succession that the mechanics are always having to adjust, and the learning process is continually disrupted.

excess capacity

An alternative explanation for the lack of an appreciable learning curve in A3410 may be that the shop actually has a certain degree of excess capacity which, due to the combination of incoming supply variability and downstream delivery pressures, is difficult to reduce. When production is delayed due to detail part shortages and rejection tags, the reaction is to increase the assembly resources in order to shorten the flow/cycle times, thus enabling the shop to still meet schedule. But, when production is stabilized the labor resources utilized to catch up remain assigned to the shop, and direct labor/unit will tend to be elevated over what is really necessary. In order to realize learning or experience curve effects, direct labor per unit must be forced down via personnel reductions.

This type of planning is what Industrial Engineering - Shop Load tries to do, based on a theoretical learning curve, the cumulative units produced, and actual experience. In practice, however, countervailing pressures complicate efforts to reduce labor costs. The A3410 shop is still held accountable for meeting the prime division "jig-load" dates even though details may have arrived very late. Enough reserve capacity, in the form of equipment and labor, must be retained so that the "normal" flowtimes can be accelerated when necessary. Often, overtime must be utilized, which drives per unit costs even higher. This excess capacity, which cannot be turned on and off, may be a leading cause of the continuing high direct labor per unit. This concept is illustrated in Figure 5.2.

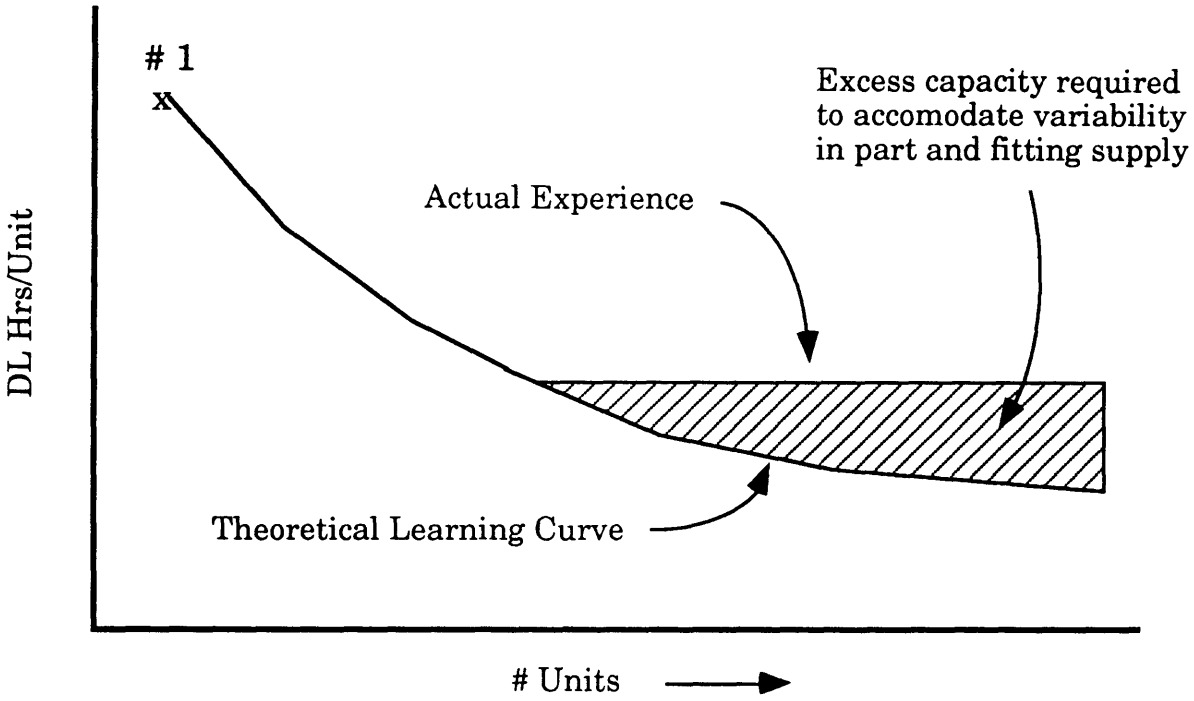

Figure 5.2: *Theoretical Learning Curve vs. Actual Experience in A3410*

With a given number of hourly workers and a given production rate, one will never observe significant learning effects and direct labor per unit reductions. In effect, the mechanics are salaried employees, and labor costs are in fact fixed, not variable. This situation results in a disincentive for the workers to be any more productive than they have to, as long as they meet rate. If the mechanics work too efficiently, they will run out of work, only to be assigned to menial jobs such as paperwork or floor-sweeping. The alternative is to go home, but then they have to take sick leave or vacation. Therefore, when the mechanics perceive there are not enough detail parts/fittings to support their normal production rate, they tend to reduce their work pace. This dynamic will tend to increase the labor hours expended on a given unit. This observation is by no means unique to composites. If aluminum structure assembly or any other manufacturing process which depends on an incoming supply of parts experiences a high degree variability and uncertainty, then these effects will be seen.

With a set production rate and set number of mechanics, the average direct labor/unit over a period of time will not fall below the simple quotient of allocated man-hours per month divided by units per month. In short, due to human nature, the mechanics will want to insure there is always some work to do, and will tend to pace themselves accordingly. Evidence that there is excess capacity is seen in the detail parts delivery schedules, of which a typical example is shown in Figure 4.5. Also, further evidence of excess capacity is provided by the low realization factors typical of many of the A3410 shop stations, as described in Chapter 4.

high variability in direct labor/unit

Similar dynamics may help to explain the high variability in direct labor from one unit to the next. The effect of parts supply variability (uncertainty) on the mechanics' work rate, and the consequent effect on the total direct labor hours charged to a particular unit is illustrated in Figure 5.3, "Work Rate Dynamics". When the mechanics see that there are not enough detail parts/fittings on the inventory racks to complete the current assembly, or subsequent assemblies, their work rate slows and direct labor charged to a particular unit accumulates.

The rationale described above may explain the labor productivity data typical of A3410 and shown in Figures 4.1.a and 4.1.b; specifically, the highly varying labor hours expended per unit, and the generally flat learning curve over time. This analysis suggests that these results are attributable to supply problems "upstream" in the manufacturing process, specifically the detail part and fitting shortages from the composite fabrication shop and the machine shop.

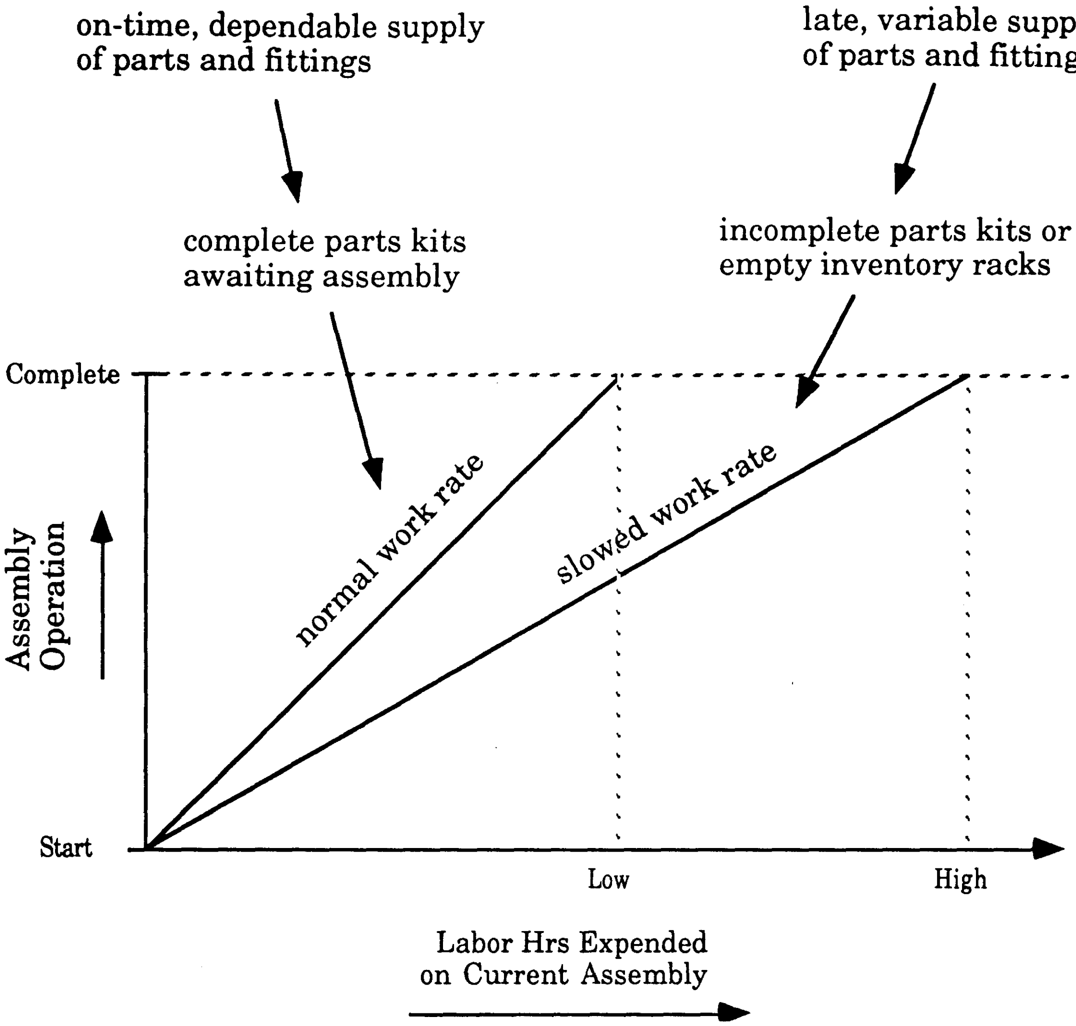

Figure 5.3: *Work Rate Dynamics - illustrating the effect of parts supply variability on mechanic work rate, and the consequent effect on the total direct labor hours charged to a particular unit*

Justification of Excess Capacity in the A3410 Shop

A review of queueing theory suggests that, due to the highly varying supply of detail parts and fittings, the excess capacity observed in the A3410 shop is justifiable and actually necessary to smooth the overall composites manufacturing process flow. This excess capacity serves to accomodate the relatively random part arrivals from the fabrication shops, and still consistently meet the final assembly jig-load dates at the prime divisions. According to queueing theory, there is an interesting relationship between a process stage's utilization factor and the average queue length (backlog) of parts kits awaiting assembly. In this analysis a process stage is an A3410 assembly station, or a floor assembly jig within a station. The station or jig's utilization factor is defined as the mean arrival rate of parts kits (i.e., throughput or production rate) divided by the station or jig's mean service rate (i.e., nominal capacity in units per time, given a fully functioning crew and parts kits always available for assembly). The plot in Figure 5.4, based on the queueing model shown below, illustrates how the average queue length increases exponentially as the utilization factor increases towards 1.0. This indicates that in order to avoid large wait times and queues, a process stage subject to random arrivals must have a utilization factor substantially less than 1.0, or in other words, more capacity than is required to meet the average production rate.

A more thorough description of the queueing model follows:

λ = mean arrival rate of parts kits awaiting assembly, which is equivalent to throughput or production rate, in units per time

μ = mean service rate, which is equivalent to a server's (station's, jig's) nominal capacity, in units per time. Nominal capacity is defined as the normal capacity with full worker staffing, and assuming parts kits are always available for assembly.

$\rho = \lambda/\mu$ = utilization factor

$M = 1/\mu$ = mean service time, in time per unit served

σ = standard deviation of M

$$\text{Expected wait time } W = \frac{\lambda(M^2+\sigma^2)}{2(1-\rho)}$$

$$\text{Expected queue length } L = \lambda/W$$

Certain conditions are assumed in the derivation of these queueing model equations. These underlying assumptions are:

- poisson (random) arrivals (of complete parts kits to assembly)
- queue lengths not constrained, meaning there are no queue capacity limits
- first-in, first-out queue discipline
- randomly varying service times
- a single server (station) for each type of assembly

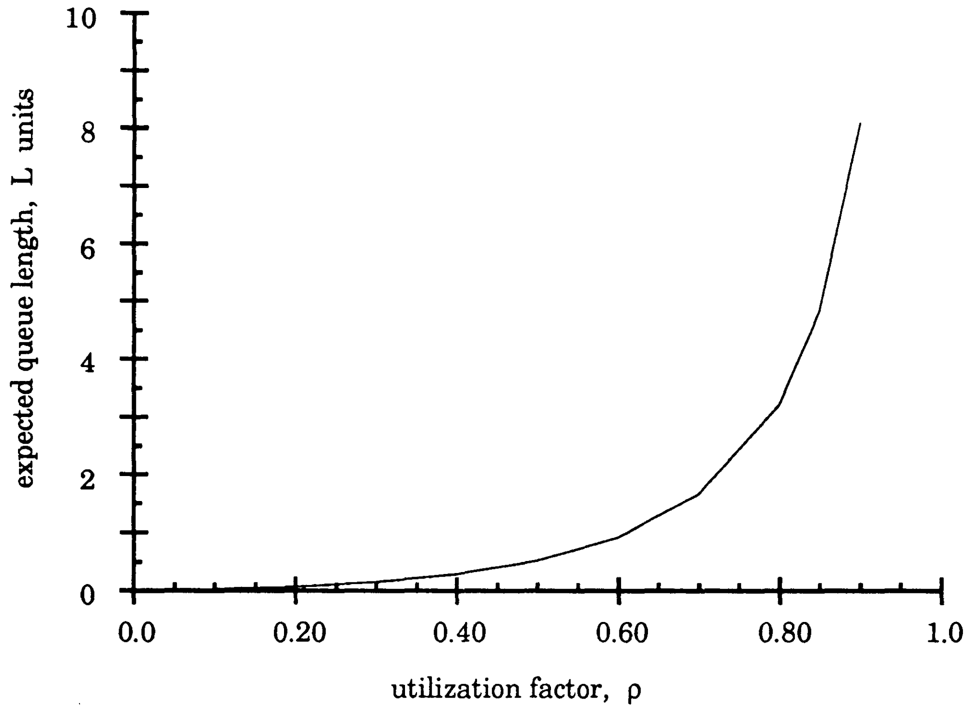

Figure 5.4: *Expected Queue Length versus Server Utilization Factor, assuming Poisson (random) arrivals of units. This is analogous to the average backlog of unassembled parts kits at A3410 assembly stations versus each station's utilization factor.*

This example indicates that the desired utilization factor of the A3410 stations, given the variability in part arrival rates, is substantially less than 1.0. Thus, the excess capacity observed in A3410 appears to be justified in order to accomodate the stochastic (random) variability in part arrival rates, and to minimize wait times and queue lengths for parts kits awaiting assembly. Once detail part fabrication processes are streamlined and brought under better control, with consistently higher yields and the provision of sufficient capacity to handle the random/planned perturbations, the excess capacity which the assembly shop has had to retain (assembly personnel levels, assembly jigs, and other resources) could be reduced. If the variability in parts supply can be reduced, the utilization factor in the assembly shop can be increased (via decreasing capacity or increasing the production rate) without increasing the average queue lengths.

5.3 Other Process Attributes

In addition to the variability in the supply of acceptable detail parts to the assembly shop, other attributes of a manufacturing process exist which can have an adverse effect on overall productivity. These attributes are: 1) the size of schedule and inventory buffers, and 2) the quality assurance process

5.3.1 Schedule and inventory buffers

As shown in Chapter 4, the allocated flowtimes for the assembly of the composite structures studied during this project are four to five times the actual assembly activity period. The policy of maintaining large work-in-process (WIP) inventories was also described. These production planning practices are products of Boeing's time-honored commitment to meeting their production schedules. As in many manufacturing operations, substantial amounts of flowtime and inventory buffers are placed in the production flow, to protect delivery schedules by absorbing production disruptions or uncertainty. However, such practices results in high inventory carrying costs and production process inefficiency. The large inventories help create the feedback delays from the downstream customer in a production process to the upstream supplier, since by the time a part defect is found in assembly, many more copies may have been produced with that same defect. Also, the existence of large flowtime buffers presents a weak incentive for the production workers to improve process efficiency. Without some level of induced worker stress, as in a low buffer just-in-time (JIT) production system, there is little motivation to reduce defects, save time, and eliminate other forms of waste in the manufacturing process. In today's increasingly competitive manufacturing environment, maintaining large schedule and inventory buffers is outdated and not characteristic of world-class manufacturing.

It can be argued that the large flowtime and WIP levels are a direct result of parts shortages and supply uncertainty in composites manufacturing, and in any other manufacturing system with the same characteristics. The flowtime and inventory buffers combine with the excess capacity in A3410 to "smooth out" the variability between fabrication and assembly, enabling a steady, on-schedule supply of completed assemblies to the prime divisions. Until the production variability in composites fabrication is significantly reduced, it will be hard to convince anyone to decrease the planned flowtimes and inventory levels. This underscores the importance of achieving greater control of the fabrication processes and reducing the supply variability from one manufacturing stage to the next, or at least accounting for the variability when allocating resources. By improving the throughput at the fabrication "bottlenecks", and ensuring a stable, streamlined production flow of parts, flowtimes and inventories can ultimately be reduced.

5.3.2 Quality assurance process

The assembly shop labor allocation results discussed in Chapter 4 indicated approximately 20% of the mechanics' time was spent waiting for quality assurance (QA) inspection and rejection tag disposition. This is a substantial percentage of time, and indicates significant improvements in process eficiency may be gained by modifying the QA inspection procedures to allow the mechanics to be held directly responsible for the quality of their work, by minimizing errors which lead to rejection tags, and by streamlining the rejection tag disposition process altogether.

6.0 Recommendations for Improving Composites Assembly Productivity

In this chapter, recommendations are presented for improving the composites assembly process (i.e., less labor intensive, less rework, more efficient production flow) through (1) engineering design considerations, (2) manufacturing process technology, and (3) operations management practices. The context in which this chapter is written is: what can be done in these three areas to improve the productivity of composite aircraft structure assembly operations.

6.1 Engineering Design Considerations

This section presents the engineering design considerations which affect graphite/epoxy structure assembly, and which should be considered by designers of future composite aircraft structures to contribute towards improved composites assembly productivity. The composites assembly issues identified in Chapter 5 which are directly addressed by the engineering design considerations discussed in this section are indicated in Figure 6.1, at the end of this chapter.

Balance fabrication and assembly tolerances

Designs must be producible from a fabrication point of view, but without excessive gaps between parts in assembly. These two countervailing pressures in the manufacture of detail parts for assembly into structures, apply to any material, not just composites. To facilitate optimal assembly, detail part tolerances should be as tight as possible, with the ideal case being all parts produced to their nominal dimensions. However, if this was the requirement, it would be very difficult, if not impossible, to fabricate detail parts within specification. When fabricating detail parts, it is preferred to have the largest allowable tolerances to minimize unacceptable parts which would have to be scrapped or reworked. Thus, the design and manufacturing process engineers must weigh both fabrication and assembly considerations in some proportion when specifying detail part tolerances. In other words, engineers must optimize designs for fabrication and assembly as a whole, and not just for fabrication or just for assembly.

Develop more precise design allowables for pull-up gaps/loads

From an assembly perspective, the allowables currently specified are considered by many engineers to be perhaps too conservative. This conservatism is understandable, however, given the lack of confidence in understanding how to accurately calculate the induced strains caused by pre-load across gaps. However, if through a comprehensive study higher pull-up load and gap limitations could be established, it would give the shop mechanics more flexibility in assembling composite structures, and reduce the amount of shimming and rejectable parts. It would be useful to conduct further analysis and testing on composite materials to determine more precise allowables for gaps and pull-up loads.

Reduce per ply thickness variation

One of the most significant issues in the assembly of composite structures is the variability in laminate thicknesses, based on per ply thickness variation of up to 7% over the nominal thickness, which result in part fit-up difficulties and shimming requirements. Therefore, it is recommended that composite manufacturers encourage the pre-preg material vendors to reduce ply thickness variability, through improved process capabilities and statistical process control techniques.

Minimize mating surface ply-drops

Ply-drops on composite laminate mating surfaces should be minimized by the designer due to the greater potential for shims being required to fill the resulting gaps. Consideration should be given to the impact on assembly of ply-drops as well as to the weight savings obtained by tailoring the laminate thickness. Also, where possible, designers should specify adjacent ply butt-splices versus lap-splices along mating surfaces.

Minimize fiber break-out

Fiber breakout was identified by manufacturing and engineering personnel as a source of substantial rework and repair in the drilling of composite laminates comprised of uni-directional tape plies. This condition can be greatly alleviated by the use of exterior fiberglass, Kevlar, or graphite/epoxy fabric plies. Concerns regarding excess weight should be traded against concerns for producibility of the design.

Minimize dissimilar material stack-ups

Due to the widely disparate optimum drill bit material, drill rotation speed, and feed rate for drilling through graphite/epoxy and titanium, it is recommended that consideration be given to the difficulty of drilling through stack-ups of this type when selecting materials for the structural components of a design. From an assembly perspective, drilling through all-graphite/epoxy, graphite/epoxy-steel, or graphite/epoxy-aluminum stack-ups is preferable to graphite/epoxy-titanium.

Specify easy to install, reliable fasteners

The assembly operation could be significantly accelerated through the introduction of free-spinning fasteners described in Chapter 4. As discussed earlier, this type of fastener is demonstrably easier and quicker to install, provides greater consistency in clamp-up load, thereby resulting in less rework of fasteners, and is quicker and easier to inspect. Designers should also seek greater standardization of fastener types . This would further facilitate the assembly operation by making it easier for a mechanic to correctly locate and identify the specified fasteners. Fastener standardization would also improve the economies of scale in purchasing quantity, and reduce the expense of maintaining inventories of unique, less frequently utilized fasteners.

Increase co-curing/co-bonding of structures

From an assembly point of view, improved composite designs could feature fewer detail parts and fewer mechanical fasteners. Drilling operations and the subsequent installation of fasteners were identified by the assembly labor allocation study as consuming a combined 35% of labor in secondary structure assembly. The labor-intensiveness of these operations is a function of, among other variables, the number of mechanical fasteners required by the composite structure design. Advanced composite designs could feature increased co-bonding and co-curing of composite structures. The stiffening of secondary structure skins with bonded honeycomb core is an example of an improved design, which reduces the number of mechanical fasteners required over traditional panelized-rib construction. The co-bonding of stringers to the skin panels of the 777 composite horizontal stabilizer is another example of such a design improvement. For example, with traditional methods of mechanical fastening, several thousand fasteners would be required for the 777 horizontal stabilizer's lower and upper skin panels, respectively. With co-bonding, the number of fasteners required for each panel is reduced by over an order of magnitude. Reducing the number of fasteners required, through more efficient designs, fewer parts, more integrally-stiffened structures, etc., will streamline the assembly task. However, one must be careful not to simply push assembly labor-intensiveness and quality control challenges upstream into fabrication via co-curing and co-bonding if these processes are not well understood and able to be well controlled. Another consideration is that mechanical joints will continue to be required because of inspection requirements and the need for access to the structure for repair and maintenance purposes.

Avoid composites for small, complex geometry parts

One final recommendation for designers of future composite structures is to avoid the temptation of utilizing composite material for parts which are small and/or have complex geometries, simply on the rationale of reduced weight. Such parts tend to be difficult to fabricate with consistently high quality, which subsequently impacts the supply of sufficient parts to downstream process stages. Strong consideration should be given to other materials and processes, such as traditional forming of metal parts, from the viewpoint of ease of manufacturing and cost-efficiency.

6.2 Manufacturing Process Technology

This section presents the key manufacturing process technology considerations for improving composites assembly productivity. The composites assembly issues identified in Chapter 5 which are directly addressed by the manufacturing process technologies discussed in this section are indicated in Figure 6.1, at the end of this chapter.

Reduce detail part and fitting variability

Based on the results of this study, it is clear that one of the most important goals of manufacturing process technology should be to more consistently produce dimensionally accurate detail parts and fittings, or in other words, to better control part dimensional variability. There are several ways in which this can be done, each of which involves reducing tolerances and overall tolerance build-up in the manufacturing process.

Improve control of mating surfaces during part fabrication (or, cure)

As discussed in Chapter 4, tool side mating surfaces are preferable to bag-side mating surfaces in assembly. The use of male tooling (lay-up mandrels) in the lay-up and cure of composite detail parts, such as spars and ribs, generally results in bag-side mating surfaces. By nature, bag-side surfaces are not closely controlled as are tool-side surfaces. Several conditions detrimental to precision fit-up of detail parts result. One is part dimensional variation, either undersize or oversize, from nominal. Another is the relative roughness of a bag-side surface. The end result is significant potential for shimming for any joint with a bag-side mating surface(s). Female tooling would allow well-controlled tool-side mating surfaces, but is considered to be more expensive and to have inferior quality characteristics compared to male tools. Another alternative to female tooling is the use of caul plates to provide improved mating surface control during cure. The relative advantages and disadvantages of caul plates should be considered for parts formed on male tools.

Improve tooling accuracy and coordination

The many mold transfers required in the construction of composite tools lead to tolerance build-up and poor tool coordination between master models, lay-up mandrels , hand routing fixtures, and assembly jigs. As discussed in Chapter 4, with current tool construction technology it becomes very expensive to achieve tooling tolerances below 0.003", due to geometrically increasing machining costs. New capabilities of the 100% digitial design definition via the CATIA computer-aided design system may revolutionize tool construction techniques. If CATIA and numerical-controlled (NC) machines could be utilized to fabricate lay-up mandrels, tooling accuracy may be greatly increased. Better coordination of tooling between the fabrication shops, assembly shops, and final assembly plants was also identified as an important consideration for improving composites assembly processes.

Select compatible, durable layup mandrel material

The lay-up mandrel material's coefficient of thermal expansion (CTE) and durability are two important factors which should be considered by manufacturing process engineers. Highly differential CTEs between the graphite/epoxy part and the tool on which it is formed can create residual stresses in the part after cure, leading to warpage. While the differential expansion and contraction amounts can theoretically be calculated and compensated for, according to sources interviewed during this project this has proven to be very difficult to achieve in practice. Durability of tools is also a key consideration, in terms of the number of cure cycles a tool can experience before degrading, and in terms of impact or other damage from mishandling.

Improve assembly processes

Further research and development is recommended in the area of drilling operations on composite laminates. Drill and cutter systems which generate cleaner holes in less time, even when drilling through dissimilar material stack-ups, would reduce the labor and rework in composites assembly. Greater applications of automated drilling processes should be explored where possible, given the reported successes on some military programs.

6.3 Operations Management Practices

Based on the findings of this study, substantial productivity gains in composites assembly may result from improvements in the area of operations management. The recommendations in this section are based on an analysis of composites assembly productivity issues, but are generally applicable to manufacturing systems in general. The composites assembly issues identified in Chapter 5 which are directly addressed by the operations management practices discussed in this section are indicated in Figure 6.1, at the end of this chapter.

Emphasize delivery performance between each process stage

Based on this study, it is recommended that equivalent management attention should be given to schedule performance (parts shortages, delays) between each stage of the manufacturing process. Currently, it appears that the majority of emphasis is placed on meeting the prime division jig-load dates, with less emphasis on whether or not the assembly shop receives its detail parts and fittings on schedule.

Eliminate process flow bottlenecks

It is strongly recommended that actions be taken to reduce the considerable flowtime and inventory buffers which charaterize the composites manufacturing processes at the Fabrication Division, and perhaps other manufacturing processes as well. Substantial cost savings and improved process efficiency can be realized by significantly reducing the so-called "Puget Sound Flowtime Between Operations (FTBO)" buffers inherent to every production schedule. By scheduling and managing production activities and downstream deliveries per the real schedules, instead of to a schedule known to contain substantial buffer time, schedule credibility will be enhanced and a more efficient just-in-time production flow can be implemented. Such a transformation would allow significant reductions in flowtime and in-process inventory. A follow-on benefit of reducing inventory would be to expose the process bottlenecks, which could then become targets of focused productivity improvement efforts. Other characteristics of a more nearly just-in-time (JIT) production system would be reduced lot sizes (for machined fittings, for example) and quicker feedback mechanisms between process stages.

Account for less than 100% part fabrication yields

As illustrated in Figure 5.1, the on-schedule availability of all parts of a given assembly is sensitive to the average process yield for that set of parts. As a result, fabrication process yields should be considered when determining the number of parts and fittings to plan to produce for a given planning cycle. Accounting for historically high rejection rates in production planning may be the best way to sustain a sufficient supply of acceptable parts to the downstream process stages. If rejection rates are significant enough, tooling capacity (i.e., the number of tools for a given part) may need to be increased to insure sufficient good parts are produced. In other words, consideration should be given to not only improving the quality of the detail part fabrication tooling, but in providing additional tooling capacity to account for:

1. less than 100% yield in graphite/epoxy composite part fabrication
2. lay-up mandrel degradation over time
3. other tooling attrition due to handling damage
4. tooling downtime due to scheduled and unscheduled maintenance

A detailed cost/benefit analysis would have to be performed, due to the high capital investment required for tooling and equipment. However, the benefits gained from a consistent, reliable supply of good parts, not only in terms of streamlined process flows in the next production stage, but in all subsequent process stages, may be quite substantial. The important point is that poor production yields in fabrication can have a profound effect on downstream productivity, and any analysis to determine the minimum required resources in a given process stage should be careful to avoid sub-optimizing just for that stage, and should instead consider the potential effects on the entire manufacturing process.

As suggested above, a short-term process improvement strategy would be to increase the planned production rate (throughput) to account for fabrication yields less than 100%. One recommendation is to begin monitoring and recording individual part and fitting yield (or scrap) rates over an extended period of time. By accurately determining mean scrap rates, one can establish order quantities and planned production rates which will result in the required number of good parts being produced within the specified scheduled time period. For example, if a given composite detail part such as a 757 elevator rib has a given historical fabrication yield rate, then it is recommended that this be accounted for in production planning by the following equation:

Planned prod rate = (1/yield) x number of parts required

Assume a 757 elevator rib has a yield = 85%
Assume the required number of ribs = 20 per month

Then, the planned prod rate = (1/0.85) x 20 = 24 ribs per month

By accounting for the average historical yield rates, the supply of ribs to the assembly shop will be maintained without requiring expedited replacement parts and the resulting disruption to other part fabrication schedules. It must be emphasized that planning part production levels above the nominal production rate is suggested only as a relatively easy to implement, near-term mitigator of parts supply variability. The organization must be careful to not allow less than 100% yields to become the expectation or the standard, in such a way that process yield improvement efforts are hindered.

A second use of comprehensive yield rate information would be to perform a Pareto analysis on the rejection rates of all parts in a given composite assembly, and focus quality improvement efforts on those parts with the highest rejection rates first. In the long-term, continuous improvement of the manufacturing process technologies discussed in the previous section would be required to increase yields. Until average part fabrication yields are increased to close to 100%, it will be difficult to implement a just-in-time production system, with corresponding reduced flowtime and in-process inventory buffers.

Modify the Quality Assurance process and function

The results of this study indicate that the current QA process is somewhat inefficient, characterized by the worker idle time attributable to QA inspection and rejection tag disposition, and insufficient because it only addresses quality from a pass/fail perspective. In order to reduce the amount of idle time spent waiting for QA inspection and rejection tag disposition, it is recommended that modifications to the present QA system be considered which would streamline these processes. Perhaps changes could be made which would assign more responsibility for quality to the mechanics. The QA personnel could be retrained in statistical process control techniques with which they could supplement their role as inspectors. The first steps towards applying statistical process control techniques in fabrication and assembly would include determining and then measuring the key parameters which define a part's quality. A process which systematically collects data on the key characteristics of detail parts and fittings is critical to understanding the process, generating corrective actions, and receiving feedback. Simply inspecting quality on a pass/fail basis does not provide enough information for process improvements to be identified and realized.

Provide increased training

Each person new to composites assembly should have a certain period of hands-on training to develop skills and experience working with composite parts prior to actually being assigned to the assembly shop. The trainees would use real power tools to practice drilling, reaming, and countersinking scrapped composite parts. A continuous training program, where mechanics would undergo new or refresher training periodically, is also recommended.

6.4 Issue-Recommendation Correlation Matrix

The composites assembly issues identified in Chapter 5 which are directly addressed by the engineering design considerations, manufacturing process technology, and operations management practices discussed in this chapter are indicated in Table 6.1. This table is provided to clarify the assembly issues on which each of the recommendation categories could have a positive impact.

	Recommendation Categories		
Assembly Issues	**Engineering Design**	**Manufacturing Process Technology**	**Operations Management**
Ease-of-Assembly of Graphite/Epoxy parts			
part fit-up, shimming	X	X	X
drilling operations	X	X	X
fastening	X	X	
Detail Part Supply Variability			
production variability	X	X	X
feedback delays			X
Other Process Attributes			
schedule and inventory buffers			X
QA process	X		X

Table 6.1: *Composites Assembly Issues Addressed by Engineering Design Considerations, Manufacturing Process Technology, and Operations Management Practices*

7.0 Concluding Remarks

This research has produced several significant results regarding the cost-effectiveness of composite aircraft structure assembly. These results are summarized in this concluding chapter.

7.1 Summary

The central question asked in this study is: What are the underlying design and manufacturing process attributes which impact the efficient assembly of composite aircraft structure? To answer this question, research was conducted on composites manufacturing at the Boeing Commercial Aircraft Group's Fabrication Division in Auburn, Washington.

An introduction to composite structures, their applications on aircraft, and an overview of the thesis objectives are presented in Chapter 1. A literature review on composites manufacturing and previous studies on composite assembly issues is provided in Chapter 2. In Chapter 3, a description is provided of the composites manufacturing process at Boeing's Fabrication Division, with particular emphasis on assembly. During this study, quantitative data and qualitative information were collected regarding design and process attributes, labor allocations to each assembly task, rework rates, schedule flowtimes, and parts availability. This data and information is presented in Chapter 4. An analysis of the data and information, presented in Chapter 5, identifies three categories of composite assembly cost and quality issues. These categories are:

(1) *The "producibility" or "ease of assembly" of composite structures* - due to composite material properties, tolerance build-up between fabrication and assembly, various design practices, part dimensional inaccuracy and variability. These issues tend to increase the direct labor and the amount of rework required in composites assembly.

(2) *Parts supply shortages* - caused by low process yields and resulting bottlenecks in fabrication, which have a detrimental impact on assembly shop productivity.

(3) *Other process attributes* - such as large schedule and inventory buffers, and the idle time resulting from the quality assurance process.

In Chapter 6, recommendations are presented which address the composites assembly issues identified in Chapter 5. These recommendations are divided into the following three areas which should be considered in the manufacture of future composite aircraft structure: engineering design, manufacturing process technology, and operations management practices.

7.2 Major Findings and Conclusions

The composite design attributes which are identified as having potentially significant impacts on the assembly of composite structures are described in detail in Chapter 6, and are reiterated below:

- fabrication and assembly tolerances (relative to each other) or, the combination of tight assembly tolerances and uncontrolled mating surfaces in fabrication
- pull-up load and assembly gap limitations
- ply (and therefore laminate) thickness variability
- ply drops on mating surfaces
- fiber breakout in tape laminates
- dissimilar material stack-ups
- average time to install composite fasteners
- reliance on mechanical assembly of composite detail parts
- overuse of graphite/epoxy for applications better suited for metals, such as small, complex geometry parts

A key contribution of this project is the quantitative assessment of labor allocation in the assembly of composite secondary structure. Based on the composite assemblies investigated in this study, part fit-up and shimming together account for about 20% of total labor effort, hole drilling and fastener installation account for approximately 35%. Other large time categories include waiting for rejection tag disposition and performing rework, and waiting for detail parts and fittings to become available for assembly.

Another important finding of this study is that the bending stiffnesses of the component parts being mated appears to be a key factor in the amount of shimming required in assembly. Bending stiffness is a function of the gage thickness of the component parts, and for thicker parts a given pull-up load limit will not close gaps as readily as for thinner gage parts. As a result, the amount of shimming required in the assembly of relatively thin composite laminates in secondary airfoil structures (control surfaces) is comparatively less than for relatively thick composite laminates in primary airfoil structures (stabilizers, wings).

One of the greatest opportunities for improving assembly productivity (i.e., reducing labor expenditures and rework requirements, and increasing throughput) appears to be in the fabrication of detail parts and fittings. The key characteristics of detail parts and fittings are dimensional accuracy and consistency, which in turn are functions of the interactions between composite structure designs (primarily, tolerances and assembly gap and pull-up load limits), and manufacturing process capabilities (primarily, tooling accuracy and curing process variability). Part and fitting dimensional accuracy and consistency affect the ease of assembly operations downstream in the assembly shop as well as process yields in fabrication. In assembly, the ease of part fit-up and shimming operations are clearly impacted by dimensionally inaccurate and varying parts, even though the parts may be within tolerances. Out-of-tolerance parts which never make it out of fabrication must be scrapped and refabricated. If the resulting sub-100% process yields are not accounted for in production planning, the supply reliability of parts and fittings to the assembly shop will be impacted. An example is presented which demonstrates the sensitivity of an assembly process schedule to fabrication yields which average even slightly below 100%. Such yields cause disruption not only in assembly, but also in fabrication due to the need to build replacement parts. The analysis is continued to suggest that variability in the parts supply to assembly leads to worker idle time or at least an understandable tendency to slow down the work rate to make the current jobs last. It is proposed that the slowed work rates and idle time are key contributors to the absence of a decreasing trend in assembly labor requirements, and the high variability in labor expended from one unit to the next.

It is suggested that in conjunction with continuous efforts to improve composite fabrication processes, short-term parts supply reliability improvements can be achieved by accounting for less than 100% yields in fabrication. Records of part yields should be tracked in order to determine average yield rates with which to modify planned production volumes to account for expected scrap rates, and to explicitly identify problem parts on which to focus process improvement resources.

A general conclusion related to the above observations is that by evaluating individual shops (or process stages) independently of the entire manufacturing process, incomplete or inaccurate conclusions may be drawn regarding the nature of productivity issues. In this case, the highly varying direct labor per unit data for the A3410 assembly shop led many to conclude that the processes internal to A3410 were out of control. This study has attempted to show that, while some process variability may be due to assembly operations in A3410, possibly greater contributions come from sources completely external to the assembly shop. Thus, one must analyze and evaluate the performance of the entire manufacturing process, including the interactions between discrete stages, and not simply analyze each stage independently. Independent evaluation of each separate stage (shop) tends to minimize each stage's costs without regard to impacts on other process stages. Sub-optimization during resource planning can de-optimize the overall manufacturing process.

Along this line of reasoning, an analysis is presented which illustrates that the observed excess capacity in the assembly shop may be justified given the apparent variability in the parts and fittings supply. A queueing model is presented which illustrates the need to keep assembly shop utilization factors significantly below 1.0 (i.e., retain higher than nominal capacity in assembly) until the parts supply variability is improved, in order to smooth the overall production process flow and provide completed composite structure assemblies to the final assembly plants consistently on schedule.

It is also noted that the disruptive effects of parts supply variability to the assembly shop are invisible to management through the current shop performance measurement methods, which track labor expenditures and late deliveries to the prime division customer, but do not account for the lateness of incoming parts and fittings from fabrication.

Boeing should consider significantly reducing the large flowtime and inventory buffer goals which currently characterize their manufacturing operations. This will become particularly important as continuous improvement efforts lead to reduced manufacturing process variability. Such reductions will result in substantial savings in inventory carrying costs, a more streamlined and efficient manufacturing process flow, and reduced process feedback delays.

7.3 Recommendations for Further Study

The unresolved questions and potential issues for composite structure assembly which are identified in this thesis serve as candidates for further study at Boeing and in university research programs. These questions and issues are summarized below:

- Additional work is needed towards producing more consistently accurate composite detail parts. Efforts could perhaps be focused on issues such as reducing material ply thickness variability, improving fabrication tooling materials, tooling fabrication methods, controlling part mating surfaces during autoclave curing, and reducing overall tolerance build-up.

- It is suggested that Boeing may wish to further investigate the causal relationship between parts supply shortages and the variability in direct labor expended in assembly. By collecting and maintaining detailed records of part shortages (measured in part-days late beyond scheduled assembly start dates), statistical analyses can be performed to determine the correlation of parts shortages to direct labor hours expended.

- A comprehensive analysis and empirical testing program is needed to better determine pull-up load and assembly gap limitations. Such a program would be worthwhile by improving understanding of the effects of pre-load and gaps on composite materials.

- Further development of automated drilling processes for application to commercial aircraft composite structure assembly is recommended to reduce labor requirements and improve hole quality and consistency.

- Composite part co-bonding and co-curing technology promises to reduce the number of mechanical fasteners in composite structure. However, these processes have cost and quality control issues which require further development.

- A very interesting and important area of investigation, which was largely outside the scope of this study, is a thorough comparison of composite and aluminum subassemblies. While this study focused on composites assembly cost and quality issues, many questions are left regarding how composite structure assembly is different from, and similar to, aluminum structure assembly. Are the traditional methods of comparison, such as direct labor costs or cost percentage allocated to assembly for each material type, truly adequate or relevant? Or, are the structural design, fabrication, and assembly characteristics of composite and aluminum components so fundamentally different as to render inadequate any one-to-one comparisons of their respective assembly costs?

- Finally, it is suggested that studies of composites manufacturing issues and challenges be extended further "downstream" in the production process flow to the final assembly operations at the prime divisions. Are there significant differences in the experiences with composite and metal subassemblies during final assembly? Are there any impacts to the final assembly (or, installation) of composite structures resulting from Fabrication Division composites assembly operations, similar to the interactions between fabrication and assembly identified in this study? Do composite structures have to be treated or handled any differently from metal? These and other questions reinforce the point that the entire manufacturing process, from design all the way through delivery and operational service, should be analyzed as a whole. Although most large manufacturing processes consist of many stages which each invite independent analysis and sub-optimization, the real objective should be optimization of the whole.

BIBLIOGRAPHY

Anderson, B.W., "The impact of carbon fibre composites on a military aircraft establishment", *J.Phys. D: Appl. Phys* ***20*** (1987) pp. 311-314.

Cardaba, Lence, and Gomez, "Design and Fabrication of the Carbon Fiber/Epoxy A-320 Horizontal Tailplane", *SAMPE Journal*, Jan/Feb 1990, p.9-13.

Hadcock, R.N., "Design of advanced composite aircraft structures", *International Journal of Vehicle Design, Special Publication SP6*, 1986, p.292.

Hilton, Peter D., and Kopf, Peter W.,"Aerospace Market for Composites Poised to Take Off", *Research and Development*, Feb 89, p.95.

Kandebo, Stanley W., "Manufacturers Seek Reduced Costs Through New Fabrication Techniques", *Aviation Week & Space Technology*, July 21, 1986, pp. 73-77.

Lambert, Brian K., "Find Low-Cost Methodology When Machining Composites", *Cutting Tool Engineering*, December 1987, p.20.

Nahmias, Steven, Production and Operations Analysis, 1989.

Pilling, Mark, "The Leading Edge", *Aerospace Composites and Materials*, Winter 1988-1989, pp.48-50.