Quality in Composite Sandwich Fabrication

by
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B.S.E., Chemical Engineering
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Abstract

A survey of the A3430 composites fabrication shop at Boeing was conducted to understand the quality issues in the area. In its efforts to ensure timely shipment of acceptable parts and to lower its operating costs, the A3430 shop is focused on reducing its scrap, repair, and rework costs. This investigation examined the quality costs, yields, and defect counts for various parts and production processes in the A3430 shop. From an assessment of its overall quality system, this study intends to identify opportunities for improvement and provide recommendations from an operational and technical perspective.

Data from the quality information systems attributes the lay-up process as a primary source of defects. As a result, lay-up was studied to understand the variability within the process and the impact of uncontrolled parameters. In particular, the compaction cycle and material properties were evaluated. Of the various defects, voids in the radius area of parts are a common cause of rejection. Experiments were conducted to better understand the lay-up process and void formation. During this exercise, the overall quality system was also studied. Opportunities to improve the responsiveness of quality efforts were sought.

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Finally, I wish to thank my fellow classmates who motivated me to complete this thesis. They served as role models, as compatriots, as conscience, and as friends.

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Chapter 1

Introduction

1.1 Composite Structures

Composites are materials which consist of reinforcing fibers intermixed within a continuous matrix phase. The fibers provide strength and stiffness to the material, while the matrix acts as a cohesive binder. Together, these components demonstrate unique properties which are extremely advantageous in many industries, including the aerospace industry.

Composites exhibit high strength, stiffness, and impact resistance which address the rigorous needs of aircraft manufacturing. Because of these superior structural properties, composites can satisfy demanding performance requirements with less material. Increased use of composites can realize weight savings of up to 30% over other materials [Shipp, 26]. Composites also demonstrate high resistance to corrosive environments.

These properties lead to safer and longer lasting aircraft which can withstand the repeated stresses and wear of flight. Operating costs are also reduced through more efficient fuel consumption and lower maintenance costs.

Until recently, use of composites in commercial aircraft has been limited to secondary structures. While their applications have been increasing, composites still represent a newer and less understood technology than their metal counterparts. Their developing environment is consequently accompanied by high operating costs. As a result, corporations are actively involved in programs to enhance their knowledge of composite fabrication and to reduce their manufacturing costs.

1.2 Problem Definition

The A3430 composites shop internally supplies Boeing composite part details and sub-assemblies. In its efforts to ensure timely shipment of acceptable parts and to lower its operating costs, the A3430 shop is focused on reducing its scrap, repair, and rework costs. This research sought to analyze quality within the shop using a variety of metrics, such as cost, yields, and defect counts. From an assessment of its overall quality system, this study intends to identify opportunities for improvement and provide recommendations from an operational and technical perspective.

1.3 Methodology and Content

The initial portion of this internship was spent understanding quality as it applied to composite fabrication. Since quality often appears as an abstract term, it is important to recognize the objectives and the meaning of quality improvement. Chapter 2 provides background on the quality theme.

A second significant effort in this project involved collecting and interpreting information from a variety of databases, records, and people to gain insight into the A3430 quality operation. Both the quality system and part fabrication were studied as processes which influence the production of quality parts. Chapter 3 discusses quality evaluation in the A3430 shop.

Ideally, an understanding of the overall operations would suggest relationships between defects and possible causes. Data was obtained and subsequent analysis was performed to support the effort to discover improvement opportunities. Interpretation of the available data is given in Chapter 4.

Data evaluation associated the lay-up process with a large number of non-conformances, or defects. During lay-up, the composite part is built in this labor intensive step. Chapter 5 describes the lay-up process and its sources of variability.

Experiments were conducted to understand the effect of several variables on lay-up. These included compaction parameters and material properties. Chapter 6 contains the experimental plan, while Chapter 7 interprets the results of experimentation.

Because labor is a significant component in lay-up, Chapter 8 analyzes aspects of the A3430 quality feedback system. Finally, Chapter 9 presents general conclusions and recommendations.

Chapter 2

The Importance of Quality

2.1 The Emphasis on Quality

Many corporations have emphasized quality to compete in today's business environment. Increased competition, discriminating customers, and demanding shareholders have challenged industry to become even more efficient. Quality has emerged as an important lever for improvement.

Controlling the quality of one's products benefits the company by reducing costs and increasing revenues. Clearly, lower costs result from improved efficiencies and fewer scrap and rework hours. Product cycle times shorten if the hours spent inspecting, repairing, diagnosing, and rebuilding parts are eliminated. Fewer defects in the field will minimize warranty and future repair costs.

Revenues also increase through greater customer satisfaction, which then generates higher demand. Quality can differentiate the services or products of one company from its competitors. As a result, a company may command a premium for its superior quality.

Finally, quality improvement can have intangible benefits by recognizing successful efforts and boosting worker morale. In addition, the emphasis on quality provides a spirited focus for company growth. This focus can help direct and motivate those employees who are removed from high level decision-making and help them understand the impact of their efforts.

2.2 The Impact of Poor Quality

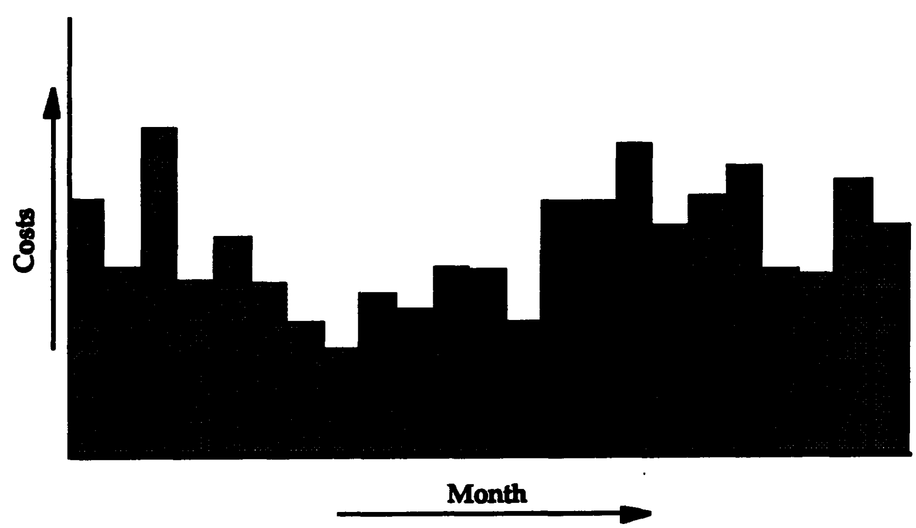
When a problem occurs, its resolution involves a number of people, such as shop workers, quality inspectors, manufacturing engineers, research and development, engineering designers, product managers, information analysts, among others. As a result, a non-conformance, or defect, requires the time of many to properly investigate and resolve the concern. A large percentage of fabrication labor may be used to address quality problems.

In addition, part failure poses a tremendous risk due to the visibility, interdependence, and the scale of the aerospace industry. Government regulatory agencies and the public constantly scrutinize the activities of these corporations. Documenting and ensuring the continued performance of an airplane incurs large costs.

2.3 Benefits to the Composites Shop

In the Boeing A3430 composites shop, improved quality operations lead to several immediate gains. Figure 2.1 illustrates scrap, rework, and repair costs by month. The cyclical costs suggest opportunity for quality cost control.

Figure 2.1: Monthly scrap, rework, and repair costs for the A3430 composites shop



Furthermore, every non-conformance has a fixed cost, regardless of how trivial the defect may be. These result from the efforts of the Material Review Board (quality assurance, engineering, manufacturing) who investigate the non-conformance to determine the disposition of the part and to prescribe corrective action. This consumes valuable time from their other activities.

Each defect also generates documentation which must subsequently be handled, at additional costs to the central files and information systems groups. Of course, repairs and scrapped parts represent the largest costs. Therefore, every attributed non-conformance increases operating costs.

Finally, defect reduction supports the drive to shorten product cycle times and to achieve aggressive schedules. In addition to the rework and rebuild delays, parts spend an average of 3 days waiting for disposition. Since planning accounts for these delays as part of the normal schedule, gains may be achieved through defect and disposition time reduction. These times are substantially longer for the more complicated parts which contain more defects and require longer repairs.

2.4 Measuring the Cost of Quality

The effort to improve quality also absorbs employee time and company resources. As a result, one must first measure the costs and benefits of a quality program before pursuing it. In a world of limited resources, one must prioritize every program.

Cost of Quality (COQ) can serve as an effective tool for quality management. By providing a quantitative measure and weight to quality, decision-making becomes less ambiguous. Historically, in the attempt to balance the tradeoffs between schedule, cost, and quality, quality has been sacrificed as a qualitative trait. However, COQ concepts help manage quality against schedule and cost.

COQ also provides a convenient means to analyze and focus on problems. It serves as an accounting system which signals the onset and sources of problems. It supports budgeting by justifying or rejecting expenditures on a tangible financial basis. For example, the decision to outsource or to internally supply parts often confronts the composite aircraft industry. One must include quality, in addition to manufacturing costs, in determining the choice of suppliers.

Finally, COQ acts as an improvement process. It establishes standards and measures to evaluate the effectiveness of one's actions. Specific goals are defined, in terms of COQ.

The American Society for Quality Control (ASQC) divides quality costs into the following four categories:

Prevention: Costs incurred to *prevent* future non-conformances. Training, planning, process improvement, design review, and maintenance are common means to reduce the occurrence of non-conformance.

Appraisal: Costs incurred to measure and control production to assure conformance to requirements. People, supplies, and equipment associated with inspection fall into this category, as well as products which are lost during destructive testing.

Internal failure: Costs generated before a product is shipped as a result of non-conformance to requirements. Scrap, rework, repair, schedule delays, and process troubleshooting contribute to this cost category.

External failure: Costs generated after a product is shipped, as a result of non-conformance. These include loss of customers, losses on returns, warranty costs, service work, and the processing of complaints and returned goods.

Typically, costs to correct non-conformance progress in the following fashion:

External > Internal > Prevention

Therefore prevention spending is more cost effective than resolving external failures. The Boeing A3430 composite shop follows this philosophy as they endeavor to prevent external failures, by shifting their efforts to the prevention, appraisal, and internal failure categories. In most industries, internal failures comprise the largest aggregate portion of quality costs.

By monitoring each of these costs, opportunities for improvement become obvious. Of course, cost data must be practical to collect, report, and analyze. This research focuses on internal failure costs as the significant cost category and as an available data source.

2.5 Conformance and Non-Conformance

A part is acceptable if it satisfies the latent customer needs. In other words, the product demonstrates "fitness for use" by performing as intended. However, manufacturers have limited access to the customer's use of the product, and thereby develop robust criteria to anticipate the product's ability to satisfy the customer. By adhering to these specifications or requirements, the products should then be "fit for use." This is referred to as conformance to requirements.

Likewise, product failures are defined as non-conformances to these requirements. These non-conformances include deviations from the designed product attributes or departures from the process specifications. The part is then designated for further action, using one of several dispositions:

Use-as-is (UAI): No repair work is needed. Although there is a non-conformance, the part is still fit-for-use (there may be no attribute changes).

Rework: With additional labor, the part can be corrected so it satisfies the engineering specifications exactly. For example, missing holes or excess trim can be entirely eliminated.

Repair: The non-conformance can be reduced, but not eliminated. While the part will not meet the original specifications, it can be repaired to an acceptable use level.

Scrap: It is not cost effective to correct the non conformance. The part is discarded.

The methods which Boeing uses to identify non-conformances are discussed in Chapter 3.

2.6 Quality in Composites

The composite fabrication shop produces a variety of components which differ in structure, function, and manufacturing process. The initial challenge involves defining quality for this broad set of parts and determining methods to measure quality. Quality in composites has generally emphasized the physical and mechanical properties of the cured part as performance metrics. A large number of standard testing procedures exists in the industry from the American Society for Testing and Materials and the American Society of Mechanical Engineers.

In general, four basic characteristics govern the structural performance of a laminate [Hinrichs, 10]:

Void or porosity content: Gaseous pockets which are cured into the laminate. These unfilled air spaces weaken the laminate's ability to withstand stresses.

Level of laminate consolidation: Resin content, fiber volume, and associated distribution gradients. Again, proper consolidation ensures the high strength, high impact composite.

Degree of cure: Formation of the polymeric resin and structure. Proper crosslinking of the polymer matrix reinforces the integrity of the composite.

Fiber orientation: Conforming to the design requirements.

While structural integrity is critical to the aircraft composite, other aspects such as contour, dimensions, weight, and thermal and chemical resistance, also play large roles in defining the composite quality. Many of these properties are measured after the part has been cured, through either destructive or non-destructive testing. Standard mechanical tests for these final physical attributes of the composite currently exist.

The actual process of building and curing the composite resembles a chemical process. The composites shop, in this respect, has transformed from a traditional organization which purchased and assembled materials into one which converts prepreg materials into a composite. Table 2.1 presents examples of the shift from material user to material producer in composite manufacturing.

Table 2.1: Manufacturing transition [Hinrichs, 1]

Material User	Material Producer
Existing Materials are bought already containing all engineering properties.	Materials must undergo a chemical reaction process before they achieve engineering properties.
Manufacturing operations are primarily numerically controlled machine shaping and forming.	High-performance aerodynamic shapes are formed simultaneously with the cure formation process.
Mechanical robotics processing, routine precision operation, X-Y-Z drilling positioning.	Chemical process control automation required. Dependent on skilled craftsmen.
Very tolerant of manufacturing errors. Functions (mechanical fastening, shaping, or heat treatment) do not change intrinsic properties.	Structural quality totally dependent on process. Material properties not tolerant of manufacturing errors.
Preceding items limit design and flexibility, cause weight penalties, and lower performance efficiency. Approach is rapidly becoming obsolete.	Flexibility to compete in future aerospace structures design and production. Approach expands customer base and engineering design capability.

As a result, process variables, as well as final characteristics, become increasingly important. Identifying these key process parameters will facilitate the composite shop's effort to manufacture high quality parts.

Chapter 3

Quality Evaluation

3.1 Non-Conformance Classifications

While any defect is undesirable, non-conformances may differ in cost penalty, corrective action, or impact. As a result, Boeing tracks its non-conformances in several levels, by issuing either a *pick-up* or *rejection* tag to signal a deviation from the manufacturing plan.

Pick Up Tags

Pick-up tags are issued for non-conformances which require minor attention. These include paperwork errors and defects which are readily repaired in the normal process area, as opposed to a separate rework station. Pick-up tags do not require engineering disposition to authorize corrective procedures. Pick up information is recorded in an on-line database.

Rejection Tags

Rejection tags are issued for non-conformances which require engineering disposition to designate the part as use-as-is, rework, repair, or scrap. Rework and repair may be further classified as Control Code 4 (CC4) if more than 4 hours of repair time are *estimated*. Labor hours for CC4 are recorded separately. Information on rejected parts is tracked in both on-line and historical databases.

Pick-ups are preferred over rejection tags because no engineering disposition is required and they have a lower fixed cost. On the other hand, rejection tags command more attention and alert others to problem areas. Therefore, different incentives may exist behind the choice of tag issuance.

3.2 The Inspection Process

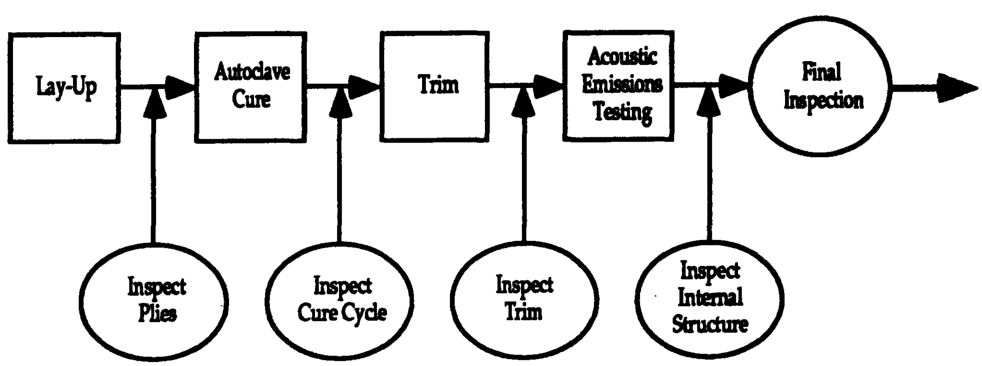
"The worst of all defects is to be unaware of them"

- Publius Syrus, Sententiae [Périgord, 21]

Because processes are not completely reliable, inspection is necessary to filter any defective products and to check the general operation of the process. As inspection can be time consuming and costly, it is important to identify proper levels of inspection and the appropriate inspection points. Of course, the fundamental goal should be defect prevention, rather than defect detection.

The Quality Control (QC) group generates pick up and rejection tags based upon non-conformances which are detected by the QC inspectors or lead personnel in the process shop. Inspection occurs at several points during the composite fabrication process, as illustrated in Figure 3.1.

Figure 3.1: Inspection points for a typical composite part



The various inspection criteria are described for each area:

Lay-up: Inspection ensures that the plies have been applied properly. This includes examination of ply sequence, orientation, overlap, splicing technique, and the absence of foreign material. The integrity of the bagging prior to cure is also inspected. Typically, any non-conformance in this area can be corrected readily, since the part has not yet been cured.

Autoclave Cure: Quality control verifies the process parameters during the cure cycle. These include temperature, pressure, rates of heating, rates of cooling, and processing times. Some visual inspection is performed.

Trim: Dimensions of the parts are checked. Visual inspection is also conducted.

Through Transmission Ultrasound (TTU): This non-destructive test utilizes ultrasonic transmission to detect discontinuities in the composite. These may represent voids, delaminations, and disbonds. Statistical Quality Control determines the sampling rate of TTU inspection; despite this, many parts are still 100% inspected because they periodically experience defects.

Final Inspection: Dimensional, contour, visual, and miscellaneous inspection is performed.

Documentation exists to define acceptability levels and to assist inspectors with the decision-making process. Quality is typically evaluated on an attribute, or pass/fail basis. Information, other than autoclave processing data, is generally not collected on a variable basis.

Because certain criteria tend to be subjective, such as visual inspections, the experience and ability of the inspector plays a critical role in interpreting problems. Much information and training is transmitted verbally between inspectors, especially since each inspector rotates through the various inspection areas.

Data on non-conformance tags is entered into quality information systems. While the data on pick-ups is recorded, no standard action is taken to track their causes. Rejection tags are investigated by the Corrective Action Group (CAG) to determine means to prevent problems in the future.

3.3 Quality Information Systems

The value of any Quality Information System (QIS) depends on the accuracy and scope of the data it contains. The relevance of fields, the clarity of definitions, and the consistency of user input, all contribute to the integrity of the information. In addition to data storage, a complete QIS collects, analyzes, and reports pertinent information. It should provide real time data, perform off-line analysis, generate reports, and allow simple use. Of course, a tradeoff exists between easy access and complexity for security reasons.

Boeing uses several information systems to measure its performance against a variety of metrics. Some of these are described:

Discrepancy Analysis System (DAS) - This on-line reporting system contains pick-up and reject part data. The database fields include the part discrepancy, the process area where the flaw is believed to have occurred, the date, and several other work order fields. A set of standard entries and codes exists for this database; however, no formal guide to define these entries currently exists. The codes are entered using the judgment of members of the Corrective Action Group.

On-line Rejection Information System (ORIS) - This historical data system tracks detailed information on rejection tags only. It discloses the disposition of the part and contains a text field which explains the rejection reason. A delay ranging from a week to months may exist before the tag is entered into this system.

JobMaster - This production information system contains data on work orders and performance in the shop. Labor hours, repair hours, and volumes for the various process areas are available. Because procedures for recording repair hours are not strict, repair labor data must be analyzed carefully.

Finance Discrepancy Cost Collection (FDCC) - This financial system generates cost estimates of the scrap, rework, and repair costs using labor hours as a cost driver. It provides total quality costs using material, wage, and overhead cost factors. Because these cost factors are determined using total shop cost data, they are appropriate on an aggregate level. This data loses relevance on an individual part or process basis.

Employees - The workers and engineers represent a valuable source of information through their direct experiences with the various parts and processes. They provide broader and more creative feedback which is not limited to the pre-defined boundaries of an information system.

3.4 The Quality Improvement Process

While the general tools for quality improvement exist, execution of the problem-solving process is difficult. Figure 3.2 outlines a general framework to initiate quality improvement.

Figure 3.2: Quality improvement process

- Identify the problem
- Define targets and objectives
- Analyze the problem
- Develop hypothesis
- Test hypothesis
- Reiterate the improvement process

Once the problem has been understood and corrective measures have been identified, implementation follows. This often poses more difficulties than the actual problem solving itself, due to barriers to change, such as organizational resistance, aversion to risk, and limited resources.

Because significant data collection and analysis is required, cost of quality, Pareto charts, scatter plots, trend analysis, and control charts, serve as useful tools to understand the operation. The quality information system should be capable of providing information in this fashion. In addition, cause-and-effect (fishbone) diagrams can help evaluate a problem. Together, these tools gather and organize information in an easily understood form. They simplify the basic points of quality problems, suggest courses of action, and facilitate communication within the working team. Chapter 4 discusses the use of these tools in analyzing quality at the A3430 composites shop.

3.5 Quality Parameters

While cost data provides an effective means for measurement and analysis, additional metrics can help assess the quality of an operation. Multiple parameters allow interpretation of the quality problem from multiple perspectives. This protects the analysis from the idiosyncratic nature of certain measures and the questionable accuracy of other data. For example, Boeing maintains cost data to evaluate the performance of its operation on an aggregate level; however, the applicability of this data is questionable when it is decomposed to a specific part or process level.

Performance parameters must be accurate and well understood; otherwise, any subsequent action will less likely be accepted. The following criteria were used to evaluate quality in the composites shop for both pick-up and rejection tags.

- Number of defects: This may be measured by the quantity of tags, the number of non-conformances (a tag can represent multiple non-conformances), or the quantity of parts rejected (a tag can represent multiple parts).
- Quality yields: This includes part and process yields, as well as part disposition.
- Costs for internal failures: This may compare total cost or unit cost for a part or process. This includes costs for repair, scrap, and overhead, and is generally based on labor hours.
- Qualitative information: Discussions with shop workers, supervisors, product planners, engineers, and inspectors were conducted.

This data is available within Boeing's various systems. Ideally, all of this information would be accessible in one integrated system which can attach costs with defects and problems. A single system eliminates duplication of effort, reduces miscommunication across the boundaries, and outperforms several sub-optimal systems.

3.6 Hidden Factors

Despite obvious and available metrics for quality, subtle quality problems may exist and remain otherwise undetected. Accepted practices or procedures which facilitate the everyday operations may alleviate the symptoms of recurring disturbances, while masking the underlying problems. Several examples are presented below:

Undocumented rework - Due to schedule pressures, the shop may independently perform repair to expedite a work order. Although documentation is not necessary when the corrective action is minor or known, it becomes difficult to identify the original causes for the rework. Control Code 4 (CC4) work orders are generally required to initiate lengthy repairs; however, because it takes additional time to issue the CC4 card, repairs may be performed without an order.

Hidden rework labor - Obviously, if no paperwork exists, it is impossible to track the associated repair labor hours. Even with the standard issue of tags, repair hours are only tracked for the CC4 orders. All other repairs, because they are *estimated* at under 4 hours, are buried within the standard work hours. Similarly, work performed to correct pick-up tags are accounted within the normal processing time. Therefore, the fabrication labor hours inherently includes non-conformance labor.

Institutionalized rework - Because some problems occur frequently and have standard corrective procedures, certain repair activities have become institutionalized as part of the manufacturing plan. While this avoids the fixed costs of issuing tags and obtaining engineering disposition, it also removes the urgency to eliminate the problem. The cost of additional repair labor is no longer connected to non-conformances; the total labor hours for these parts simply increases.

Material costs - A central purchasing group procures prepreg materials and passes an overhead expense to the fabrication shop. As a result, material utilization is directly not tracked within the various process areas of the shop. While some material losses are unavoidable due to the various geometries of the parts, some material scrap is the result of process failures. This represents an additional, undetected cost of quality.

Chapter 4

The Analysis of Quality Information

4.1 Data Collection

Using Boeing's various information systems, data was analyzed for the six month period prior to this study. Although continuous and real time data collection is desirable, an expanded interval smoothes the data for these low volume parts. The six month interval also reduces the impact of dating discrepancies between the different information systems. Finally, complete data from DAS, the most quality intensive system, was not available prior to this time frame. The initial intent of this research was not to recommend immediate actions, but to better understand quality within the shop.

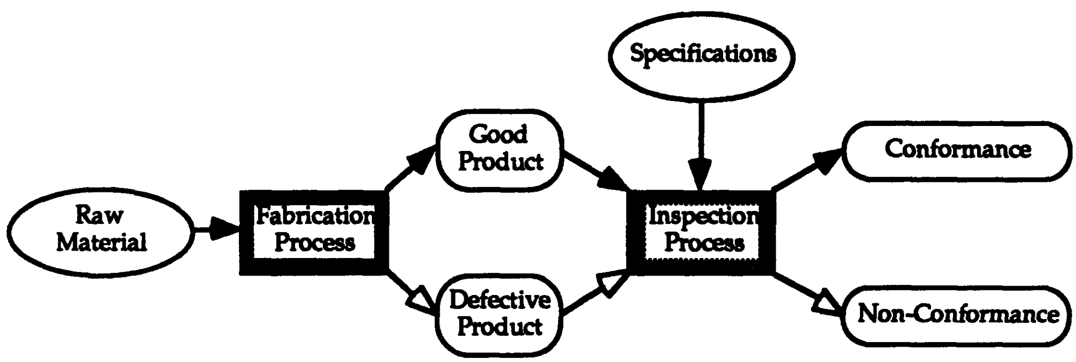
To reduce the analysis to a more manageable size, this research focused on composite parts with honeycomb core, also known as composite sandwich parts. Composites without honeycomb core, known as laminates, have historically experienced fewer problems. The presence of honeycomb core introduces additional complexities which make it difficult to fabricate. This includes the negative vacuum pressure sealed within the core, more contoured geometries, and the inherent complexity in processing a sandwich part.

Furthermore, this study excluded parts which had recently been introduced to the shop, such as new 777 airplane components or leading edge parts. Their processes were still under development, and any data would not represent the mature operation. Unknown part numbers which appeared in the quality data systems were assumed obsolete or incorrectly entered. Any known part numbers which did not appear in the databases were also ignored; their processes were most likely well controlled or of insignificantly low volume.

4.2 Sources of Non-Conformance Tags

A fundamental question to propose involves not only the causes of part defects, but also the sources of non-conformance tags. A systematic analysis of defect generation observes the basic process of issuing non-conformance tags. Figure 4.1 illustrates the factors involved in identifying a discrepancy.

Figure 4.1: The process of identifying non-conformances



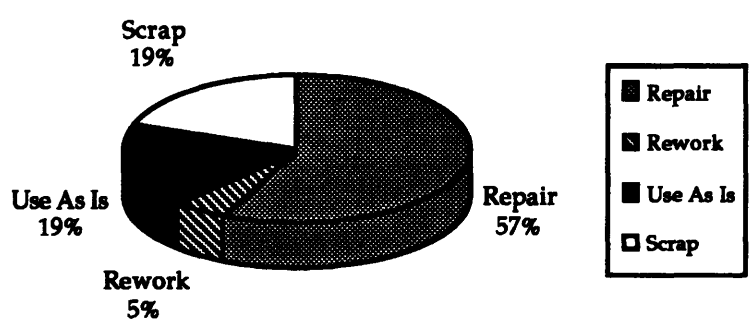
Clearly, a non-conformance can result from any of the process stages. Faulty raw materials can doom a process which is not robust. The manufacturing process itself can go awry and adversely impact the product attributes. In each instance, the result is a product which does not conform to the specifications.

However, a non-conformance tag may still be issued for a part which is fit-for-use, as with use-as-is rejections. In these instances, inspection may be a source of process failure. Specifications act as the inputs into the inspection process and must be appropriate and clear for effective defect detection. The inspector must understand these specifications to capably identify defects. Overspecified tolerances and misjudgment can therefore contribute to non-conformance tags.

Tags are also issued because many requirements lead to numerous inspection points. For example, the 757 aileron assembly, which is examined at over 160 points for contour, experiences one of the highest rejection counts in the shop. Likewise, the development of sophisticated inspection techniques enhances the shop's ability to detect non-conformances. The inspection process has therefore improved to magnify blemishes in the fabrication process. A part which previously had been acceptable may now be rejected due to higher resolution in diagnostic testing.

Figure 4.2 presents the breakdown of rejection tag disposition for the composite sandwich parts under study. Approximately 19% of these parts were initially rejected, but then returned use-as-is. However, use-as-is rejections are expected due to the conservative nature of engineering tolerances and inspection practices. Precautionary inspection is necessary due to the serious consequences of aircraft part failure.

Figure 4.2: Distribution of rejection tag disposition

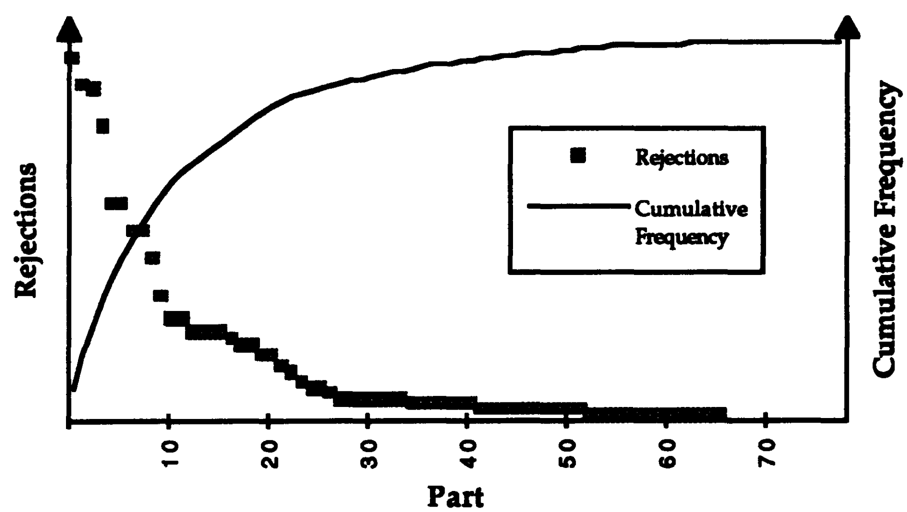


Assuming that failures in the manufacturing processes cause the majority of non-conformances, Pareto analysis can suggest potential areas for quality improvement. According to the Pareto principle, a few factors are responsible for most of the problems. The quality data was decomposed by part, by process, and by discrepancy to understand the defect distribution. These effectively cover the "who, where, and what" of the problem; ensuing analysis provides the "how and why."

4.3 Part Analysis

Defect counts were calculated for the various sandwich parts, as summarized in Figure 4.3. Each individual point represents a different part number (or part model).

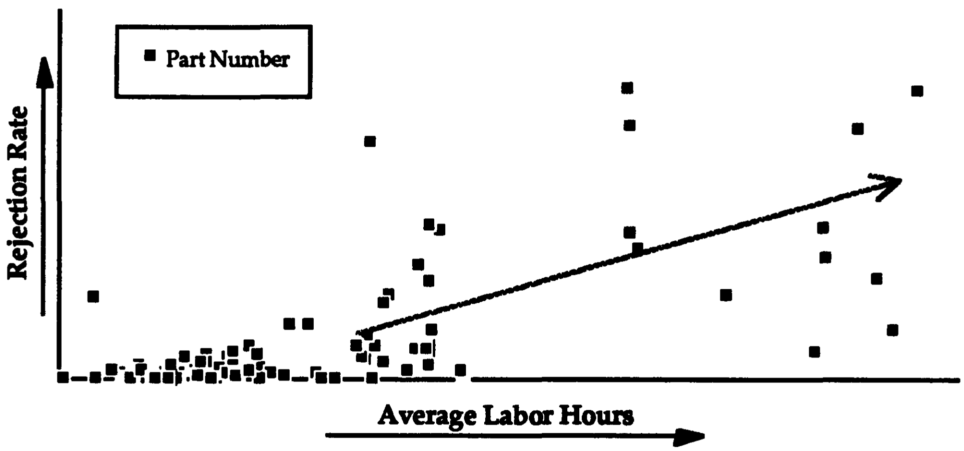
Figure 4.3: Defect distribution by part



Consistent with the Pareto principle, roughly 70% of the total defects can be attributed to 20% of the part numbers. Therefore, concentration on these select parts can significantly reduce non-conformances.

An attempt to link these parts through a common factor reveals little with respect to material or process area, since they cover graphite, fiberglass, and Kevlar materials, and all three of the lay-up stations. However, the trend in Figure 4.4 suggests that the more labor intensive parts demonstrate higher defect rates. Several explanations are possible for this observation. First, labor intensive parts are inherently more complex and therefore more difficult to build. In addition, high labor parts require more operations, and hence, provide more opportunity for error. Finally, the high labor parts generally undergo extensive inspection, partially because they are larger. Therefore, more defects are discovered.

Figure 4.4: Rejection rate by average part labor hours



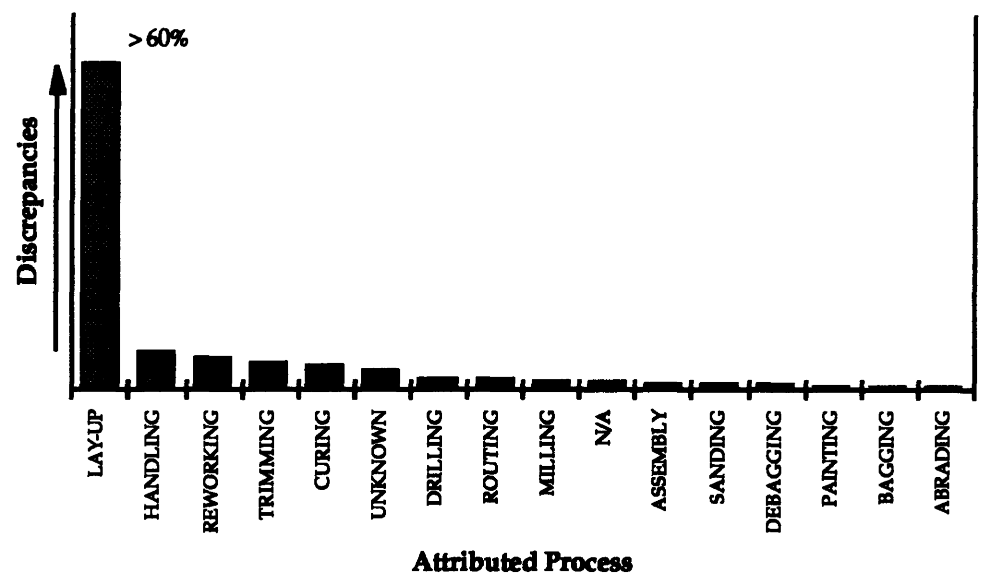
Efforts should consequently focus on only several of these parts. Qualitative data within the plant agrees with the general analysis, as quality improvement projects rally around the few parts identified above. Awareness of part problems is generated by both schedule pressures and quality metrics.

4.4 Process Analysis

After a defect has been found, the Corrective Action Group (CAG) attempts to identify the causes of non-conformance. During this process, they may draw from their experience or consult shop workers, engineering, or manufacturing to ascertain the probable area of process failure. This information is retained in the quality information systems.

Analysis of the defects by process area reveals that over 60% of defects occur during lay-up. Handling represents the second largest cause of rejects as seen in Figure 4.5.

Figure 4.5: Defect distribution by process

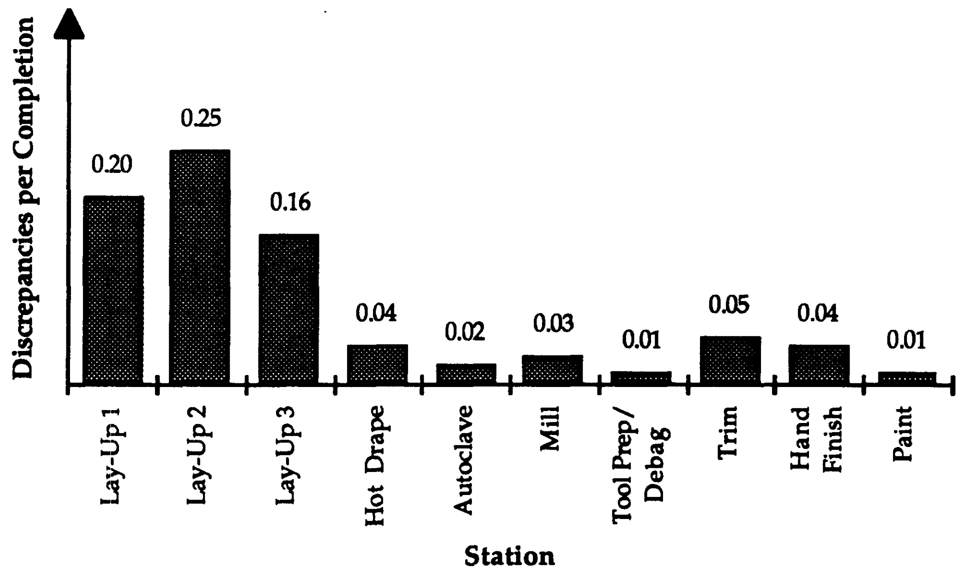


Defect rates for the lay-up stations average 0.20, 0.25, and 0.16, as shown in Figure 4.6. In comparison, the other work stations operate between 0.01 and 0.05 defect yields. This discrepancy rate is determined as:

$$\frac{\text{Number of non-conformances}}{\text{Orders completed}}$$

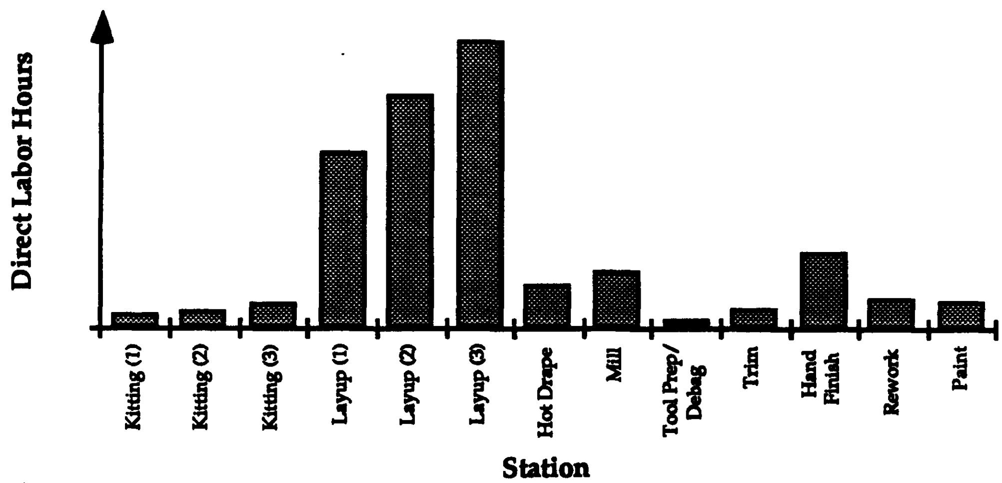
It appears that the lay-up process presents a substantial opportunity for quality improvement. As a result, research ultimately focused on this area. This conclusion relies on the information contained in the quality databases, which requires the judgment of the CAG investigator.

Figure 4.6: Discrepancy rates by station area



The large number of defects associated with lay-up is not unexpected. Figure 4.7 demonstrates that lay-up requires the most labor hours of any process, and consumes a majority of direct fabrication labor. Since any labor intensive process is subject to high degrees of variability, tight control of the lay-up process is inherently more difficult.

Figure 4.7: Average labor hours per order by station



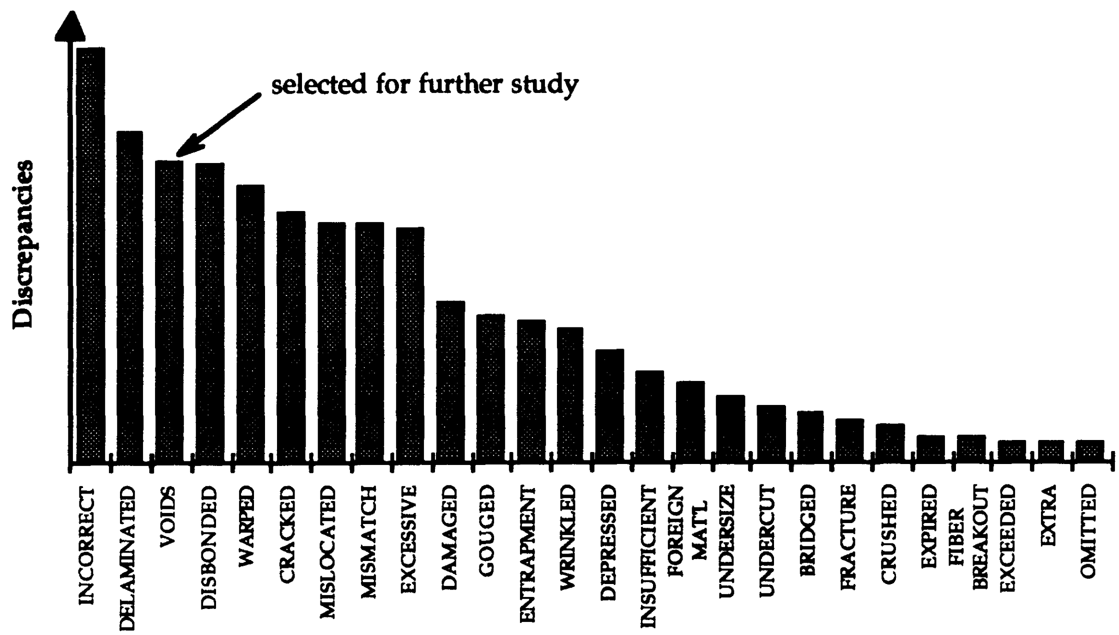
In addition, lay-up contains the greatest number of process steps. These operations are generally more complex and less precise than processes such as trimming or drilling, where exact specifications and control methods exist. Therefore, deviations are more likely to occur during lay-up.

Finally, as a database field, *lay-up* also includes failures in material, kitting, tooling, and even bagging. Since it encompasses more areas, it will naturally exhibit more defects as a larger category.

4.5 Discrepancy Analysis

Figure 4.8 presents the defect distribution by discrepancy. A large number of discrepancies are possible, which contributes to the broad and gradual distribution.

Figure 4.8: Defect distribution by discrepancy



The descriptiveness of the defect is further refined by the associated feature or location of the discrepancy. In Figure 4.8, the discrepancy "incorrect," is ambiguous until it is described as "incorrect core." The 10 most common discrepancy and feature codes are combined in Table 4.2 for all rejected parts. In Table 4.3, decomposition of lay-up process defects generated similar results to Table 2.

Table 4.2: Major shop discrepancies

Discrepancy	Feature	Number
Warped	Contour	57
Mismatch	Toolside	46
Cracked	Ply	31
Entrapment	Toolside	29
Voids	Radius	27
Mislocated	Detail	25
Delaminated	Edge	24
Incorrect	Core	22
Excessive	Cavity	20
Disbonded	Toolside	18

Table 4.3: Major lay-up discrepancies

Discrepancy	Feature	Number
Warped	Contour	57
Mismatch	Toolside	46
Cracked	Ply	31
Voids	Radius	24
Incorrect	Core	21
Excessive	Cavity	18
Mislocated	Detail	16
Incorrect	Edge-Trailing	15
Disbonded	Toolside	14
Incorrect	Flange	12

Interestingly, certain discrepancies are almost exclusively associated with specific part numbers. For example *warped contour* and *cracked ply* are 757 aileron defects and *mismatch toolside* is a 757 landing gear door discrepancy. Therefore, their high counts are the result of a part failure, rather than a general process failure. Further analysis removed these extreme parts from the data set. Table 4.4 presents the discrepancy-feature data, without the outlier parts.

Table 4.4: Discrepancy and feature defect counts

Discrepancy	Feature	Number
Voids	*Radius*	*24*
Incorrect	Edge-Trailing	14
Disbonded	Toolside	11
Wrinkled	Bagside	10
Mismatch	Toolside	10
Insufficient	Thickness	9
Entrapment	Toolside	7

From this, voids appear to be a more generic malady, as it affects multiple parts with an affinity to the radius area. Chapter 6 later describes experimentation which investigated voids induced by the lay-up process.

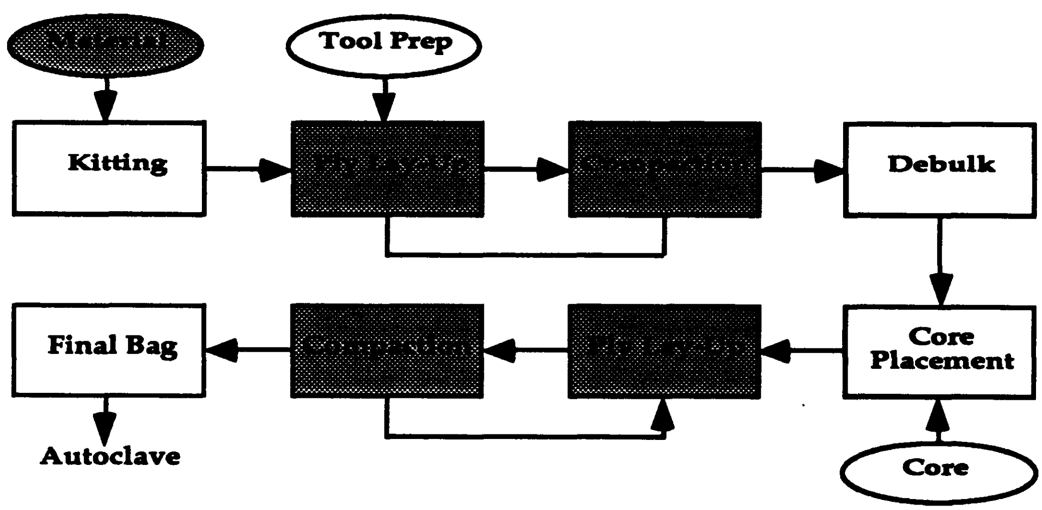
Chapter 5

The Lay-Up Process

5.1 Process Flow

Figure 5.1 outlines the process steps in transforming the prepreg materials into a cured composite sandwich. The shaded areas will be discussed in more detail as sources of variability.

Figure 5.1: The lay-up process



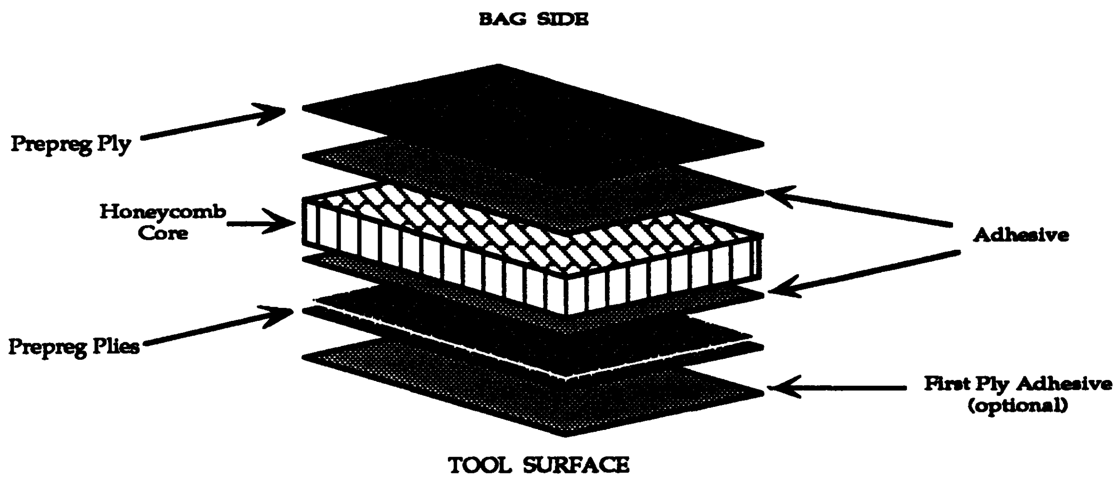
5.1.1 Raw Materials

Figure 5.2 gives an exploded view of the layers in a composite sandwich.

The A3430 composites shop predominantly uses *prepreg fabrics* for its commercial aircraft parts because they are easier to handle and apply over contoured tooling. Prepreg fabrics are woven fibers which are pre-impregnated by uncured resin. The fibers may be graphite, fiberglass, or Kevlar, while the resin is typically epoxy based. Various sheets, or plies, of prepreg material are then layered on top one of another in the design sequence to form the laminate part.

Adhesive layers are high flow materials which interface between the laminate and core. They are placed between the tool and the first ply and also between the honeycomb core and its surrounding plies.

Figure 5.2: Sequenced layers of a composite sandwich



Both prepreg and adhesive are stored at low temperatures (below 10°F) to prevent moisture pick-up and premature curing of the resin. Because the resin is uncured, it may advance, or gel, with time and temperature. The degree of cure is indirectly determined through ***exposure units***, a measure of the time a material has been exposed to room temperature. Prepreg is usually allowed ten days of exposure time.

Honeycomb core increases the shear and stiffness properties of a composite with little added weight. Before lay-up, the core is machined and formed to fit properly over the tool. Boeing purchases some pre-formed core, but also internally machines and forms pieces from bulk. Core must be stored in clean, dry environments to prevent contamination and moisture pick-up.

5.1.2 Tool Preparation

The physical dimensions of a part are determined by the lay-up mandrel or tool. Each ply is successively applied over the tool and conforms to the mold geometry. Before lay-up, the mandrel is cleaned with solvent to remove any debris. Application of liquid mold release agents ease the removal of the part from the tool after cure. Good surface condition helps prevent leaks, poor bag sealing, and rough toolside finish.

Tools are built from fiberglass, graphite, aluminum, steel, or metal alloys. The mandrel is sometimes heated to promote first ply adhesion.

5.1.3 Ply Nesting and Cutting

The plies for a part generally differ in size, shape, and orientation. As a result, many different patterns must be cut from the prepreg sheet. Prepreg can be machine cut or manually cut with utility knives, straight edges, and templates. Machine cutting is generally faster, more reliable, and more efficient. Computerized nesting determines the optimal layout of plies which maximizes material utilization. Each ply is labeled to identify its location in the composite layers.

5.1.4 Kitting

Once the plies have been cut, they are manually sorted and packaged into kits. Each kit contains the specific plies needed to build a certain part. These plies are packaged together in plastic to prevent contamination. Kits are labeled and held in cold storage until needed.

5.1.5 Lay-up

The lay-up process consists of two main operations which are continuously repeated for each ply. These are ply lay-up and compaction.

Before the lay-up process begins, a bag is first built over the tool.

Bagging

A reusable nylon bag is built to cover and compact the part. For complex geometries, the bag is pleated to provide excess material in angled areas. This allows the bag to remain in contact with the part surface during compaction, especially over contoured areas. The bag is temporarily sealed to the tool using a chromate gasket adhesive. In addition, vacuum nozzles are attached to the bag to draw vacuum during compaction.

During ply lay-up, the bag is partially removed from the tool to apply the prepreg sheet. The bag is completely resealed against the tool for compaction. Building a new bag is the most time consuming step in the lay-up process; consequently, the bags are reused until final bagging.

Ply lay up

In the lamination process, the prepreg patterns are successively applied according to the design sequence. The exact location of one ply over another is determined by the ply locating template (PLT), which is positioned on fixed reference points of the tool. The locations of the subsequent plies are then traced on the current ply. Markings on the tool identify the location of the first ply. Core placement similarly uses a CLT or core locating template.

Once the ply has been positioned and oriented, workers manually smooth the ply over the mandrel. The fabric is stretched accordingly and pressed into contours to conform to the tool and to remove excess air. Workers also splice and overlap adjoining plies as needed. Any excess material is trimmed using a utility knife.

Prepreg properties, such as tackiness or stickiness, can affect the ease of ply lay-up.

Compaction

After a ply has been applied, the bag is resealed over the tool and vacuum is drawn through the vacuum nozzles. Barrier layers, such as Teflon or FEP (fluorinated ethylene propylene) films are inserted between the part and the bag to separate the prepreg from the nylon. Breathers, such as polyethylene rope or silicone rubber, are placed underneath the bag to provide a sufficient gas path to draw vacuum.

As air evacuates, the nylon bag is pulled tightly against the part. The pressure of the bag consolidates the plies together. Vacuum is held for a recommended 3-5 minutes; however, the exact time of compaction is not monitored. After compaction, the vacuum is released and the bag is removed for the next ply.

The lay-up and compaction steps are reiterated, according to the sequence described in the part's work plan.

Debulk

Debulk is an intermediate process step to remove trapped air and compact the lay-up. The part is subjected to heat, pressure, and vacuum to induce minor flow of the material and better shape conformance.

5.1.6 Final Bagging

After the final ply has been compacted, the temporary bag is discarded and a final bag is built. The bagging techniques for final bagging are similar to those in temporary bagging. However, because this bag will undergo cure, the seals and integrity of the bag must be leakproof; only a tiny loss in vacuum pressure is allowed. In addition, thicker breather materials, usually polyester mats, are used to provide a better gas path. Specific workers are generally dedicated to the bagging operation.

5.1.7 Autoclave Cure

The curing process crosslinks the resin, consolidates successive plies, vents entrained air, purges void-nucleating volatiles, removes excess resin, and promotes resin impregnation of fibers. During autoclave cure, the part is subjected to high temperatures (250 °F to 350 °F) and high pressures (45 - 85 psi). Under these conditions, resin melts and flows through fibers and plies. Autoclave pressure maintains the shape of the composite until it solidifies to form the final part.

5.2 Process Control

Control of the lay-up process is achieved by examining the incoming material rolls, the application of plies, and the integrity of the final bagging. These inspections prevent obviously flawed parts from continuing to the cure step. However, defects do occur at later processing stages, supposedly as a result of the lay-up process. The current inspections cannot entirely predict the quality of a part after cure.

Ideally, statistical process control (SPC) can prevent defects from occurring in the first place. SPC strives to alert workers to the onset of process deviations and provides a means for workers to chart process performance. However, in order to utilize SPC, variable data which represents the final part quality is more useful; currently, parts are inspected on a pass/fail attribute basis.

In addition, the key characteristics of the process must be understood and controlled. Because lay-up is labor intensive, workmanship is an important process parameter. To standardize this factor, diagrams for each part, lay-up guidelines, and specific work plans are provided. New workers receive training by working on parts in parallel with experienced operators.

Material characteristics also contribute to the final quality of the part. As a result, a number of properties are evaluated when material is received. Exposure units are also tracked for every roll and kit. Although resin can age during this time, no further testing is performed to directly evaluate the material.

Vacuum pressure can fluctuate between 20 and 28 inches Hg due to varying demand throughout the day. Workers may use pressure regulators to limit pressures to 10 inches Hg for sandwich parts. The use of lower vacuum reduces the amount of vacuum which may be sealed in the core. Negative core pressure can contribute to void formation.

SPC intends to maintain process performance by controlling the few parameters which significantly impact the quality measurements. It is not clear that the key process parameters are well-known, consistently controlled, or connected to final quality measurements. Without a stable process, SPC's value diminishes.

5.3 Sources of Variability

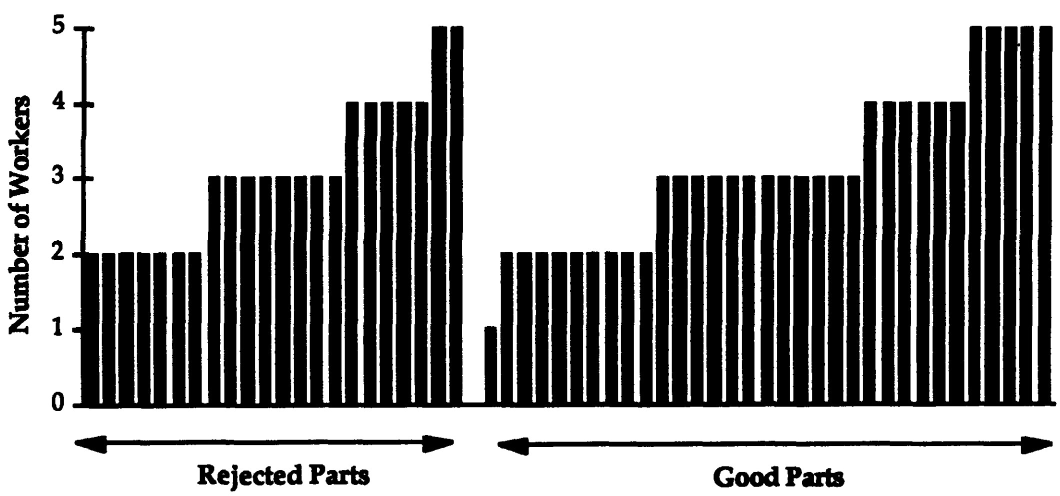
The inherent tenet in process control assumes that variability is undesirable. However, while robust processes can tolerate some deviation, generally, only a few parameters govern the repeatability of an operation. The challenge involves identifying these parameters, relating their impact on the part attributes, and finding methods to monitor and maintain these variables. With these, the capability of the process can be defined. Analysis of the lay-up process identified the compaction cycle and material properties as potential process drivers which display degrees of variability.

5.3.1 Labor

Differences in worker experience, skills, and technique contribute to labor variability. In addition, parts are scheduled over several shifts, so multiple workers are responsible for an individual part. Depending upon the availability of people and the urgency of the schedule, more than one worker may be assigned to a part.

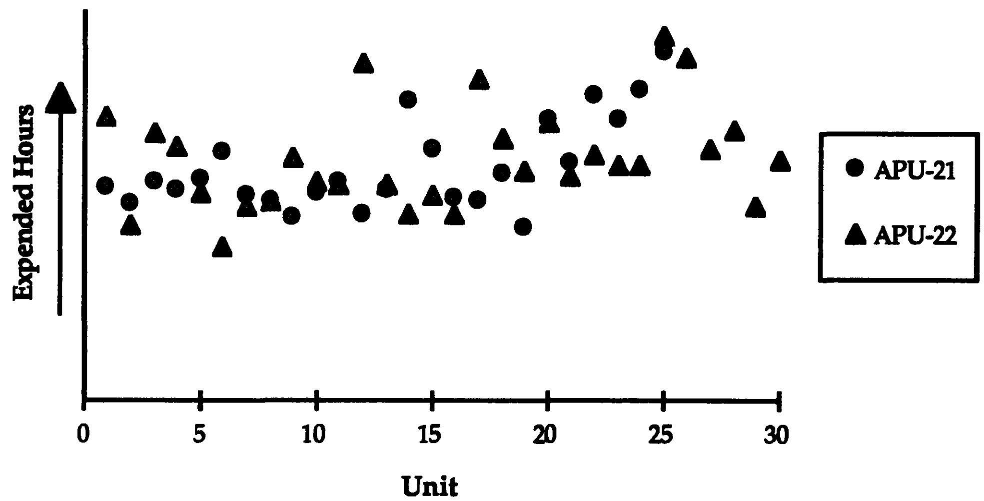
Figure 5.3 shows the work distribution on the 767 APU "S" Duct during lay-up. The outcome of the part was related to the total number of different workers who worked on the part within and across shifts. Interestingly, there does not appear to be a clear distinction between the number of workers and part quality.

Figure 5.3: Worker and part information for 767 APU "S" duct parts



Workers also rotate among the different part numbers. Although workers who are familiar with certain parts may work on those parts more often, allocation of workers is generally schedule dependent. Figure 5.4 illustrates the variability in labor hours for the halves of the 767 APU "S" Duct.

Figure 5.4: Labor hours for 767 APU parts



The recent high turnover in the A3430 shop provides an additional source of instability. Since the work force is not constant, greater variability is introduced with each new worker. Furthermore, workers are continually performing on the learning curve, where defects are more likely to occur. Experienced workers, such as transfers from military composite operations, also contribute to variability with different training and practices. However, these differences also promote a broader learning environment.

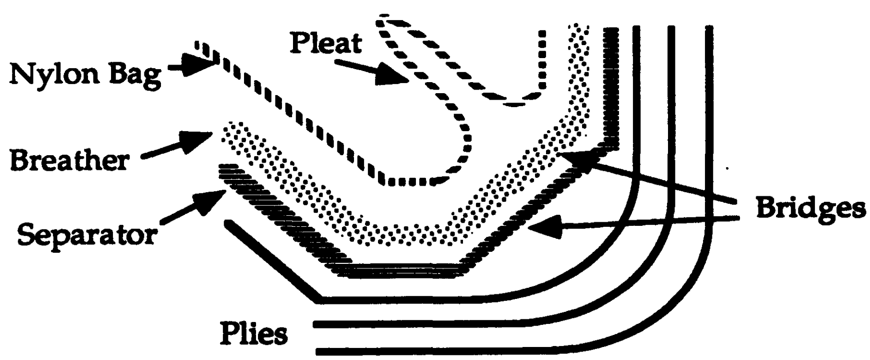
5.3.2 The Compaction Cycle

The parameters in the compaction cycle include the applied vacuum pressure and time of compaction. The first source of pressure variability involves the fluctuation of available vacuum due to varying demand throughout the day. Indirectly, the bag integrity, the bag seals, and the presence of breather materials can have a greater affect on the drawn vacuum. Leaks in punctured bags or weak seals reduce the vacuum through pressure loss. This condition occurs frequently as the reusable bag wears.

The absence or mislocation of breather materials (polyethylene ropes and silicone rubber cloths) can also prevent uniform vacuum pull. In the absence of breathers, the bag can effectively pinch off gas flow, especially against angled sections, leading to low pressure regions.

Plies in contoured radii areas may also experience lower pressure due to bridging. Figure 5.5 conveys the bridged condition, where the nylon bag does not contact the part due to insufficient elongation of the bagging material. This can occur because there is not enough material or because the pressure is weak. Pleats attempt to alleviate this condition.

Figure 5.5: Bag bridging over a contoured area of a composite



An informal survey of bagged parts revealed varying degrees of bag pressure between and within parts. Under vacuum, some bags were held tightly against their part, while other bags could be pulled away easily by hand. Vacuum pressures can range from 5 inches Hg in the proximity of a leak to 28 inches Hg for a perfect bag.

However, strong vacuum can produce adverse effects. As mentioned earlier, high vacuum can create negative pressure conditions inside the core, which induces volatile void formation. In addition, intense consolidation of plies can trap entrained air and volatiles by closing available gas paths. In both instances, voids are generated and the part is defective.

While 3-5 minutes of compaction time is recommended, no firm requirement exists in the specifications. Time is not monitored, and can shorten if the part is a rush order, or lengthen if compaction occurs over a break period.

5.3.3 Material

After initial receiving and inspection, no further material testing is conducted. Material properties are indirectly measured through exposure units, until an expiration of 10 days. At this point the material is discarded. During the 10 day window, the prepreg cure advances slowly and accumulates moisture due to the hygroscopic nature of epoxy resins. This may adversely affect the final composite.

5.4 Void Formation and Transport

Voids are undesired vacant spaces which are trapped within the resin-fiber matrix. These discontinuities occur in composites due to three phenomena - void formation, growth, and transport. In conjunction, these lead to the development of a void which can deteriorate the structural properties of the composite.

5.4.1 Void Formation

Voids initially form by mechanical entrapment of air or by nucleation processes. Air may be trapped as intralaminar or interlaminar voids through several mechanisms. These may occur in the following fashion [Kardos, 14]:

- Entrained gas bubbles within the prepreg from the resin mixing operation
- Bridging voids from large particles or particle clusters
- Voids from wandering tows, fuzz balls, or broken fibers
- Air pockets and wrinkles created during lay-up
- Ply terminations such as ply drop, overlap and splice areas

The mechanical entrapment of air is highly dependent upon the quality of the prepreg and the practices in lay-up. The processes of the prepreg supplier dictate the amount of entrained air and the initial integrity of the prepreg. Particulate contamination, broken fibers, wrinkles, and gaps near ply terminations are inadvertent products of the lay-up process. As described earlier, procedures to minimize these imperfections exist.

Nucleation of voids occurs either homogeneously (within the resin) or heterogeneously (at a resin/fiber or a resin/particle interface). Water vapor, air, or other volatiles can provide stable void nuclei in the prepreg. In addition, particulates disrupt the interface between plies to serve as nucleating sites for void formation.

5.4.2 Void Growth and Stability

Once a void has been initiated, it may grow to the detriment of the part, or it may collapse and disappear. Void growth occurs as water vapor or air diffuse into nuclei sites, or as nearby voids coalesce. Kardos, et.al., have observed a synergistic effect of water on void stability [Kardos, 14]. Vaporization of volatiles can also induce void growth if the internal void pressure overcomes the hydrostatic resin pressure and the resin-void surface tension. This pressure gradient allows the void to successfully expand. After the thermoset resin has cured, the void is permanently set in the matrix structure.

Vacuum pressure which is sealed in the honeycomb core can lower the hydrostatic resin pressure in localized areas. Low resin pressure allows volatiles to emerge from solution, vaporize, and create voids in the matrix. These bubbles also provide nucleation sizes for further void growth.

Changes in temperature and pressure can suppress void expansion by increasing the solubility of vapor in the resin and dissolving the void. High hydrostatic resin pressures can collapse voids into solution. Therefore, autoclave conditions can play a significant role in void growth and stability.

5.4.3 Void Transport

Although voids may exist and grow in a composite, transport of vapor away from the part can eliminate the void. As the plies collapse, resin migrates to fill any vacant areas to form a solid composite matrix. However, the vapor must flow freely through the resin to escape as vented gas. This gas path requires free travel through the resin and the breather materials in order to exit the part. The bagging arrangement can impact void transport in this respect.

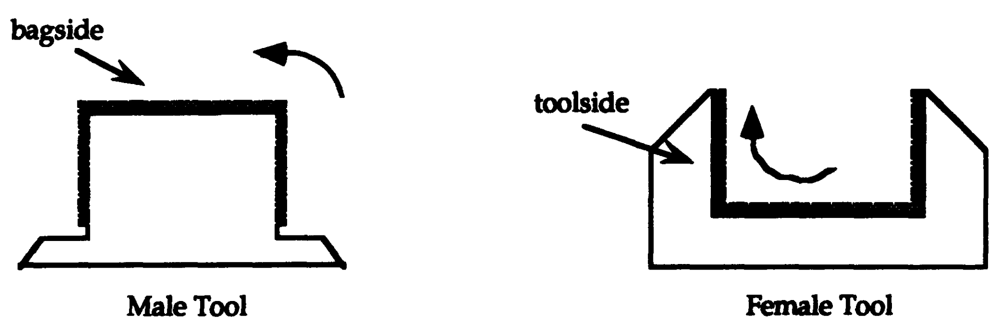
While vacuum compaction is intended to remove air pockets from loose lay-ups, it may inadvertently seal gas paths during consolidation. Jensen has observed that tacky material and wide edgebands form tighter seals to prevent air movement [Jensen, 12].

5.5 Voids in Radii

While voids represent a generic problem in composite fabrication, voids in the radii, particularly female radii, introduce additional complications during manufacturing. Figure 5.6 compares a tool with male and female radii. Female radii present more problems because the concavity of the mandrel is less accessible. It is more difficult for workers to smooth the plies into the female radii than it is to smooth plies over the male radii.

However, female radii provide tighter control of the outside flange area of parts. These areas interface and mate with other parts in assembly and must be smooth and dimensionally accurate. Therefore, this surface requires the even and stable finish of the toolside. Bagside surfaces, since they are cured against the atmosphere, assume the rougher imprints of bagging materials. Female radii match the mating surfaces of parts with the toolside.

Figure 5.6: Characteristics of male and female tooling



The previous section discussed several factors which promote voids in composites. Of these, it is believed that mechanical entrapment of air represents the cause of most radial voids, due to the inherent challenge in lay-up. Ply bridging can introduce gaps in the radial area which are unrecoverable. Voids resulting from these gaps are larger than those induced by volatilization.

Other factors which increase the likelihood of void formation are summarized below. Figure 5.7 illustrates the possible causes for any defect in a fishbone diagram.

Mechanical

Manual lay-up: Placement of plies may lead to bridges or gaps. First ply adhesion is especially important in radii.

Compaction: Compaction may fail to consolidate plies and remove air. Bagging techniques (pleats, breather materials), time, vacuum, and debulk affect compaction.

Process

Resin flow: During cure, resin may not flow into vacant areas due to material properties or process conditions. Resin may also migrate away toward low pressure areas.

Ply movement: Plies may not slip or stretch to fill vacant areas during cure. Large ply areas may lock in place as a result of friction.

Volatilization: High void pressures can overcome low hydrostatic resin pressure and surface tension to increase void volume.

Gas paths: Air paths must be present to allow entrapped air and volatiles to escape. Bagging and compaction may seal off available gas paths.

Materials

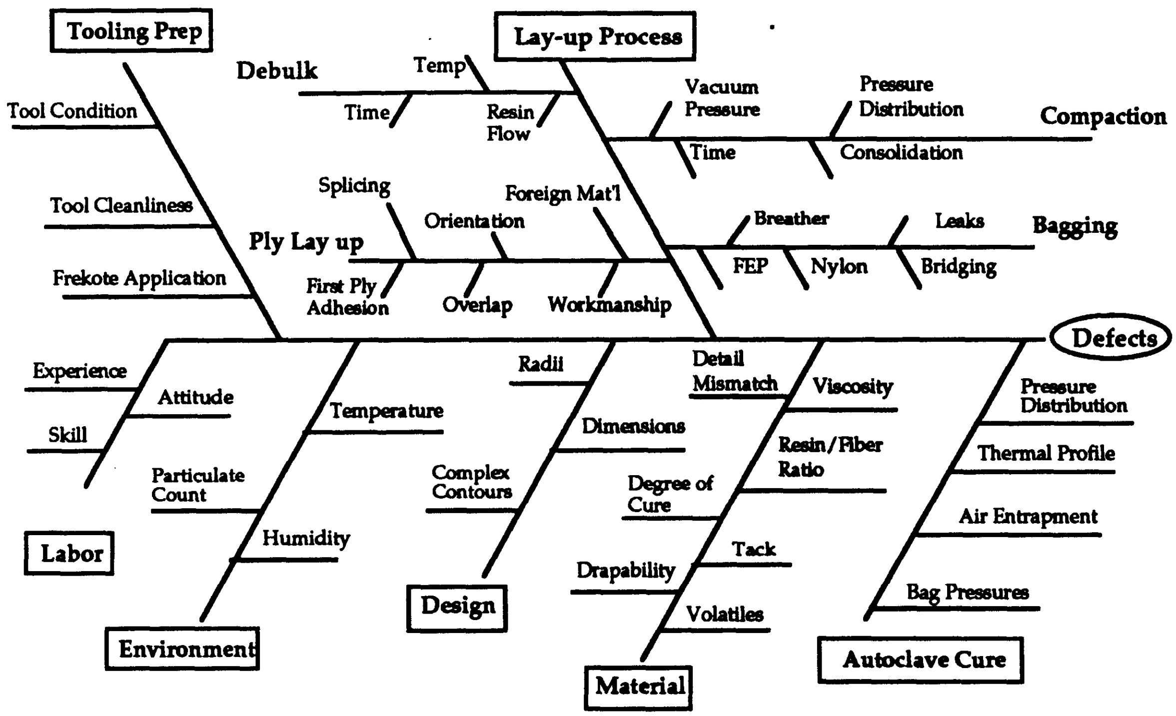
Prepreg: Volatile and air content contribute to void formation. Viscosity and gel time properties also affect resin flow.

Core: Core is sometimes situated in female radii. A mismatch between core contours and tool geometry leads to gaps.

Design

Radii: Sharp radii are more difficult to work. Plies can be pressed more easily into smoother radii.

Figure 5.7: Cause and effect diagram for defects in composite processing



Chapter 6

Lay-Up Experimentation

6.1 Objective

Given the perceived variability within the lay-up process and the associated defects, experiments were conducted to better understand the impact of process variables. In particular, the compaction cycle and material properties were investigated. Several goals were outlined at the onset of the experimental program. These were:

- Understand how varying degrees of compaction times and pressures affect void formation and transport.
- Understand the sensitivity of composite fabrication to material exposure time in terms of void formation.
- Perform a case study in the formation of voids in the female radius area of composite sandwich parts.

Variability is recognized to exist in the lay-up process. These experiments intend to determine whether these sources of variability are key characteristics or whether they are insignificant.

6.2 Experimental Design

Given the time consuming nature of composite fabrication, few composite samples could be constructed during the time frame of this study. To obtain maximum information, a screening laboratory test and a manufacturing experiment were conducted concurrently.

The screening test would determine the effect of compaction pressure on the consolidation of the composite and on the presence of gas paths. Because this experiment could be performed in a more controlled environment, it would hopefully provide purer data. These trials used simple laminate parts for testing.

The manufacturing experiment produced composite sandwich parts using various compaction cycles and material. These parts were scaled down versions of the 767 APU "S" ducts, which have historically experienced radial voids. Experimentation with actual production parts would require significantly more time and incur higher costs. In addition, the limited quantity of part tools prohibited the prolonged use of production mandrels.

6.3 Laboratory Testing

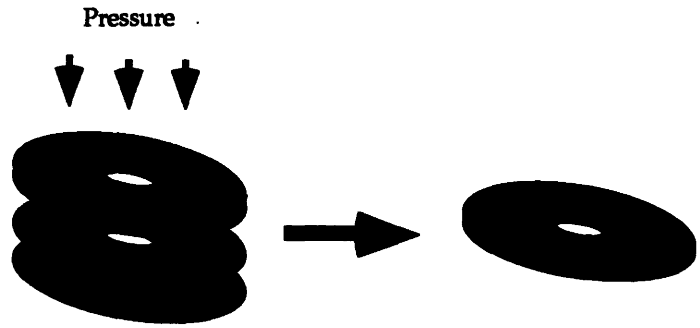
This experiment varied compaction times and pressures to test their effects in lay-up. In particular, the extent of compaction and possible void formation were targeted response variables. Air flow through plies was also measured to estimate the presence of gas paths and the degree of compaction.

The presence of gas paths suggests entry ways between or within plies, and therefore incomplete compaction. Conversely, complete consolidation implies the absence of any openings. A balance between the competing phenomena in compaction and gas flow must be obtained.

6.3.1 Part Design

Compaction studies were performed on a 10 ply graphite fabric lay-up, layered in a 0/90 orientation. Figure 6.1 illustrates the part geometry. Each ply was patterned into an 8 inch diameter circle, with a 1 inch diameter hole in the center. This opening was used for gas flow experimentation.

Figure 6.1: Test part for laboratory testing



6.3.2 Response Variables

This study aimed to evaluate voids, the extent of consolidation, and gas flow as a result of different compaction conditions. The experimental response variables and their accompanying measurement methods are provided below: It was uncertain whether TTU would detect the presence of voids, if any, in the laminate. As a result, part thickness was used as a gauge to the degree of consolidation and likely void presence. By comparing pre-cure and post cure part dimensions, the individual contributions of compaction and cure on consolidation can be separated. Shorter part heights indicate greater compression and evacuation of air.

Air flow is intended to determine of the presence of gas path. Gas flow through the part was achieved by pulling vacuum through the center opening, and measuring the amount of air which passed. Figure 6.2 in Section 6.3.4, on experimental procedure, illustrates the laboratory set-up.

Weight is measured only as a check against part thickness measurements. Although a small amount of weight loss could occur due to volatile emission, this is likely to be insignificant or within measurement error. Significant weight loss, most likely due to resin bleeding, would signal a thickness which would not be suitable for comparative measurements.

Table 6.1: Response variables and measurement methods

Response Variable	Measurement Tool	Comments
Void content	TTU (Ultrasound)	Capable of detecting voids of several mm diameter. Laminate may reveal little or no voids.
Pre-cure thickness	Tinius Olsen	Mechanical measurement after each ply addition.
Cured panel thickness	Calipers, gauges	Mechanical measurement.
	Pulse Echo (Sound)	Transmission of a standard signal is correlated to the laminate thickness.
Air flow through prepreg	Volumetric air flow	Constant vacuum is pulled through the part center opening. Air then flows between plies.
Weight loss in cure	Scale	Weight loss primarily occurs due to resin bleed. Excessive bleeding may reduce final part thickness.

6.3.3 Experimental Factors

The manipulated variables included time of compaction, and the pressure applied during compaction. The experimental values are provided in Table 6.2.

Table 6.2: Experimental factors

Factor Description	# of Levels	Values
Compaction Time (min.)	3	0 3 15
Compaction Pressure (in Hg)	3	0 10 22

This series of variables produces 5 feasible combinations of parameters. The zero time and zero pressure set is a unique condition which is not paired with any other value. No time and no pressure each imply an uncompacted lay-up. The values were chosen to provide a broad range of reasonable figures.

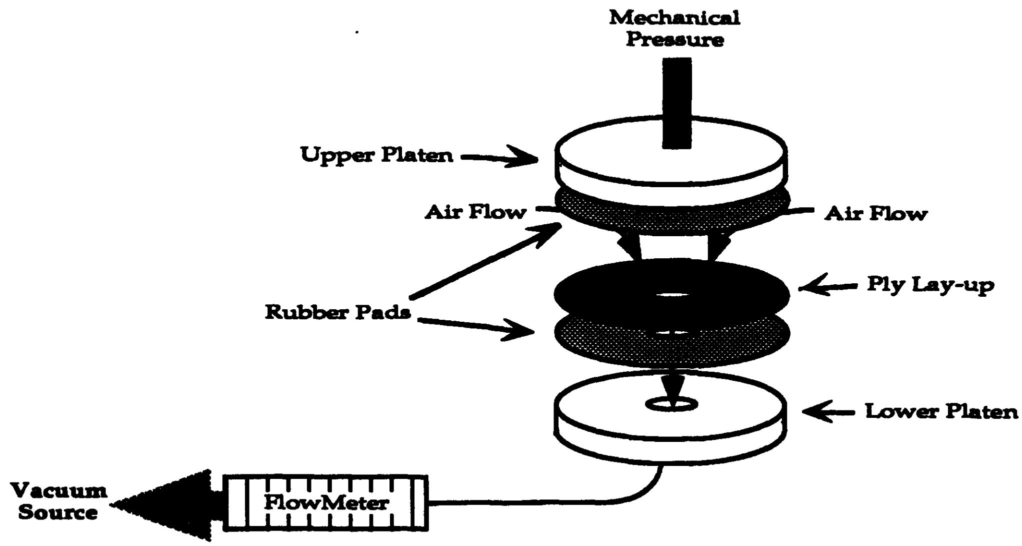
Compaction pressure was controlled through the application of mechanical rather than pneumatic pressure, using the Tinius Olsen. The above values for compaction pressure, in terms of vacuum, were accordingly converted to pound force figures.

All other factors remained constant. Each part was constructed using graphite material from the same roll. All kits were cut and packaged at once, and then held in cold storage until needed, to maintain the same material exposure units. Parts were subsequently cured using standard 250 °F, 45 psi conditions for the graphite composite.

6.3.4 Experimental Procedure

Figure 6.2 illustrates the laboratory set-up using the Tinius Olsen as a mechanical pressure source and as a measurement tool. The ply lay-up is surrounded by rubber padding and applied onto the stationary metal platen. The padding is used to simulate a pneumatic condition by conforming to the prepreg surface and to prevent adhesion to the metal platens.

Figure 6.2: Laboratory set-up using the Tinius Olsen



After each ply has been added, the upper platen is dropped until the onset of pressure. The platen is then lowered to attain the desired mechanical pressure for the intended duration. The amount of compression is recorded for each ply. This process is repeated for the entire lay-up and the total part thickness is measured.

The lower platen and pad contain a central opening which is connected to a vacuum source. The center hole in the laminate part corresponds to this opening. As vacuum is pulled, air is drawn from outside the part, through the center, and to the vacuum source. The rubber gaskets prevent air flow through the exterior surface of the ply lay-up, thereby neglecting intralaminar air flow which may occur during normal compaction. This technique intends to measure interply gas pathways.

A volumetric flowmeter is placed between the vacuum source and the platen opening. The amount of air which flows through is measured before, at the beginning, and at the end of compaction.

This experimental procedure was conducted for the 5 different pressure and time combinations and then replicated for a total of ten runs. The experiments were sequenced randomly.

6.4 Manufacturing Experiment

This experiment constructed larger composite parts to introduce complexities and reality into the part design. This experiment aimed to understand the effects of compaction and material on void formation.

A larger level of experimental noise existed in this study with the introduction of bagging arrangements and lay-up techniques; however, this situation approaches the actual production environment. Any practical solution to the void problem should tolerate this additional variability.

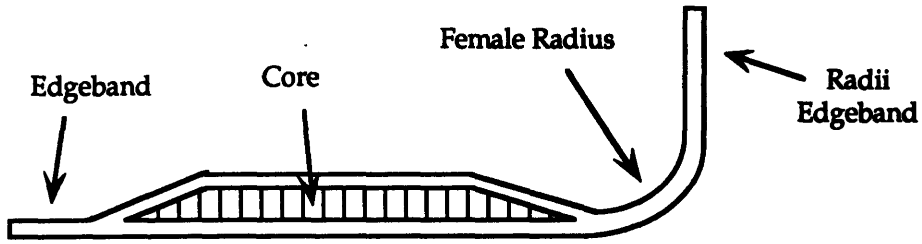
6.4.1 Part Design

This experimental part followed the basic ply sequence of a standard panel which is used by Boeing's Manufacturing R & D (MR&D) to analyze porosity. This panel contains honeycomb core, filler plies, and doubler plies, which are conducive to void formation.

This experimental part also undertook elements of the 767 APU "S" duct which experiences periodic problems with voids. Primarily, a sharp female radius of 7/32" was introduced. This radius is more severe than the radius observed in the APU duct. This radius was selected from among the available tools to encourage the formation of voids. The part tool was constructed from high temperature fiberglass.

The part was composed of graphite prepreg which would undergo a 250 °F, 45 psi cure. Figure 6.3 illustrates the general part geometry. Appendix A provides the detailed part design and dimensions. The initial design included a shorter vertical edge band which will be further discussed in Chapter 7.

Figure 6.3: Graphite experimental part with female radius



6.4.2 Response Variables

This study aimed to evaluate the presence of voids as a result of different compaction conditions and material age. This series of experiments also intended to subject test parts to conditions closer to the actual manufacturing environment. The response variables and their accompanying measurement methods are provided below in Table 6.3:

Table 6.3: Response variables and measurement methods

Response Variable	Measurement Tool	Comments
Void content	TTU (Ultrasound)	Capable of detecting voids several mm diameter.
	Visual	Real time X-ray to view discontinuities in parts. Microscopy to examine cross sections.
Cured panel thickness	Calipers, gauges	Mechanical measurement.
	Visual	Measurement from microscope photographs.

Similar to TTU, real time X-ray non-destructively detects part discontinuities. While TTU compares the transmission of sound to give decibel values, real time X-ray evaluates the transmission of energy beams to produce a visual output. Microscopy of cross sections provides greater detail, but is destructive and time-consuming. Furthermore, a single cross section may not represent the overall quality of a part.

Pre-cure and post cure thicknesses are more difficult to determine in contoured areas. Calipers and gauges did not provide accurate or repeatable measurements of the radii area. DEA analysis, a coordinate measurement machine, seemed accurate and promising, but was not pursued due to logistical and scheduling constraints. Again, deviations in the thickness of the radii and flat areas would indicate variations in compaction or lay-up.

6.4.3 Experimental Factors

The manipulated variables included time of compaction, the pressure applied during compaction, and the material exposure units. The experimental values are provided in Table 6.4.

Table 6.4: Experimental factors

Factor Description	# of Levels	Values
Compaction Time (min.)	3	0 3 15
Compaction Pressure (in Hg)	3	0 10 22
Material Out Time (days)	2	0 8

This series of variables produces 10 feasible combinations of parameters. As with the laboratory part, zero time and zero pressure each represents a single, uncompacted condition. The values were chosen to provide a broad range of reasonable figures. The eight day material time enabled two additional days for lay-up, before reaching the maximum ten day limit.

Compaction pressure was controlled by regulating the amount of vacuum drawn in bagging. Material was simply allowed to age at room temperature for eight days and then held in cold storage until needed. The exposure time of the material affects other material properties which influence void formation, such as tack, volatile content, and degree of cure. Exposure time was selected as a simple parameter to dictate.

All other factors remained constant. Each part was constructed using graphite material from the same roll. All kits were cut and packaged at once, and then held in cold storage, to maintain the same exposure units. Bagging techniques were standardized to minimize any potential variability, such as compaction pressure gradients. These included the number and location of vacuum nozzles, the choice and use of breathers and separator films, and the general integrity of bagging. Parts were subsequently cured using a standard 250 °F, 45 psi cure for the graphite composite.

6.4.4 Experimental Procedure

Parts were constructed and bagged in the MR&D lay-up area according to the experimental plan in a randomized sequence. Afterwards, parts were labeled and sent to the A3430 production shop for the appropriate cure cycle. After cure, the part was returned to the MR&D facilities and examined.

Chapter 7

Results and Discussion

7.1 Laboratory Data

7.1.1 Ply Compression

The following table summarizes the measurements for parts built under each compaction condition. Low and high pressure correspond to 245 and 540 pounds, respectively. Low and high times refer to 3 and 15 minutes. The results presented are averages of the replicated experimental runs.

Table 7.1: Results for the various compaction conditions

			Thickness (in)	
Pressure	Time	Voids	Pre-Cure	Post Cure
Lo	Lo	-	0.096	0.091
Lo	Hi	-	0.093	0.091
Hi	Lo	-	0.094	0.090
Hi	Hi	-	0.093	0.090
None	None	-	0.106	0.090

Through transmission ultrasound (TTU) did not detect voids in any of the 10 panels. Voids were either too small for observation or absent within the part. The flat geometry of the laminate generally does not promote void formation.

Evaluation of part thickness indicates small differences between the various conditions. Parts formed without any compaction (zero pressure, zero time) were thicker prior to cure at 0.106 inches versus 0.093 - 0.096 inches. Even in the absence of compaction, some compression of plies does occur. An individual ply measures approximately 0.012 inches in thickness, leading to a theoretical 10 ply panel of 0.12 inches.

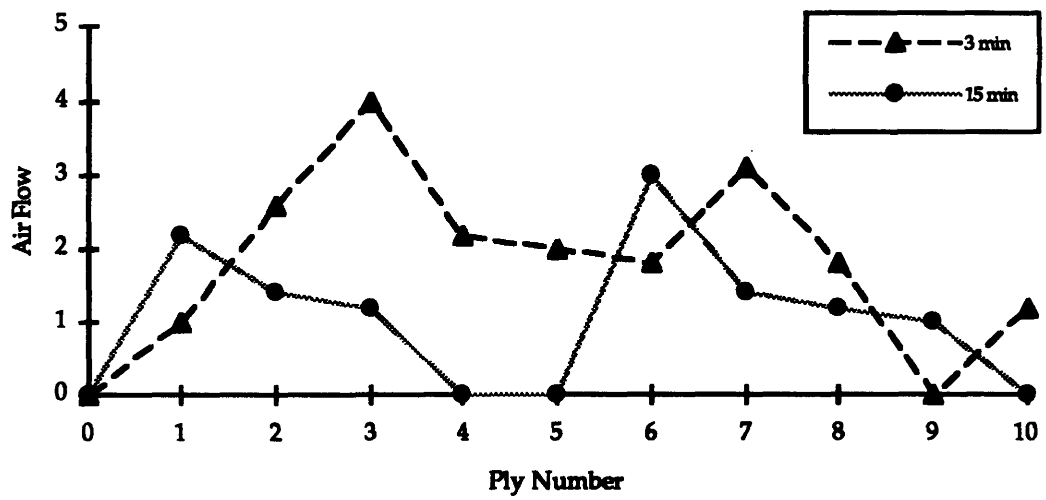
However, all parts demonstrated comparable final thicknesses after cure. Apparently, the permanent dimensions are primarily determined during the curing process. While compaction did induce different initial compression, it plays little role in affecting final part thickness for these simple laminates. The effect of compaction in void repression or dimensional control is uncertain for larger, more complex components.

7.1.2 Air Flow Results

This study also attempted to characterize air flow as a function of compaction condition. However, these readings were subject to high degrees of variability, although they fluctuated around certain ranges. Interestingly, air flow did not incrementally increase with the addition of each ply. The original hypothesis assumed that interlaminar (between plies) air flow would provide escape paths for any entrapped air. Therefore, more ply interfaces would provide more interlaminar air paths. Air flow should increase with each additional ply.

Figure 7.1 illustrates the lack of constant growth in air flow during ply lay-up. The absence of this effect seems to contradict the assumption that interlaminar air flow provides significant gas pathways. In addition, air flow was detected for the single ply which was sandwiched between two rubber pads. Meanwhile, two pads in series registered no flow. Air is apparently passing between the pad and the exterior plies, and thereby confounding any measurements. Air may require tiny escape routes which are insignificant when compared to the observed air flow between the pad and surface plies.

Figure 7.1: Air flow during ply addition for two of the experimental runs.



7.2 Part Analysis

7.2.1 Edgeband Effect

The original part design included a 2 inch wide laminate section which extended past the radii. This laminate area, which surrounds the core, is known as the edgeband. In the experimental part, the size of the edgeband mimicked a similar section around the APU duct radii. Approximately 1 inch of material is useu in the flange section, with an additional 1 inch excess for trim.

After cure, this first part revealed some excess resin in the radii area; however, no voids were detected. Photo 7.1 below presents the cross section of this part, without any discontinuities. Resin migrated to fill potential voids, as conveyed by the lighter regions in the laminate. This initial part was processed at high pressure, low time conditions (22 in Hg, 3 minutes).

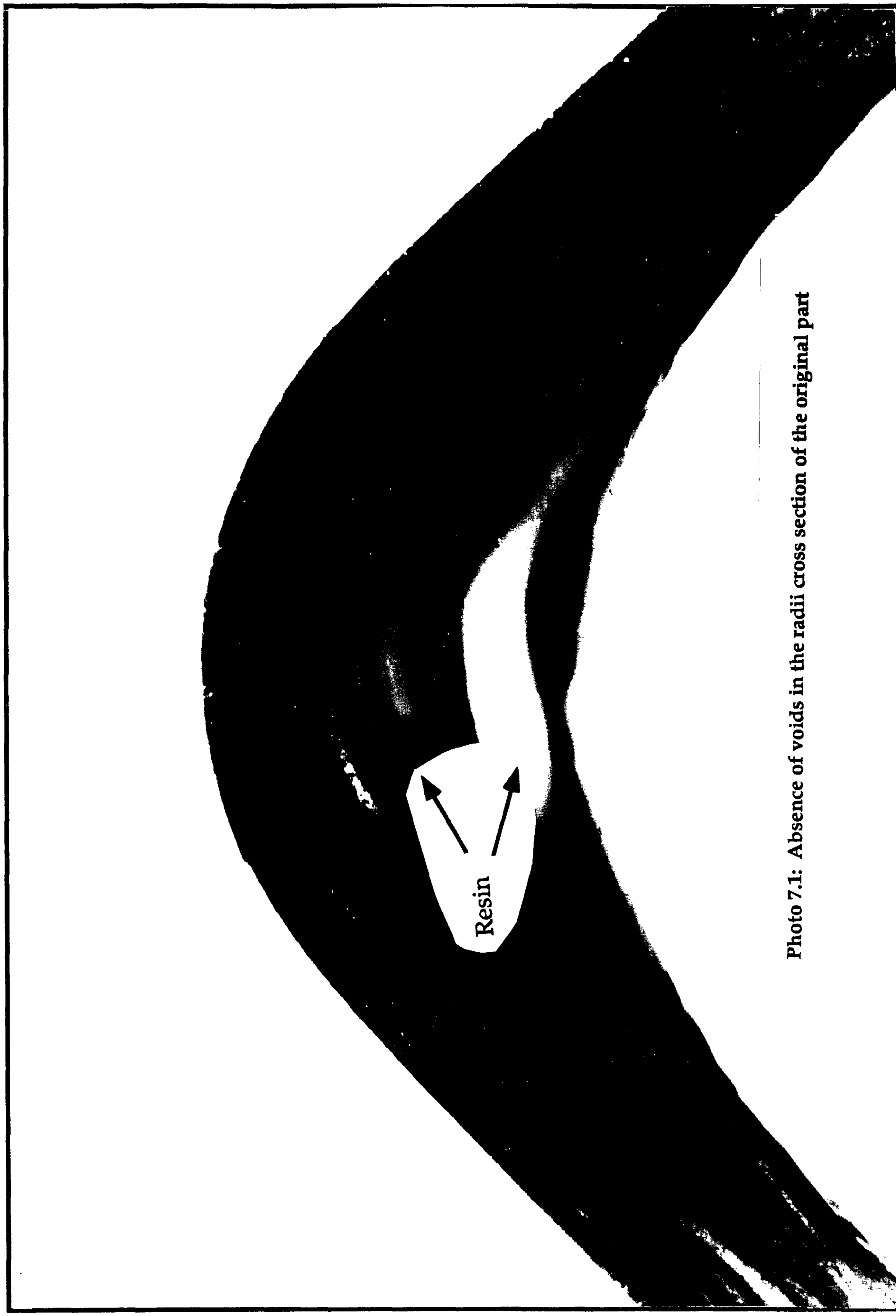


Photo 7.1: Absence of voids in the radii cross section of the original part

However, this study intended to evaluate the degree of void formation in the manufactured parts. The possible absence of voids in all parts, as with the laboratory laminate, would not provide discrimination between the changes in process conditions. As a result, the configuration of the part was modified to encourage void formation.

The original 2 inch wide radii edgeband was extended to an 8 inch section. The longer laminate section provides greater interply surface area and therefore greater interfacial friction. As resin flows during cure, the fabric readjusts its position to conform to the underlying surface. If the natural movement of fabric is prevented, possibly by high friction, then the sliding of plies into concave radii areas is impeded. Any ply bridging during lay-up could not be corrected in this instance. This redesign intended to instigate voids by inhibiting ply movement.

Photos 7.2 and 7.3 illustrate subsequent part sections which now exhibit voids. In Photo 7.2 (microscopy of a cross section), two voids are seen as the dark cavities between plies. Photo 7.3, a real time X-ray portrait, demonstrates that voids can extend throughout the radii of the part. All subsequent parts contained voids. The addition of material to the edgeband section apparently induced void formation. However, the original part may have produced anomalous void free results. Replication would be necessary to draw any firm conclusions.

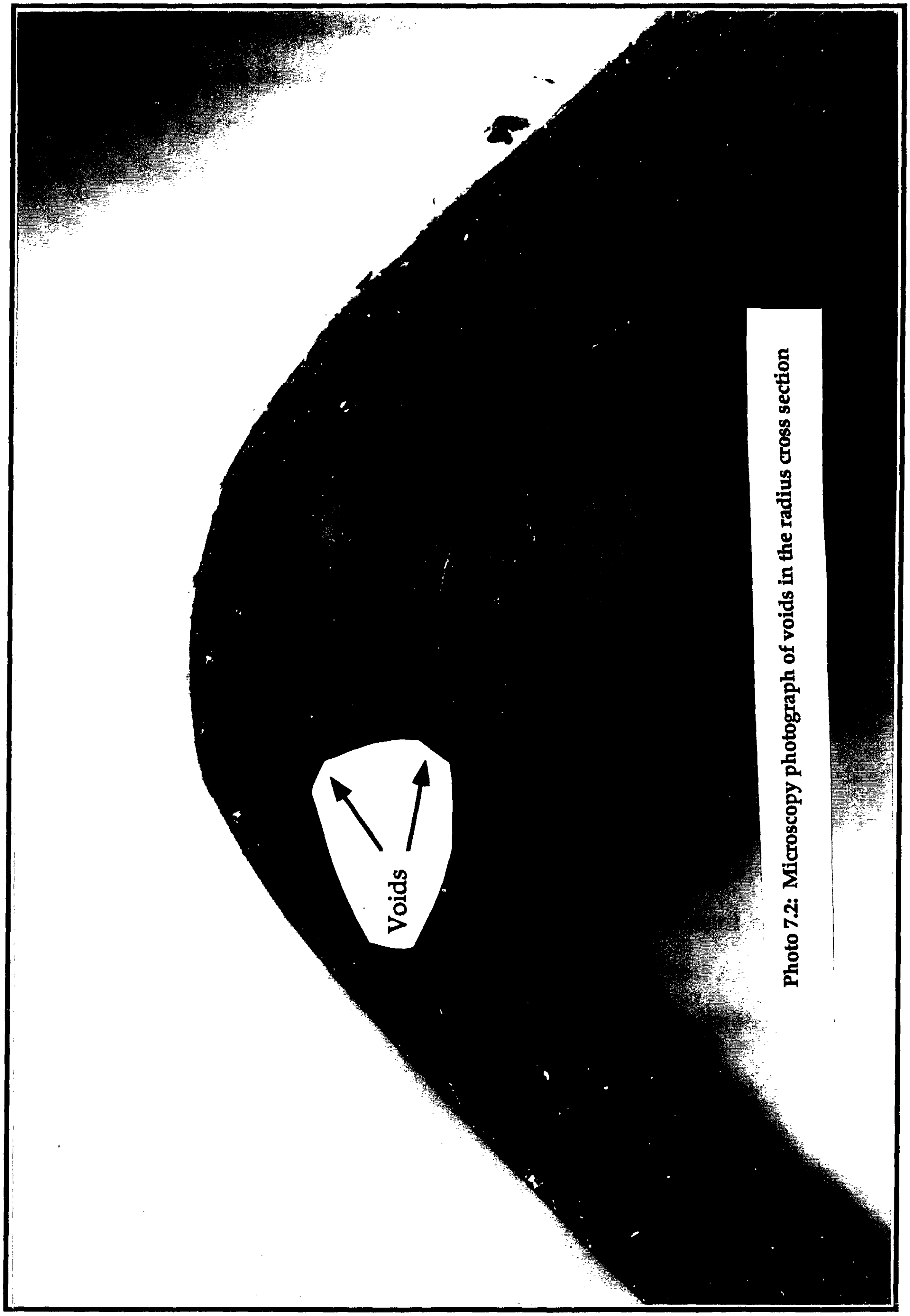


Photo 7.2: Microscopy photograph of voids in the radius cross section

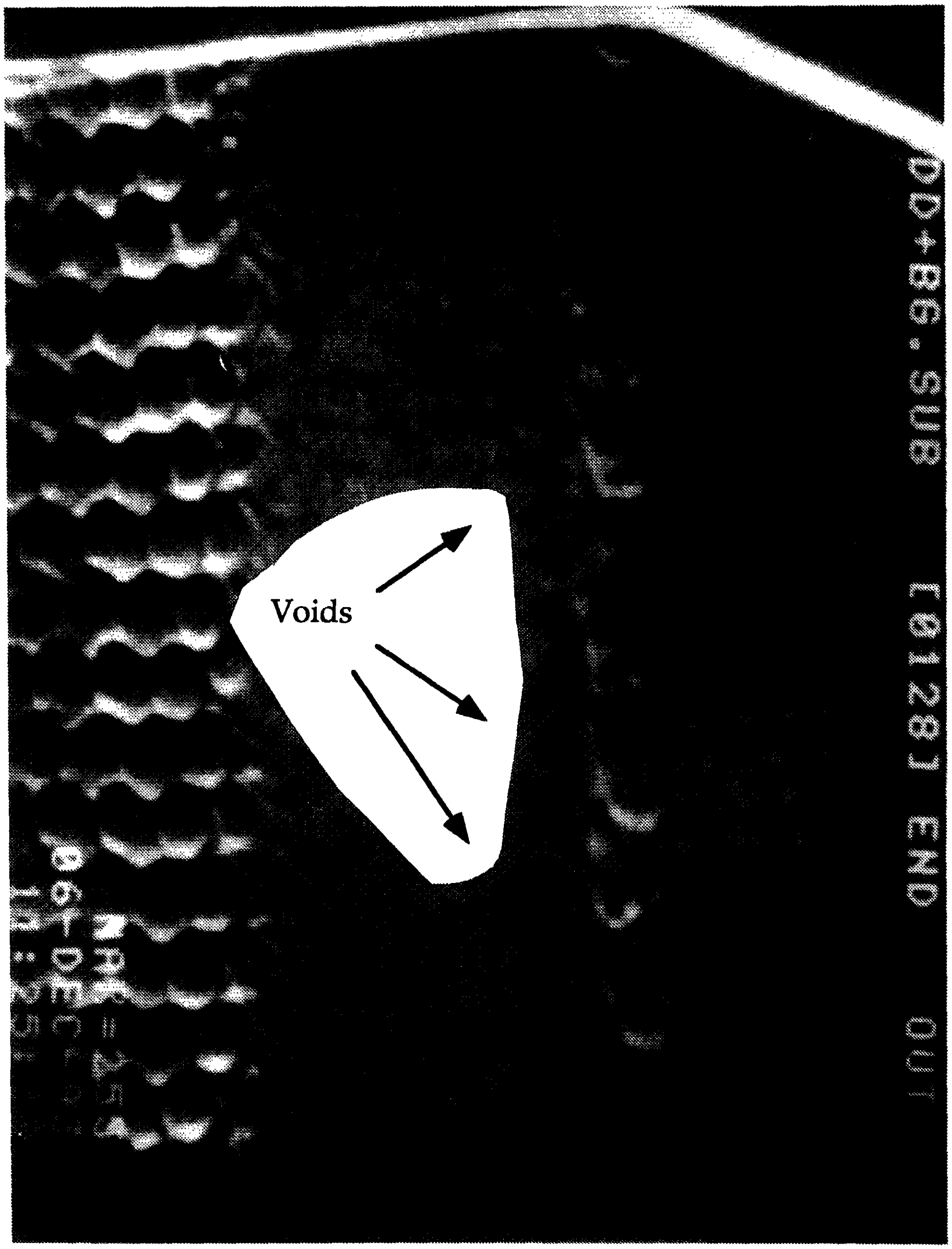


Photo 7.3: Real time X-ray photo of voids across the radius

7.2.2 Excess Resin

A simple analysis of ply movement during cure suggests several variables which could influence ply bridging and subsequent voids. During autoclave cure, the plies compress and the composite reduces in thickness. In the radii area, compression requires tangential movement of plies, since extensive ply elongation does not occur. Otherwise, the plies are fixed in place and cannot be drawn together.

A general force balance which equates the interply shear stresses and the force applied to the radius area by autoclave pressure leads to the following relationship. It does not consider the normal pressure forces on the flat edgeband sections, which would also inhibit ply movement.

$$\tau L = \sigma h$$

where: τ is the interply shear stress,
L represents the length of the contact edgeband area,
σ is the tension on the fiber, and
h is the part thickness

Further rearrangement of this expression, given a Newtonian relationship between viscosity and strain rate, yields

$$t = f\,(\mu\delta L/hPr)$$

where μ is the viscosity of the resin at a given time in cure,
δ is the amount of laminate compression,
P represents autoclave pressure,
r represents the curvature of the radii, and
t is the time required to compress and move the plies together.

Consequently, several predictable relationships exist if one considers time for ply movement a relative measure of the ease of ply movement, where shorter times signify more motion. Resin of low viscosity, and at the earlier stages of cure, induce ply movement. Likewise, large, smoother radii also enable the plies to shift more readily. On the other hand, a long edgeband results in more interply friction and less movement. Finally, a greater degree of compression also suggests increased difficulty in radial consolidation.

7.2.3 Excess Resin

Excess resin appeared in the radii section of each of the built parts. While parts could still be tested by ultrasound or real time X-ray techniques, these methods detect all discontinuities in the part. The presence of resin in the radii section unfortunately muddies the resolution of void measurement. As a result, void content could not be correlated back to compaction or material parameters. Discontinuities were detected in all parts; however, claiming that one contained a higher degree of voids over another is not possible under these conditions. The reliability of thickness measurements were also compromised by excess resin. Photo 7.4 depicts the excess resin in the radii section.

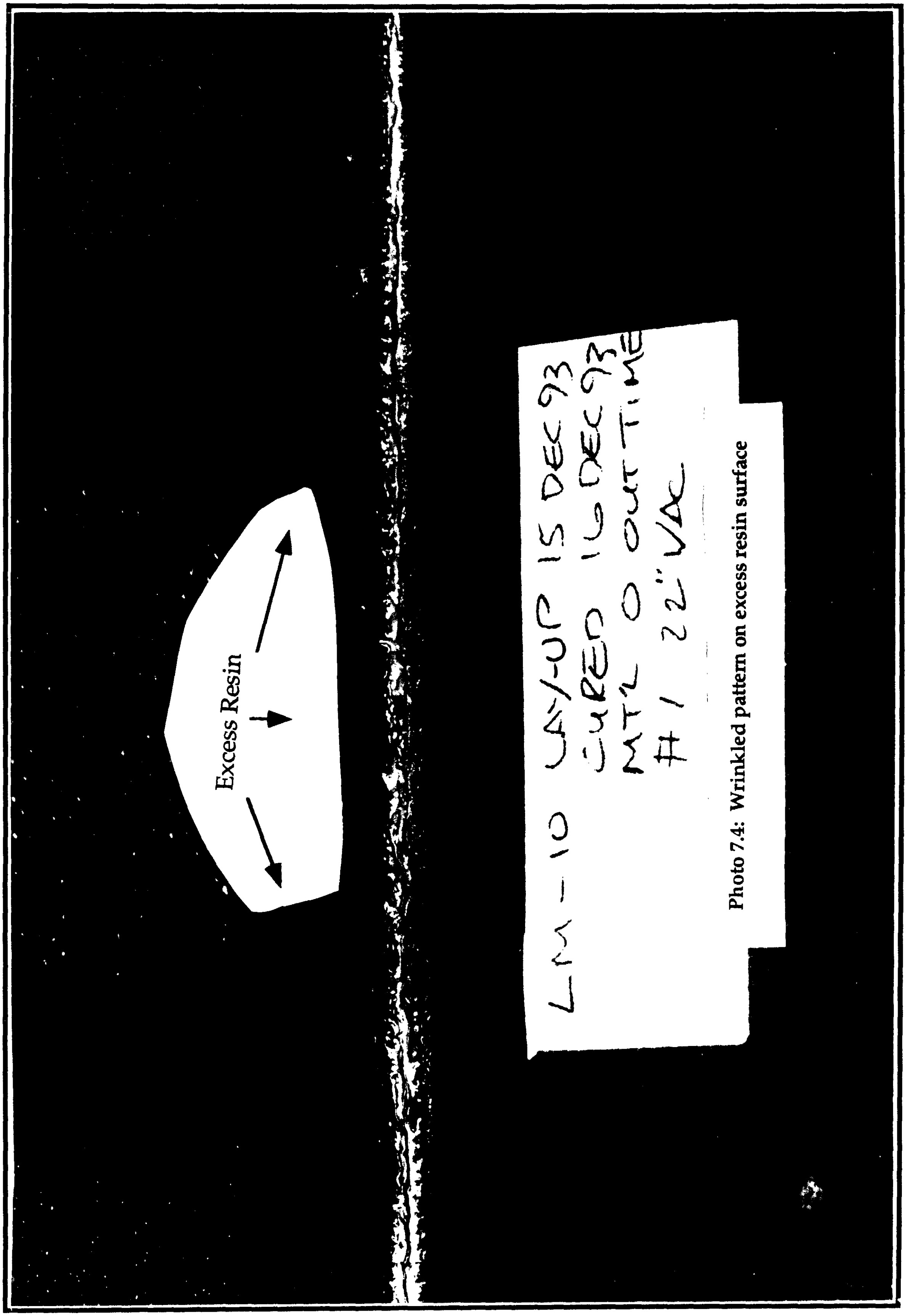
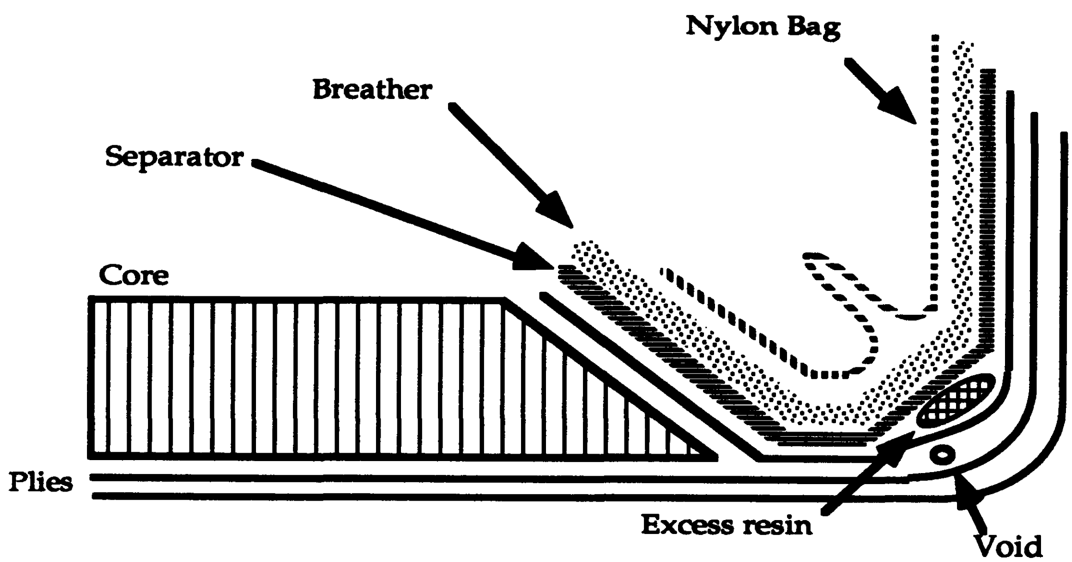


Photo 7.4: Wrinkled pattern on excess resin surface

During cure, the resin melts and gradually flows until time and temperature induce gelation. Resin tends to migrate where resistive forces are absent. For example, low pressure areas are likely to draw resin.

The presence of excess resin suggests that bridging of the bagging materials may have occurred. Figure 7.2 illustrates this condition with the FEP separator film, polyester breather, and nylon bagging.

Figure 7.2: Bridging of bagging materials



During cure, any of the bagging materials may be unable to stretch or move into contact with the part surface. This may occur from taut bagging materials, ineffectiveness of pleats, and lack of movement between spliced layers. It has been suggested that the ability of pleats to adjust and conform to contoured geometries has been overstated.

A bridge will then bear the external autoclave pressure, creating a low pressure environment underneath it. Resin may then flow into the resulting vacant area. The pattern transfer between a wrinkled FEP bag and excess resin suggests direct contact between the two, as shown in Photo 7.4. The part normally assumes the textured pattern of the breather material in flat surfaces of good contact.

Another potential effect of bag bridging is also seen in Figure 7.2. Void formation cannot be suppressed or eliminated when that local area is not subjected to full autoclave pressure. In effect, the bridge shelters all layers underneath it. As a result, it is not evident which material is primarily responsible for bridging.

Excess resin does occur in the processing of production parts. Currently, excess resin is removed through discretionary in-process sanding. Although no rejection tags are issued for sanding, additional labor is used to correct a condition which need not occur in the first place. This operation is an example of institutionalized rework which saves time and corrects the problem, but also masks an unnecessary condition.

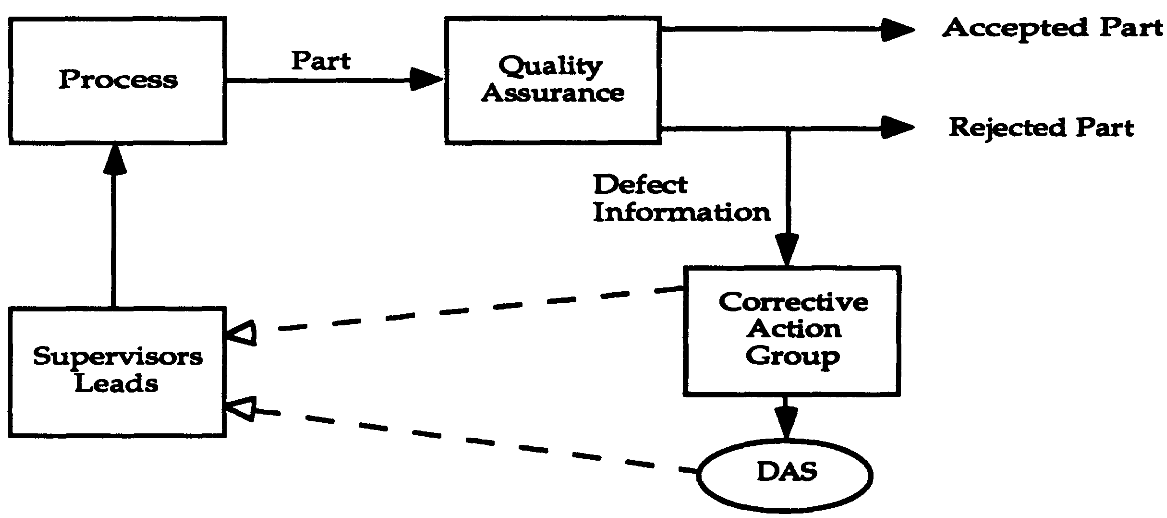
Chapter 8

Feedback of Quality Information

8.1 Information Flow

As mentioned earlier, labor plays a critical role in successful lay-up fabrication. While training and procedures improve the effectiveness of labor, the efficient feedback of information presents an additional opportunity for improvement. Evaluation of the current reinforcement system suggests an intermittent flow of information to the shop areas. The transfer of quality information is described in Figure 8.1.

Figure 8.1: Feedback loop of quality information



After a part has been fabricated, quality assurance inspects the piece and either accepts or rejects it. An acceptable part continues through normal processing and, because the lay-up process is disconnected from downstream operations, does not return. The workers responsible for building the successful part generally do not receive any indication of the part's status. Association with the part disappears after it has left the lay-up station.

Similarly, a rejected part is held until disposition, possibly repaired, and then returned to the normal process flow. In the event of a repair, a separate rework area is responsible for most repair activity. Again, lay-up workers generally do not see the non-conformances in the cured part, or the required repair labor. A different crew of workers supports the rework area.

Of course, there are occasions where effective feedback does occur. In one instance, the names of workers and the final outcome of their parts were displayed on a bulletin board, after a series of defective 747 APU ducts. This generated awareness of the status of each part and of the urgency of the situation. Similarly, workers are informed of defects when it begins to impact schedules.

While the part travels onward, the information associated with a tag is sent to the Corrective Action Group (CAG). This group assesses the non-conformance and attempts to determine the defect cause. They are also responsible for providing this information to the DAS database.

At this point, the knowledge of part outcome may stall. When CAG is able to determine probable cause and corrective measures, it communicates with the shop directly or through the shop leads, supervisors, or facilitators. However, in instances when CAG is not passing its findings, the transfer of information is halted. As a result, lay-up workers may not know the resulting disposition or defect in their work. While all information is included in DAS, certain areas regularly utilize the database, while others access it less frequently.

In addition, a reasonable time may pass before information is passed to the workers. CAG may identify the cause of a defect quickly; in other instances, it may take a longer period of time. As a result, knowledge transfer occurs in a discrete, rather than continuous, fashion.

This potential delay, coupled with a lengthy fabrication time, can impede the feedback process. After the part has spent significant time in processing, and as its information travels through QA and CAG, knowledge of the part's outcome may eventually reach the lay-up worker. However, after this lengthy time, any ties and memory of the part will have faded.

While it is unrealistic to immediately and indiscriminately release every bit of information, the transmission of the basic part status can have several benefits. These are described in the following section.

8.2 Benefits to Providing Feedback

Providing feedback directly to shop personnel contributes to the overall quality improvement process in several ways. Sharing this information can first support the corrective action effort. Because the shop workers are closely involved with the daily operations, they are more aware of the process and can recognize possible disturbances within the process. They may often have suggestions or ideas which highlight facts which were previously ignored. This can help identify the cause of defects and suggest corrective action.

In an environment of high employee turnover, feedback is especially important as an educational tool. Providing workers with performance feedback can enhance their ability to learn. Learning occurs more quickly and effectively, if workers understand the result of the efforts. They can consequently connect this with specific actions and identify areas for further improvement.

Finally, reinforcement can inspire greater ownership of the parts. A personal attachment to each piece develops personal involvement with the part's outcome. Improved attitude and pride are the results of the employee's understanding of her contributions and impact on the product. The part no longer leaves the process area as a detached order; it represents the product of one's hard effort.

An important criteria of performance feedback involves the care in using such a system constructively to develop workers and to identify opportunities for improvement. The receptiveness and effectiveness of a performance feedback system suffers if it is perceived as a mechanism to assign guilt or blame to individuals, possibly for items beyond their control. At that point, objective and open feedback is replaced by defensiveness.

Chapter 9

Conclusions

9.1 Summary

The quality improvement process strives to increase the profitability of a company by eliminating waste in its operations. In this effort, the problems must first be identified and understood before solutions can be discovered.

In the pursuit of this goal, this study collected data on the A3430 composites shop to assess opportunities for quality improvement. Findings suggested parts, a process, and several discrepancies worth noting.

In particular, the lay-up process appeared as a process area associated with a majority of defects. Of these, voids emerged as one common problem. Further research focused on addressing void formation through experimentation. During this exercise, the overall quality system was also studied. Opportunities to improve the responsiveness and support to quality efforts were sought.

9.2 Improving the Quality Improvement Process

In order to encourage employee emphasis on quality, the corporation needs to clearly present its benefits and make it easy for employees to participate. Several actions can induce greater understanding of the impact employees can have on shop productivity.

First, the proper tools must be provided to arm employees with an understanding of the benefits and methods to attain higher quality. Training programs currently exist within Boeing to educate their workers on the various concepts and tools. In the A3430 shop, Continuous Quality

Improvement programs are currently in place to resolve production problems and promote the quality theme. Boeing also sponsors quality initiatives with its external suppliers which define expectations, measures, and methods for quality improvement. Standards and programs such as these need to spread internally.

One of the most powerful aids in improving quality, is the information system. Boeing currently maintains several systems; however, some are isolated and cumbersome to use. Workers in each area must be able to learn and understand the use of the system. As a result, this system needs to integrate and include all information which is necessary for the shop to evaluate its quality performance. Instead of an individual accessing several systems, the ideal QIS should communicate with relevant databases to provide the needed statistics. In addition, the data should be reliable and clear. Workers will not use information they do not trust or understand.

Furthermore, work areas need to appreciate their impact on shop operations. The understanding of one's role and contributions is a powerful motivator to improvement. While quality metrics supports this, direct feedback to workers provides additional benefits. An emphasis on the product creates attachment with the outcome of the part. Workers may assume greater responsibility for the success of the part and strive to understand causes of failure. Because labor is a sizable component of fabrication, its utilization is a potent means of improvement.

In addition, further research in the lay-up of composites should be pursued. These are described in the following section.

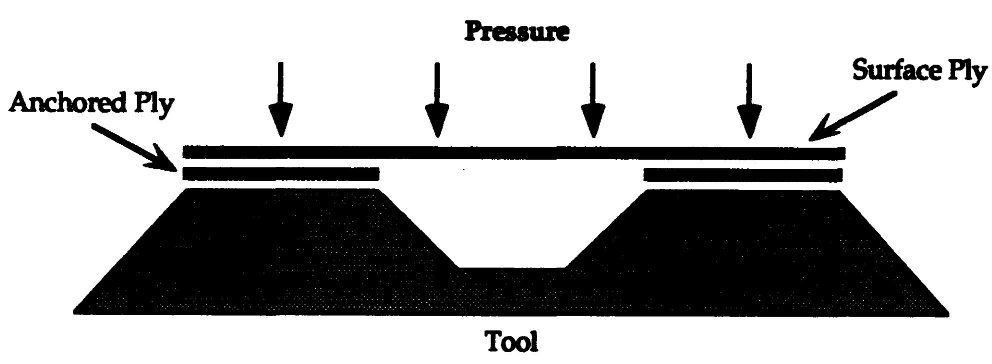
9.3 Areas for Further Study

As seen in the experiments, apparent bridging of bag materials may cause imperfect parts through excess resin and voids. Since only a few test parts were constructed, the performance of bagging materials and techniques should be further examined.

The properties of the resin during cure dictate its abilities to flow, transport volatiles, and impregnate fibers. Future experimentation should focus on the lay-up process and curing as elements of a single system. There is a high level of interdependence between the two areas.

Design for manufacturability can decrease the likelihood of part defects. Certain aspects, such as the radii dimensions, are known to greatly affect the ability of workers to fabricate the part. Determining the impact of ply dimensions on ply movement could provide valuable information to designers. If critical areas are determined, design rules can be developed to avoid future problems. Figure 9.1 suggests one possible experiment to evaluate the ability of plies to move against various contact areas.

Figure 9.1: An experimental set-up to test ply movement



In this diagram, the top ply is anchored by fixed plies which surround the cavity. Pressure can be applied and any movement of the top ply can be related to various contact areas.

9.4 Developing Controllable Processes

While quality improvement efforts and experiments effectively address problems, ideally, the processes should be designed to consistently and robustly produce parts. The development of a well controlled process supports the effort to build reliable quality into parts; however, this is often difficult, especially with a multifaceted process such as composite fabrication.

Determining the elements of a controllable process itself requires a multi-step process which aims to identify the interactions and effects of certain actions. Figure 9.2 outlines the stages of understanding in process development.

Figure 9.2: Steps toward developing controlled processes

- Define and understand target characteristics and objectives
- Determine reliable measurements to assess performance
- Identify and understand the key parameters which influence the process
- Determine methods to control these key parameters
- Monitor the performance of the process
- Continue to improve the capability of the process

In composite processing, the desired performance requirements, such as strength, stiffness, impact resistance, and dimension, are known and specified by designers. Goals involving fabrication, such as manufacturing costs and cycle times, are less defined, although historical data and cost analysis can set realistic expectations of the process. In this respect, manufacturing needs to understand the capability of the process to set its targets. An appreciation of reasonable process limits can inspire workers to maintain the process with a belief in its controllability. In addition, it serves as a standard for continuous improvement.

A greater challenge, at this point, involves developing measures to assess current performance. These measures should not only signal that a deviation has occurred, but also provide variable information which can give direction for corrective action. Currently, most data is provided on an attribute or pass/fail basis. While this successfully prevents defective parts from continuing through the system, it provides less value to the quality improvement effort. Variable data offers greater resolution and insight into the causes and sources of problems.

With voids in the radii area, ultrasound transmission detects void presence, approximate size, and number. However, this information is only conveyed in the rejection tag as an accepted or rejected part. Knowledge of the level or degree of voids would help start the development of a finely controlled process. A significant investment of time and resources are needed to induce this shift from attribute analysis. Additional development in sensor and information technology would support this effort.

Once measurement criteria have been developed, the key process parameters can be linked to the final attributes through research and experimentation. However, without a means to evaluate the variable effect of process changes on final attributes, it becomes difficult to determine the key process parameters.

Only after the development process has advanced through these steps, can the manufacturing process better control the key parameters, monitor the process performance, and provide suggestions for future improvement.

9.5 Final Comments

While this thesis emphasizes quality, a system wide analysis should address the value of quality to the profitability of the organization. Many tradeoffs exist between production, scheduling, inspection, and quality. While 100% process quality is a noble goal, in some instances the necessary preventive or inspection costs may outweigh the costs of internal or external failures.

Poor quality, though, represents wasted efforts, and therefore quality should be built into parts, wherever practical, to minimize the need for non-value added activities. Quality improvement programs will help move processes closer to this ideal.

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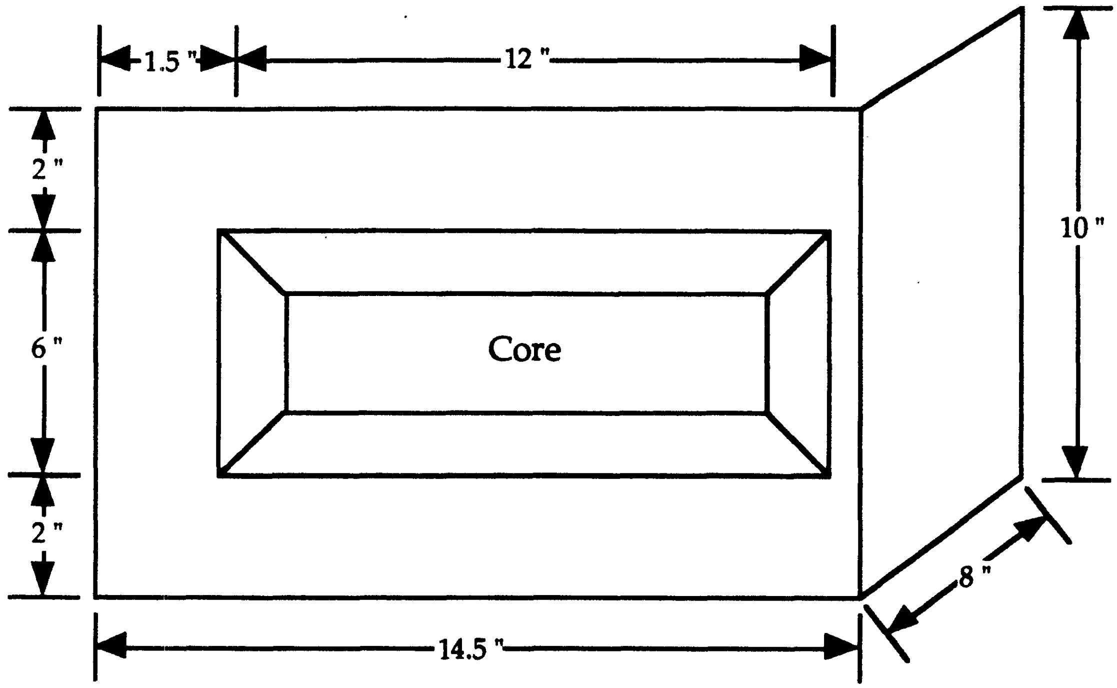
Appendix A: Radius Panel Lay-up

Table A.1 presents the sequential ply stack-up of the experimental test part described in Section 6.4. The toolside ply appears first. Dimensions of the part are provided in Figure A.1. This figure is a top down perspective of the part; Figure 6.3 (in section 6.4.1) depicts the side view.

Table A.1: Ply sequence and dimensions for the experimental part

Description	Orientation	Dimension
Adhesive		22 x 10
Full Ply	0/90	22 x 10
Full Ply	± 45	22 x 10
Doubler	0/90	22 x 10
Full Ply	0/90	22 x 10
Adhesive		12 x 6
Core	20° chamfer	12 x 6
Adhesive		12 1/4 x 6 1/4
Fillers	0/90	8 x 8, 2 x 14, 2 x 8, 2 x 20
Fillers	0/90	8 x 8, 2 x 14, 2 x 8, 2 x 20
Fillers	0/90	8 x 8, 2 x 14, 2 x 8, 2 x 20
Full Ply	0/90	22 1/4 x 10 1/4
Doubler	0/90	22 1/4 x 10 1/4
Full Ply	± 45	22 1/4 x 10 1/4

Figure A.1: Dimensions of the experimental test part



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