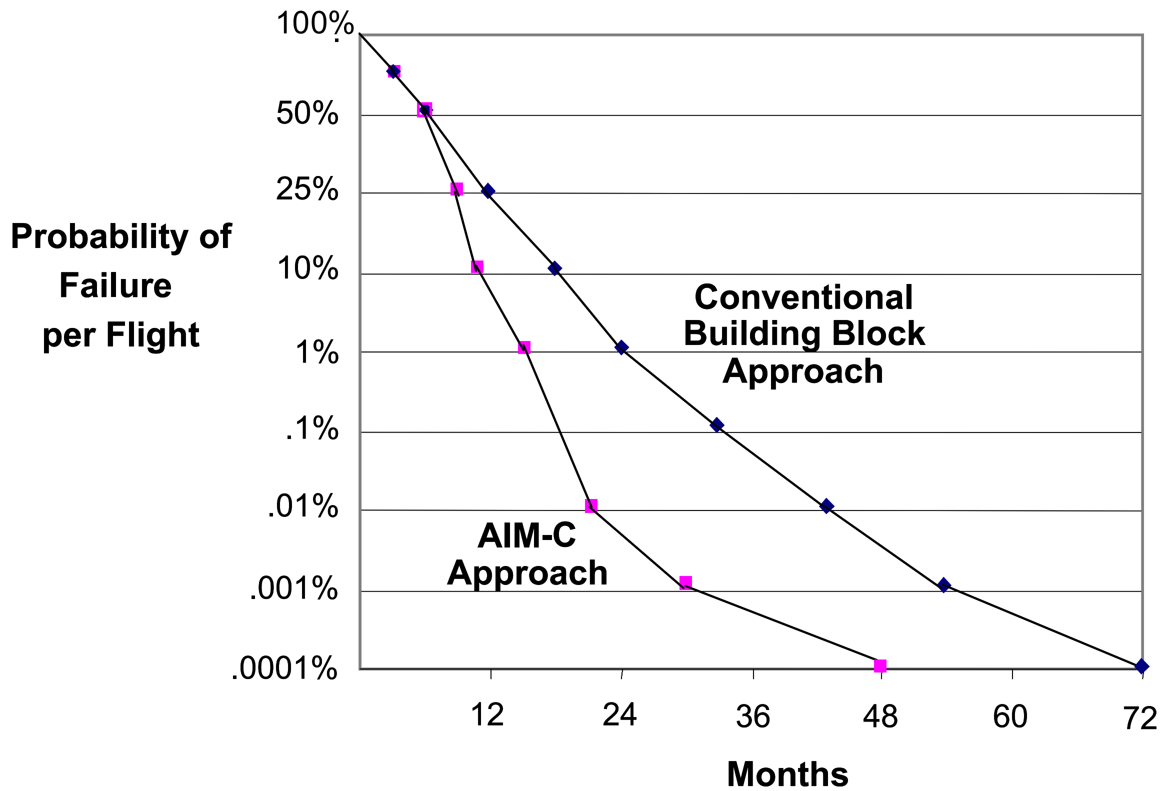


Figure 10-18. Risk Assessment for Conventional Building Block Approach Compared to the AIM-C Approach

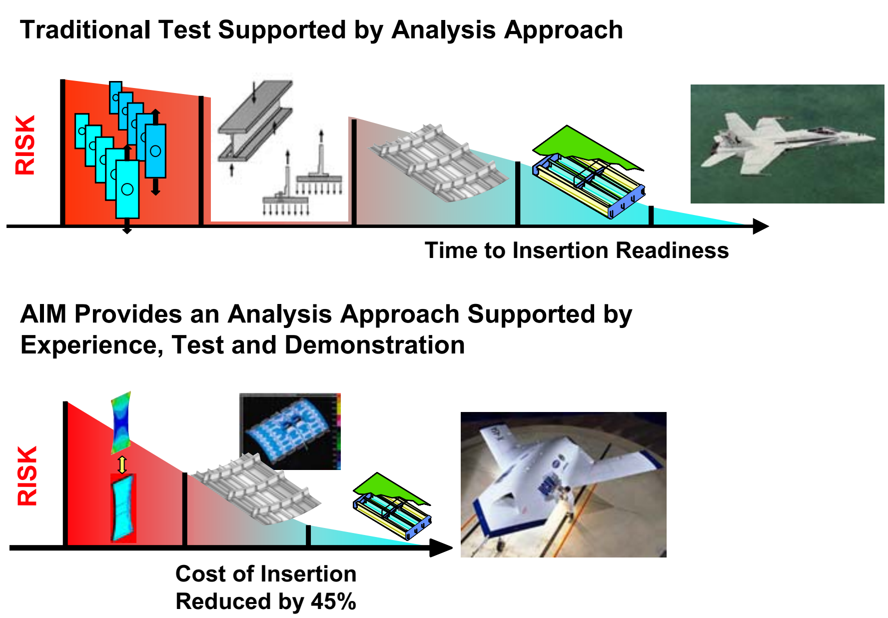


Figure 10-19 AIM-C Process Achieves Accelerated Insertion

11 AIM Materials and Process Methodology

Overview

The AIM methodology for accelerating the insertion of new materials involves characterization of new materials relative to requirements as well as exploration of the processing window for that material relative to basic material properties and application specific geometries.

Composite Materials Screening

Time Frame

Allow at least 6 months for properly evaluating composite material candidates. Consider all the data resources available: suppliers, Department of Defense (DOD) and industry experience with candidate materials, Gray Beard Reviews, and homework /legwork. Validate the source and pedigree of the information to decide its value to decision making.

Requirements

Make a list of requirements based on:

- Aircraft Specification:
    - Maximum operating temperature – corresponding glass transition (Tg) requirement
    - Operating environment – saturated moisture content and effect on the strength properties
    - Chemical resistance – understand resin chemistry, any corrosion issues due to presence of imides
    - Process control/process verification requirements
- Design Requirements
    - Assess adhesive compatibility if there is cocured /co-bonded structure.
    - Honeycomb structure will require a special cure cycle(s) if cocured to the core.
    - How thick is the thickest laminate? What is the thinnest?
    - What are the preliminary margins of safety and can we account for effects of defect in a design
    - Are there large cocured structures that will require massive tooling and slow heat-up rates?
- Manufacturing Requirements

- Optimize the number of cure cycles required.
- Address storage /out time capabilities and requirements.
- Address tack life / handling capabilities and requirements.

Data Comparison

The analyst must understand processing, cure cycle parameters, laminate quality, fiber areal weight (FAW) and Resin Content in addition to the specimen configuration and test set-up to properly evaluate data, regardless of source. It is recommended that side-by-side tests be performed (especially for hot/wet and compression strength after impact (CSAI) properties) for leading material candidates. Do not water boil hot/wet specimens. If you do not have time to fully moisturize the specimens, expose the specimens to the same conditions at approximately 190F/95%RH for at least 30 days to get a quick look at effects of moisture and temperature on material properties.

Compare suppliers "Material Specification" type test data for several batches, if available. The specimens are not representative of design allowables (usually all zero plies) tension/compression/interlaminar shear, but the data provide a better side-by-side comparison for strength and stiffness between material candidates.

Manufacturing Evaluation

A manufacturing evaluation is a must for the final material candidates' screening. Fabricate a couple of parts representing important features such as: thick tapered skins and possibly honeycomb sandwich. Assess:

- Material handling for fresh material and after 30+ days out time. Verify strength drop-off via RT/Dry interlaminar shear coupon for out-time to 35 or 40 days.
- Work with suppliers to adjust bagging schematics and cure cycle for a specific material: high/low flow, vacuum/pressure/temperature cycle.
- If possible, imbed sensors to better understand resin/adhesive flow during cure.
- Carefully perform nondestructive inspection (NDI) to document differences in porosity levels, and other possible defects for different materials.
- Take photomicrographs; perform glass transition temperature determinations, differential scanning calorimetry for degree of cure determinations, and fiber areal weight/resin content testing for specimens taken at various locations to verify degree of cure and laminate quality. Document results.

- Look for unknown particles, unusual ply patterns, etc in photomicrographs. It is better to ask questions at this stage than see inconsistent batch-to-batch properties and lower allowables.
- Check morphology of resin and chemistry.

This does not exclude the application of AIM methodology to test and evaluation at the screening level. However, for purposes of definition the rest of this section deals with the methodology after the screening level. At this point, the methodology is divided into 8 steps which generally run in sequence but which often require looping back through levels as new information and/or requirements become known. The steps are:

1. Definition of requirements
2. Assessment of capabilities
3. Definition of conformance requirements
4. Constituent level basic material data collection
5. Composite level basic material data collection
6. Basic process development
7. Process cycle space exploration and optimization
8. Structure specific material and process application

Progression through these steps involves experience, test and simulation with the relative involvement of each dependent upon the level and applicability of past experience, the relevance of available test methods to requirements, and the confidence in available simulation methods respectively. Engineering judgment is critical to determining the appropriate level of involvement of these three information-generating methods.

The final product of progressing through the AIM methodology for materials and processes is a robust processing cycle for a given material system for an intended application with understood sensitivities and limitations. The knowledgebase developed can also be used for extrapolation to other applications through methodology directed test and simulation.

For the AIM-C program this methodology was developed around an autoclave cured addition reaction epoxy/graphite composite system as applied to hat stiffened aircraft primary structure. For purposes of discussion, progression through this application will be periodically sited here. The basic methodology is universally applicable to any material and process insertion.

11.1 Defining Requirements, Assessment Capabilities and Conformance Activities

Requirements

Fundamental to the successful insertion of any new material is the clear definition of requirements for that material. Ideally these requirements have been clearly identified and universally agreed upon in all relevant categories prior to proceeding with an insertion. In reality, for complex insertion cases such as organic matrix composites into high performance aircraft, requirements evolve as designs mature and operating environment definitions change. In addition a lack of understanding of materials limitations can cause problems as a material and process are pushed into a previously unexplored processing/operating zone. Therefore the AIM Methodology requires not only the definition of performance requirements but also the definition of material and process performance relative to those requirements with an understanding of the uncertainty in both.

A system of Technology Readiness Levels has been developed as part of the overall AIM methodology. (Appendix A). These readiness levels can be used to help define what the requirements are at different stages of a material insertion. Levels referred to as "X"RLs are then developed for the specific material type (in this case autoclave cured composites) and application (Flat panels and Hat Stiffened Panels).

Knowledge of potential requirements growth areas (examples: Increase in temperature operating environment, increase in design dimensions to accommodate stiffness) should be accommodated in data collection and setup of parametric simulations where economically reasonable. Another potential growth area is the range of application for that material. If the material is to be used in a co-cured stiffened structure but the nature of the stiffening scheme has not been determined the AIM-Methodology allows for evaluation using any preexisting templates. This effort up front can save significant time and money later as changes occur by avoiding the flows associated with repeating characterization at different conditions and/or regeneration of simulations.

Assessment Capabilities

Requirements are met by comparison to results generated by one of three general assessment capability categories defined in the AIM methodology. These categories are experience, test data and simulation. These capabilities should not be confused with material and process system capabilities. Assessment capabilities are the level, pedigree and certainty associated with the categories described above.

The AIM –C system has a number of simulation templates that can be used for parametric studies in the area of producibility and process development. For example Template 9 addresses heat up rate and exotherm issues for flat parts with one or two sided tooling. This simulation can be used to project a material systems performance over a range of part thicknesses, tooling materials and thicknesses, autoclave capabilities and cure cycles evaluating thermal response, viscosity, degree of cure, and relative residual stress. However, this simulation currently does not provide information on material flow and consolidation, critical areas for successful part scale up. For these items we gain some insight by using the producibility module ASCOM simulation for edge thinning along with consulting the heuristics available with the Producibility module for general trends and performance of resins of a similar nature. Finally, depending on the remaining information required, a test plan based on producibility module guidelines will be required to cover un-addressed areas, and improve confidence in results from simulation and heuristics as necessary.

Directly related the capability of the simulation tools is the confidence in the input datasets and subsequent simulation models. During different stages of the insertion process the same simulation may be repeated with improved input data as such data becomes available. For example initial cure cycle development simulation work may be adequately performed using the processing module and template 9 with a simple kinetics and viscosity models based on limited tests and handbook values for other resin and fiber properties. When available, certain properties from datasets for other material systems that have already been entered into the AIM system may be used based on engineering judgment.

Conformance Activities

Once the insertion requirements and assessment capabilities have been established the insertion process moves to the conformance stage. Figure 11-1 shows the methodology flow that occurs independent of the insertion methodology. This basically describes the high-level conformance activities and cost relative to requirements. These activities and costs will differ depending on the proposed insertion method (Building Block, AIM, Other). Once the high level requirements and conformance activities have been selected the process moves on to the intermediate conformance level as shown in Figure 11-2.

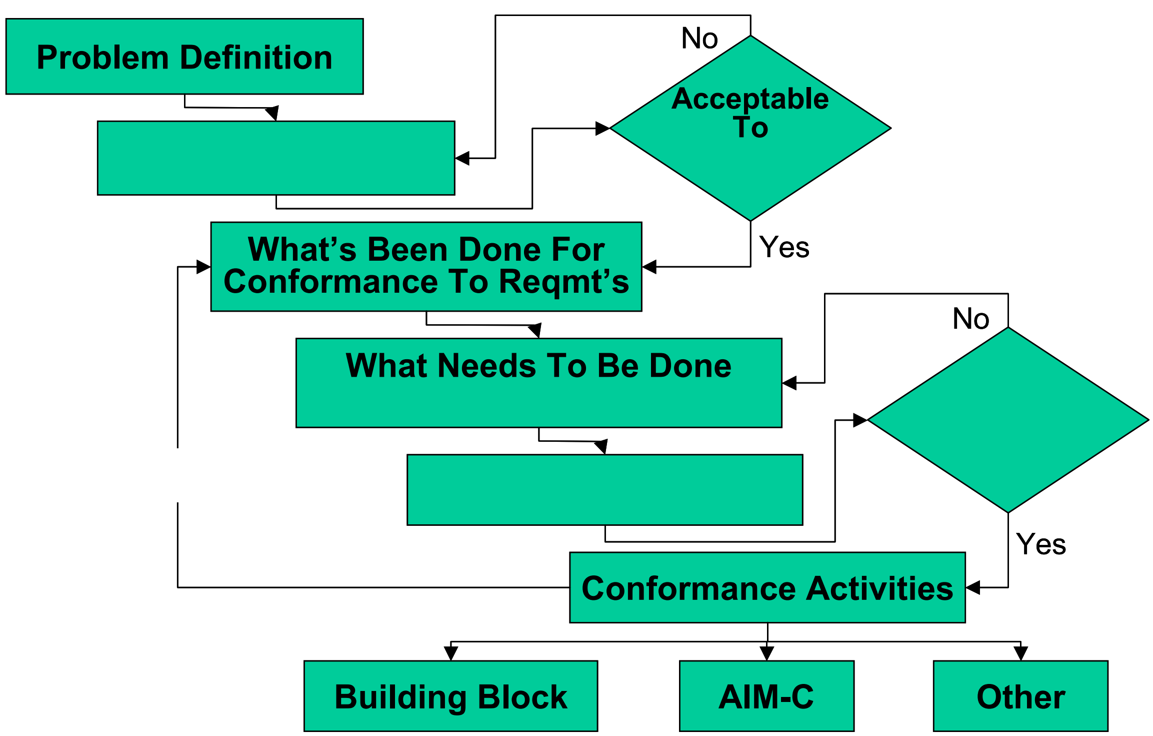


Figure 11-1 – High Level Conformance Activity, Independent of Insertion Methodology

The intermediate conformance activities are shown as a loop in Figure 11-1 indicating that conformance activities may be cycled and repeated based upon the outcome. For example heuristics may not provide adequate information on the response of a part during processing necessitating the fabrication of a test part. With the AIM methodology the results of this test part are captured in an update of the appropriate area resulting in an increase in maturity. If results are good, subsequent activity may occur (for example consulting the heuristics may help bracket the conditions for running a design scan using an analytical template, the results of which are used to establish the fabrication conditions for a test part to validate the most challenging areas of a processing window). Once the conformance summary chart requirements are met the insertion process can exit from this loop.

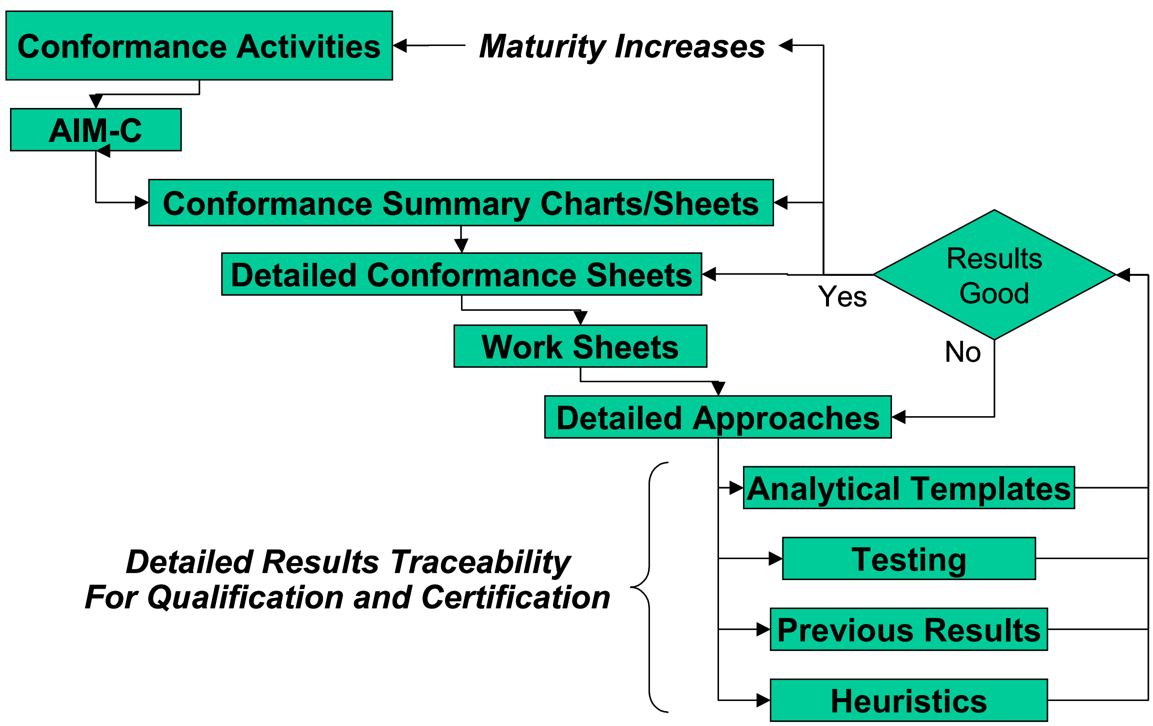
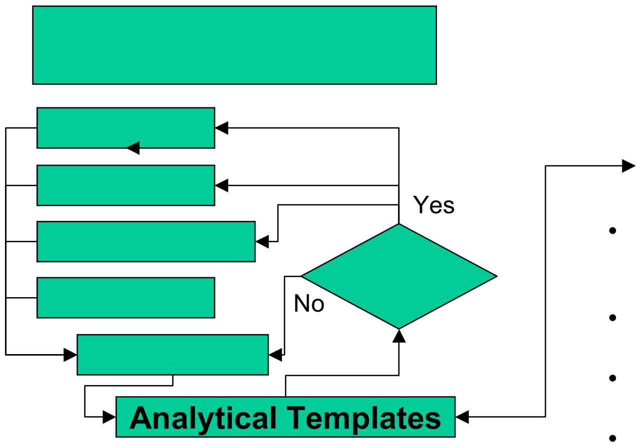


Figure 11-2 – Intermediate Level Conformance Activity Flow with in AIM Methodology

Figure 11-3 describes the benefits of the AIM Methodology and how results from conformance activities are used to satisfy multifunctional requirements. The following sections describe specific activity at this level for the AIM Materials and Processes insertion methodology.



Detailed AIM-C Examples

- Able to Meet Requirements for Multiple Areas at Same Time Using Integrated Models and Analysis
- Enables Traceability to Specific Requirements From Details and Data
- Applies The Approach of Maximizing Analysis and Minimizing Test
- Does Not Eliminate Testing But Tends to Direct It
- Enables Integrating Conformance Through Multiple Areas/Disciplines Using Common Information/Data/Test and/or Evaluation Specimens

Figure 11-3 – Benefits of AIM Methodology at Detailed Conformance Level

Material Data Collection

Material data collection falls into three categories for composite materials: constituent level (resin and fiber), laminate level, and part specific level. These categories are linked through experience and where available, simulation. It is this linkage and the confidence in this linkage that provides one of the means for insertion acceleration. Linkages can be both forward, building from constituent level properties to laminate and structure or reverse, extracting constituent level data from laminate tests. The utility of the forward linkage is self-explanatory as it offers a means of performance prediction. The reverse linkage allows difficult to measure constituent level properties to be extracted from higher-level test. Once extracted these properties have more utility than the higher-level test alone as they are no longer liked to a composite system.

Organic composite material properties are linked not only to constituent type and variability but also to processing conditions. The AIM methodology includes linkage of properties to processing conditions through simulation, test and experience. This area is still heavily dependent upon test given the current state of simulation capability. Simulations are used to help define processing limits within which the material property variation has been established by testing.

Data collection occurs in stages based on pre-existing information, schedule and technology readiness level. These stages are roughly divided into three levels
–Basic level – The basic level starts with the use of an existing characterized material which has been deemed similar by engineering judgment plus modification based on limited test data in key areas where significant deviations are known to exist from the "make from" material.

–Intermediate level – improve basic level dataset with additional test data, some validation
–Advanced level - full characterization with independent validation

Priority of the data collection is based on the activities for which the system is being tasked. The priority levels are as follows:
1 – Required information. This includes foremost, health and safety information along with cost and vendor estimated properties.
2 - Basic modeling/Heuristics comparison – These are the properties required to support basic coupon level processing feasibility through empirical evaluation and simulation
3 - Intermediate modeling/Heuristics comparison – This level is required for coupon level performance prediction/Sub element processing assessment, initial non-room temp dry performance
4 - Advanced Modeling – Required for sub element performance prediction/Element level Processing Assessment, various temp-dry performance
5 - Stochastic Modeling - Uncertainty prediction - Involves collecting uncertainty information on key inputs as identified by sensitivity studies

Constituent Level Basic Material Data Collection

As previously described the AIM insertion methodology relies on experience, test and simulation. As a foundation for materials and processes simulations for organic matrix composites constituent level data must be available. As an example Figure 11-4 and Figure 11-5 list the properties of interest for organic matrix composites along with how the property is obtained (test or analysis) and identification of test method and/or analysis type. Many constituent properties such as item 2.1.10 cannot be directly measured, therefore they are measured in laminate form and the required property back calculated using known relationships. These relationships may be embedded into AIM analytical tools or may be applied offline.

1.	RESIN - THERMOSET	How Obtained, Test or Anlaysis	Test/Analysis Identification	See Note	Priority (Note 10)
1.1	**TEST TYPE/PROPERTIES - UNCURED RESIN**				
1.1.1	Viscosity	Test	ASTM D 4473	1, 2	2
1.1.2	Reaction Rate	Test	DSC via ASTM D 3418 and ISO 11357	2	3
1.1.3	Heat of Reaction	Test	DSC via ASTM D 3418 and ISO 11357		2
1.1.4	Volatile Content/evolution temperature	Test	TGA	2	2
1.1.5	Volatile Type	Test/product knowledge	FTIR/Formula access	2	2
1.1.6	Volatile Vapor Pressure	Test			3
1.1.7	Resin Cost	Specified Value	Based on vender input		1
1.1.8	Density	Analysis	Based on cured/uncured test data	4	3
1.1.9	Resin Cure Shrinkage	Analysis	Based on volumetric test data		**3**
1.1.10	CTE	Analysis	based on TMA or linear dilatometer data	1	**3**
1.1.11	Thermal Conductivity	Analysis	Assumed to be that of cured resin	5	2
1.1.12	Specific Heat	Analysis	Assumed to be that of cured resin	5	3
1.1.13	Kinetics Model	Analysis	Based on Reaction Rate		3
1.1.14	Viscosity Model	Analysis	Based on Kinetics Model, Test Data		3
	Glass Transition Temperature	Analysis	Based on DSC or DMA Test Data		3
1.1.15	Volatile Type	Redundant			
1.1.16	Volatile Vapor Pressure	Redundant			
1.1.17	Volatile Content	Redundant			
1.1.18	Health and Safety Information	MSDS			1
1.2	**TEST TYPE/PROPERTIES - CURED RESIN**				
1.2.1	Tensile Stress to Failure	Test	ASTM D638	8	1
1.2.2	Young's Modulus, Tensile	Test	ASTM D638	8	1
1.2.3	Tensile Strain to Failure	Test	ASTM D638	8	1
1.2.4	Glass Transition Temperature	Test	ASTM D3418	6	1
1.2.5	Volatile Content	Test	ASTM D3530		3
1.2.6	Density	Test	ASTM D-792	4	3
1.2.7	Modulus as a Function of Temp	Test	Function of Temp and Degree of Cure	7	3
1.2.8	CTE	Test	ASTM E831 or linear diletometry	8	2
1.2.9	Thermal Conductivity	Test	ASTM C177		2
1.2.10	Solvent Resistance	Test	ASTM D543		3
1.2.11	Specific Heat	Test	ASTM E-1269 or Modulated DSC		3
1.2.12	Bulk Modulus	Analysis		8	3
1.2.13	Shear Modulus	Test	ASTM E143	8	3
1.2.14	Poisson's Ratio	Test	ASTM E143 (Room Temp)	8	3
1.2.15	Coefficient of Moisture expansion	Test	No Standard	8	4
1.2.16	Compression Strength	Test	ASTM D695	8	3
1.2.17	Compression Modulus	Test	ASTM D695	8	3
1.2.18	Mass Transfer Properties	Test	Veight gain vs time, Ficks Law and modeling		4
1.2.19	Viscoelastic Properties	Analysis			4
1.2.20	Toughness Properties	Test			4
1.2.21	Tg, Wet	Test	ASTM D3418	9	1
1.2.22	CME	Test			4
1.2.23	Solvent (Moisture) Diffusitivity	Test			4
1.2.24	Volatile Type	Test	FTIR or similar		4
1.2.25	Volatile Vapor Pressure	Test			4

Notes

1. Initial measurements are by test. Test data is extrapolated to other temperaturs and degree of cure
2. Similar test methods acceptable
3. Use appropriate test method for volatile type
4. Water displacement method, density gradient column, or other methods are appropriate
5. See cured resin test types
6. DMA method acceptable
7. Ref. Bogetti and Gillespi, or Johnston
8. tested at varying temperatures, modeled as a function of temperature
9. tested at varying concentrations, modeled as a function of concentration
10. Priority Key
    1 - Get in the door/Heuristics comparison
    2 - Basic modeling/Heuristics comparison - Coupon level processing feasibility
    3 - Intermediate modeling/Heuristics comparison - Coupon level performance prediction
    /Sub element processing assessment, initial non room temp dry performance
    4 - Advanced Modeling - Sub element performance prediction/Element level Processing Assessment,non room temp-dry performance
    5 - Stochastic Modeling - Uncertaitny prediction - Involves collecting uncertainty information on (TBD) inputs

Figure 11-4 –Resin Properties

2.	FIBER	How Obtained, Test or Anlaysis	Test/Analysis Identification	See Note	Priority (Note 5)
2.1	TEST TYPE/PROPERTIES - FIBER				
2.1.1	Tensile Strength	Analysis	SACMA SRM 16-94	1	1
2.1.2	Tensile Modulus E11 (longitudinal)	Analysis	SACMA SRM 16-94	1	1
2.1.3	Tensile Strain to Failure	Analysis	SACMA SRM 16-94	1	1
2.1.4	Yield (MUL)	Analysis	SACMA SRM 13-94		3
2.1.5	Density	Test	SACMA SRM 15-94		3
2.1.6	Heat Capacity (Cp)	Test	ASTM E-1269 or Modulated DSC	2	3
2.1.7	Thermal Conductivity Longitudinal	Analysis	ASTM E-1225	1, 2	3
2.1.8	Thermal Conductivity Transverse	Analysis	ASTM E-1225	1, 2	3
2.1.9	CTE - Axial	Analysis	Modeling with Lamina and resin CTE information	1, 2	3
2.1.10	CTE - Radial	Analysis	Modeling with Lamina and resin CTE information	1, 2	3
2.1.11	Filament Diameter	Test	Scanning Electron Microscopy		3
2.1.12	Filament Count	Test	Vendor		3
2.1.13	Transverse Bulk Modulus	Analysis		3	3
2.1.14	Youngs Modulus, E22 Transverse	Test	Analysis combined with mechanical test data	1	3
2.1.15	Shear Modulus, G12	Analysis	Analysis combined with mechanical test data	1	3
2.1.16	Shear Modulus, G23	Analysis	Analysis combined with mechanical test data	1	3
2.1.17	Poissons Ratio, 12	Analysis	Analysis combined with mechanical test data	1	3
2.1.18	Poissons Ratio, 23	Analysis	Analysis combined with mechanical test data	3	3
2.1.19	Compressive Strength	Analysis	Analysis combined with mechanical test data	1	1
2.1.20	Cost	Specified Value	Vendor Provided	4	1
2.1.21	T(g)	Test	DMA		1
2.1.22	wet T(g)	Test	DMA		1
2.1.23	Health and Safety	MSDS			1
2.2	TEST TYPE/PROPERTIES - FIBER SURFACE				
2.2.1	Sizing Type	Specified Value			3
2.2.2	Fiber Surface Roughness	Test	SEM or similar		3
2.2.3	Surface Chemistry	Specified Value	Surface Chemstry (XPS, etc)		3
2.2.4	Fiber CME beta1 (Longitudinal)	Test			4
2.2.5	Fiber CME beta2 (transverse)	Test			4

Notes

1 Backed out from lamina test data
2 Tested and modeled as a function of temperature
3 Predicted from basic principles
4 Based on vender supplied relationship
5 Priority Key
1 - Get in the door
2 - Basic modeling/Heuristics comparison - Coupon level processing feasibility
3 - Intermediate modeling/Heuristics comparison - Coupon level performance prediction /Sub element processing assessment, initial non room temp dry performance
4 - Advanced Modeling - Sub element performance prediction/Element level Processing Assessment,non room temp-dry performance
5 - Stochastic Modeling - Uncertaitny prediction - Involves collecting uncertainty information on (TBD) inputs

Figure 11-5 – Fiber Properties

Composite Level Basic Material Data Collection is conducted concurrently with testing performed to support the needs of fiber level data collection as most of the fiber properties must be analytically backed out of lamina level tests. These tests are described in Figure 11-5. The values for lamina shear modulus are analytically reduced to the fiber component of that shear modulus using the resin mechanical properties described in Figure 11-4. These constituent level properties, when recombined in the lamina module, will give the same value as the lamina level test. The added benefit is that a lamina level shear modulus can now be estimated at a different temperature or with a different resin system. Lamina level test results can be directly used in higher level AIM modules. Characterization of critical mechanical properties may also be conducted at the composite level after prescribed environmental exposures to operating fluids, temperatures, humidity, and loading cycles on an application specific and certification approach basis.

Characterization of the uncured composite material is conducted according to Figure 11-6. These properties are currently used directly in assessing prepreg and processing characteristics. These variables are available in the AIM architecture in the prepreg module and can be used in the future for processing simulations as capability expands in the AIM-C system.

3.	PREPREG	How Obtained, Test or Anlaysis	Test/Analysis Identification	See Note	Priority (Note 5)
3.1	TEST TYPE/PROPERTIES - CHEMICAL				
3.1.1	Viscosity	Test	ASTM D 4473	1, 2	3
3.1.2	Degree of Cure	Test	DSC via ASTM D 3418 and ISO 11357		3
3.2	TEST TYPE/PROPERTIES - PHYSICAL				
3.2.1	Resin Areal Weight	Test	digestion /burn-out ASTM D3171 or ASTM D3529		2
3.2.2	Fiber Areal Weight	Test	digestion /burn-out ASTM D3171 or ASTM D3529		2
3.2.3	Mass Fraction Fiber	Test	digestion /burn-out ASTM D3171 or ASTM D3529		2
3.2.4	Prepreg Heat Capacity	Analyisis	Rule of mixtures of cured resin / fiber		3
3.2.5	Density	Analyisis	Rule of mixtures of cured resin / fiber		3
3.2.6	Volume Fraction Fiber	Analyisis	From mass fraction and densities		3
3.2.7	Prepreg Ply Thickness	Both	Measured for unconsolidated, calculated for consolidated	3	2
3.2.8	Prepreg Areal Weight	Analyisis	From fiber areal weight		
3.2.9	Fiber Bed Permeability, x	Test	Speciallized test		4
3.2.10	Fiber Bed Permeability, y	Test	Speciallized test		4
3.2.11	Fiber Bed Permeability, z	Test	Speciallized test		4
3.2.12	Drape	Test	Generally qualitative		3
3.2.13	Tack	Test	Generally qualitative		3
3.2.14	Viscoelastic Properties	Analyisis			4
3.2.15	Prepreg Defect Probability	Analyisis			4
3.2.16	Fiber Bed Elasticity	Test			4
3.2.17	Backing Material	Specified Value			3
3.2.18	Separator Material	Specified Value			3
3.2.19	Available Widths	Specified Value			3
3.2.20	Cost	Specified Value			1

Notes
1 Initial measurements are by test. Test data is extrapolated to other temperaturs and degree of cure
2 Similar test methods acceptable
3 The prepreg module has the capability to enter either measured (test) or it will calculate the value (analysis)
4 Priority Key
1 - Get in the door
2 - Basic modeling/Heuristics comparison - Coupon level processing feasibility
3 - Intermediate modeling/Heuristics comparison - Coupon level performance prediction/Sub element processing assessment, initial non room temp dry performance
4 - Advanced Modeling - Sub element performance prediction/Element level Processing Assessment,non room temp-dry performance
5 - Stochastic Modeling - Uncertaitny prediction - Involves collecting uncertainty information on (TBD) inputs

Figure 11-6 Composite Level Prepreg Characterization

Basic Process Cycle Development and Exploration

Basic process cycle development begins with the recommended manufacturers cure cycle that is typically based upon resin testing with some limited composite testing. At this point the basic requirements for achieving a fully cured reasonably consolidated flat small flat panel are understood. The challenge is in determining the impact of cure cycle variation on the spectrum of mechanical performance requirements, scaling up part size and shape, and including other materials.

Current simulation tools can offer some insight into relative effects on residual stress from cure cycle variation but they cannot deal with the more complex issues of resin phase formation vs. time-temperature history and defect formation during cure and the resulting effect on mechanical properties. Simulations can yield information on temperature, degree of cure, edge flow, viscosity versus cure cycle, autoclave conditions and tooling conditions. Therefore for the case of organic matrix composites one must explore processing effects on mechanical properties primarily through test. Once performance has been tied to processing as a function of degree of cure, and consolidation has been tied to viscosity and time simulations can be used to ensure that the required times and temperatures are still achievable given the proposed tooling, part configuration and autoclave cure environment.

Some insight into consolidation can be achieved by using simulation but the primary means of development in this area still resides with test and experience. Feature based panels are fabricated to represent the range of expected geometries and thicknesses using material representative of production conditions including maximum and/or minimum out-time conditions and then evaluated for porosity and fiber waviness to determine the number of required debulk cycles for adequate extraction of volatile materials.

As far as the simulation capabilities the following sequence can be used to complement the information generated from test.

Assumptions:

1. Key resin time and temperature requirements defined by supplier. (Yes, See cycle below)
2. Recommended manufacturers cure schedule available (Yes, See cycle below)
3. Volatile type and content identified (No Significant Volatiles)
4. Reaction byproduct type and content Identified (No significant byproducts)
5. DOC range identified based on resin testing (Yes, 0.80 to 0.90)
6. Existing well characterized fiber used (Yes, IM7)
7. Very preliminary DSC (3 to 6) and RDS (3 to 6) data exists and has been put into initial kinetics and viscosity models (Yes, assume existing models)
8. Resin modulus and CTE Data available as a function of cure and has been entered into models (Yes, assume existing models)
9. Prepreg cure only, no cocure
10. T(g) as function of DOC available

Objective:
Establish cure cycle window using simulation tools to cover anticipated application and processing equipment.

Approach:

Step 1

Evaluate recommended cure cycle for practicality.
Manufacturers Recommended cure cycle

Autoclave - 85 PSI
Bag – vacuum at 22 inches Hg
Both prior to temperature application
Ramp Rate 1 to 5 F per minute
Hold temperature 350 +/- 10F
Hold Time 360 +15/-0 minutes
Cool down 5F maximum

Do the specified parameters fall within reasonable equipment capabilities? YES

Step 2

Simulate manufacturers recommended cure cycle maximums and minimums with 0.100 inch part on thin tooling and extract output (Representative of coupon allowable type part):

1. Run nominal case
2. Run maximum heat rates and minimum hold times and temperatures
3. Run minimum heat rates and maximum hold times and temperatures

Evaluate-
Degree of Cure
Minimum viscosity and viscosity profile
Gelation Time and Temperature
Vitrification Time and Temperature (Inst. T(g)> T)
Evaluate by Exercising resin module stand-alone with cure cycle driver

Step 3

Expand cure envelope at flat panel level through simulation

1. Run Isothermal Holds to Explore potential Hold Temperatures
2. Run design scan on heat and cool rates to limits of equipment. (if material path independent)
3. Run design scan varying cure hold temperature by double recommended range
4. Run Design scan on cycle with intermediate temperature hold as determined from viscosity profile.

Evaluate-
Degree of Cure
Minimum viscosity and viscosity profile
Gelation Time and Temperature
Vitrification Time and Temperature (Inst. T(g)> T)

Step 4

Define thin flat panel cure window based on DOC, Viscosity and reduction in residual stress requirements

Step 5

Explore effects of part and tool thickness on cure cycle window.

Evaluate part thickness and tool thickness to 2” with various tool materials, similar to template 9, with emphasis on meeting DOC and Viscosity requirements while maintaining temperature requirements. Evaluate residual stress output.

Over what range of thickness and tool materials can part temperature requirements be met given equipment limitations?

Step 6

Explore effects of 3D and tool constraint on residual stress, temperature response, degree of cure

Evaluate representative anticipated applications (I-beam?, Hat?) with different tooling materials using existing parametric meshes within the AIM system. If a high degree of confidence exists at this stage in the final configuration and a generic part model is not available, generate an application specific model .

Assess impact on residual stress in critical areas (Radius filler, flange edge)

Assess resin modulus development vs. tool expansion

Step 7

Define cure cycle recommendations for allowables panels

This sequence along with the previously described test panel fabrication will bring the user to the level of understanding for processing defect free panels with a cycle suitable for scaling to a production process with a reasonable confidence depending upon the ultimate demands of the design.

Structure Specific Material and Process Application

This section deals with the application of the selected material and basic resin processing requirements to a specific part configuration, in this case a hat stiffened fuselage panel. The objective of this effort is to down-select viable tooling and cure approaches for hat-stiffened structure while still maintaining the required basic resin cure requirements. Figure 11-7 describes the flow for traversing the AIM-C Methodology for material insertion into the hat stiffened panel demonstration, part of the initial AIM-C program.

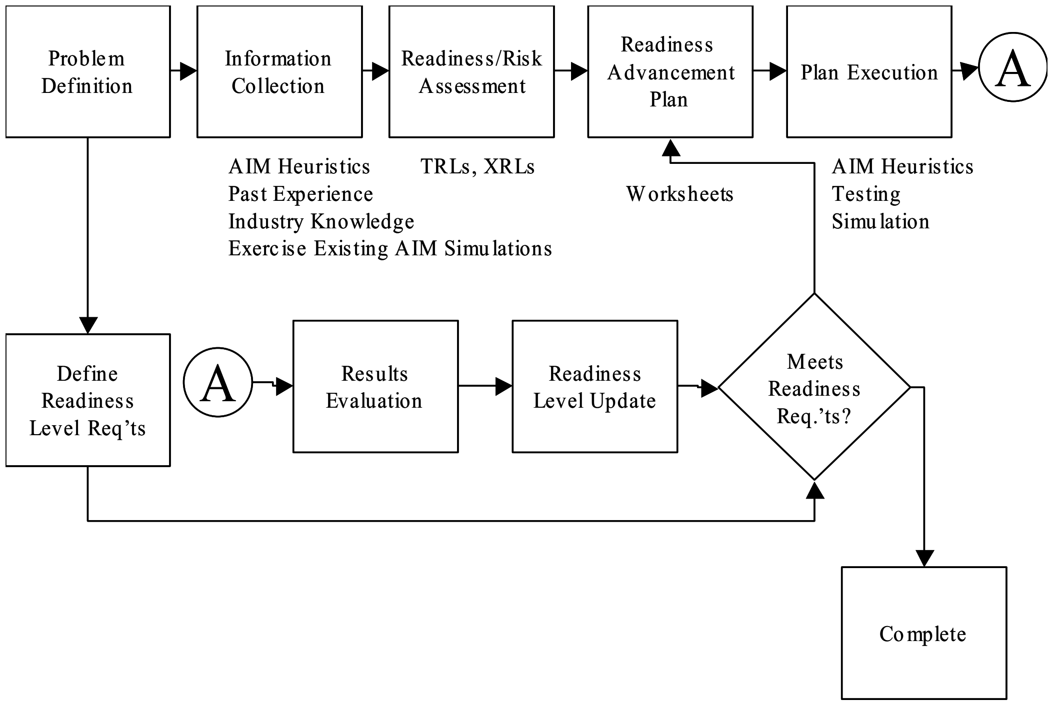


Figure 11-7 – Flow for Application of AIM-C Methodology

Figure 11-8 shows a typical mesh as generated by the AIM-C processing module parametric hat mesh generator. The decision to develop a parametric mesh generator as part of the methodology was based on the desire to be able to quickly accommodate design changes and also offer a tool with future utility for other hat stiffened applications. This is a key to the AIM methodology in order to offer future users a library of models that can be available in the early stages of material insertion to offer some insight into material performance in more complex structure.

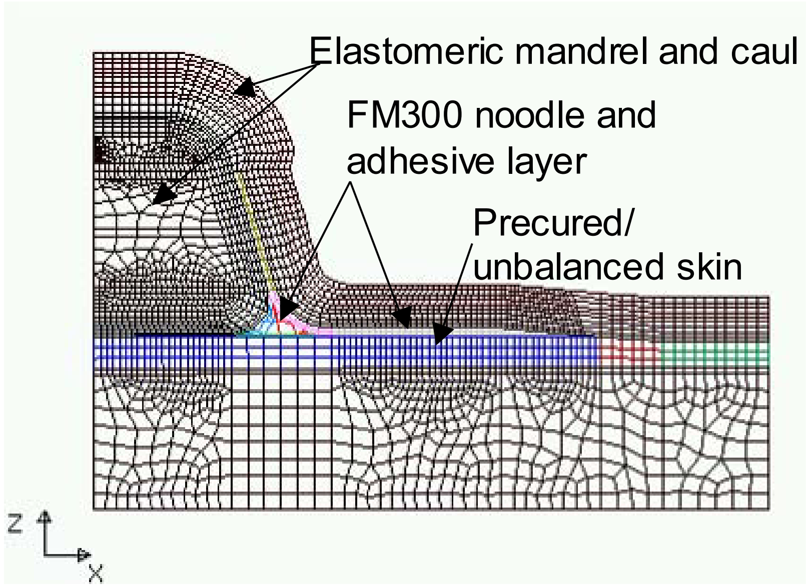


Figure 11-8 – Typical AIM-C Hat Stiffened Panel Processing Module Simulation Mesh

The methodology represented in Template 12 which is described in Figure 11-9 can be applied to any class of structures. The key ingredients are the pre and post processors which allow the insertion and extraction of key variables of interest. Investing in this architecture allows rapid reassessment of configurations and processing conditions when unexpected events occur.

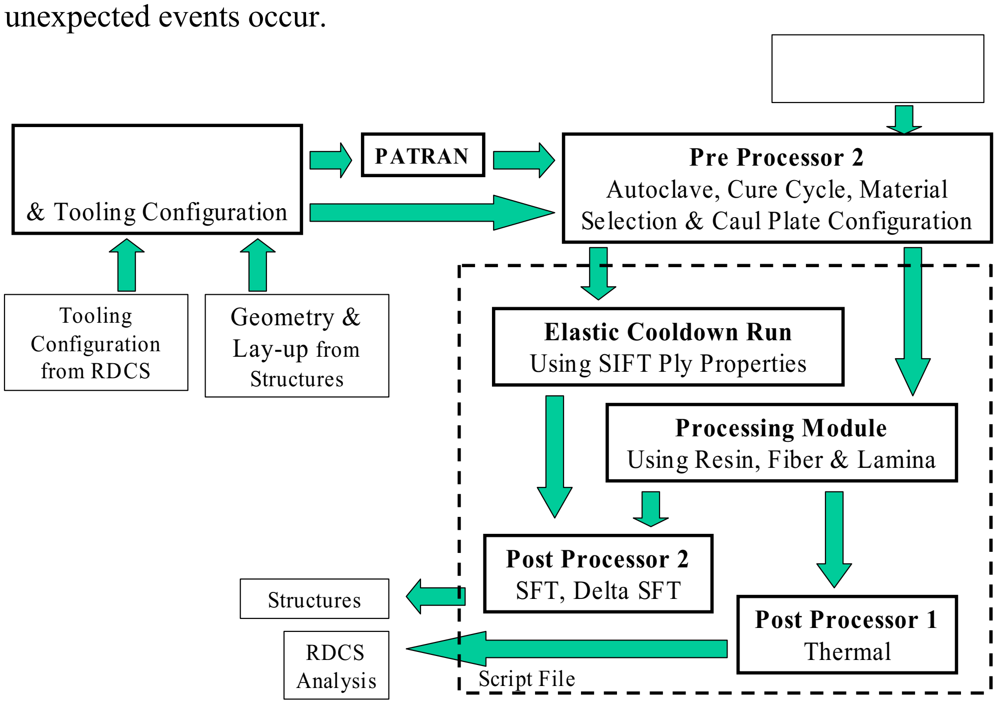


Figure 11-9 – Template 12 Flow Chart

Going into this segment of process development it was understood from previously performed tooling and part thickness sensitivity studies that meeting temperature requirements would not be a challenge. Part fabrication iteration was ultimately necessary to resolve some over consolidation issues which were not anticipated by modeling or simulation. However, with the benefit of hindsight the shortcoming in the simulation were identified (Low CTE value provided by vendor, conservative fill factor and mandrel shape interaction with caul sheet) and corrected. Three additional approaches were explored through simulation and test with success. This is an example of (1) simulation driven test followed by (2) simulation update based on test results and (3) ultimate success through test validation. Had pre-existing hat panel fabrication data been available simulation update and validation may have been possible prior to fabrication of the first test article. This makes a strong case for the AIM methodology where prior insertion cases are documented through data collection not only for process validation but also for comparison to existing simulation results and validation of future simulation results when that simulation capability becomes available for integration into the AIM system.

12. Producibility

The producibility methodology and process follows the overall process for insertion as shown in Figure 12-6. The producibility/fabrication methodology also includes an approach to using this generated information to determine if and how parts can be made to the application requirements. This could be considered a comparison of capabilities to requirements.

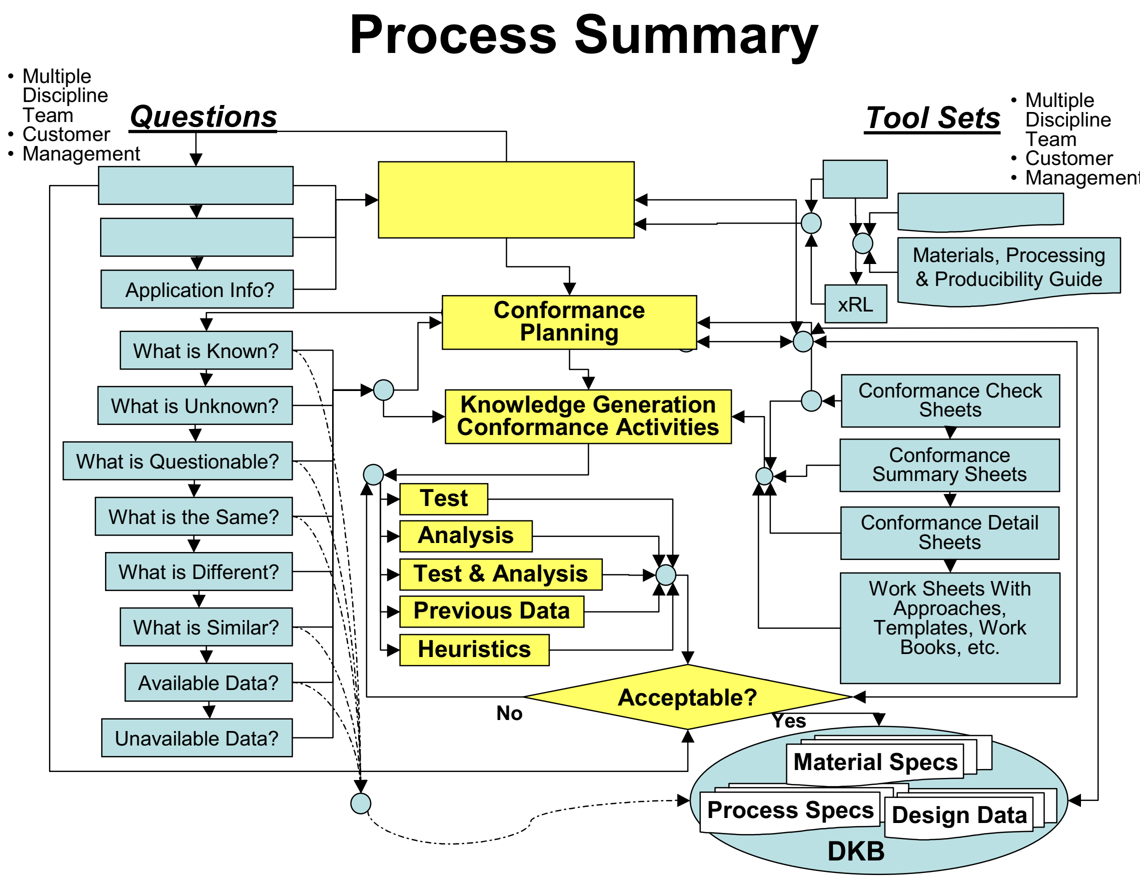


Figure 12-6 Process Summary for Methodology

The following sections give (1) an introduction and overview of the producibility methodology, (2) problem statement-requirements pertaining to producibility, (3) conformance planning, (4) knowledge generation approach, (5) knowledge generation activities and (6) part assessment methodology for producibility.

12.1 INTRODUCTION

Producibility/fabrication activities for new material insertion are conducted by multiple engineering disciplines for producibility on an integrated product team (IPT). These disciplines include Manufacturing, Material and Processing, Tooling, and Quality. The IPT establishes the producibility knowledge base for new materials or processes. This knowledge base information is used along with overall producibility knowledge for application part manufacturing assessments relative to fabrication, quality and tooling (Figure 12-7).

- **Producibility Item Knowledge Generation** Is Conducted When Qualifying and Certifying a New and/or Changed Material and/or Process to Establish the Knowledge Base
- **Part Producibility Assessment** Is Conducted When Answering Questions About Manufacturing Specific Components/Articles Using the Knowledge Base

Figure 12-7 Producibility Assessment Types

The producibility knowledge base covers the manufacturing and quality items shown in Figure 12-8. These are for fabrication only and do not include assembly or assembly related items.

Producibility Operations/Processes	Quality Aspects
• Cutting • Layup • Debulking • Bagging • Cure • Tooling • NDE	• In-process • Final Part

Figure 12-8 Producibility Areas

To achieve accelerated material insertion, there are three stages to establishing producibility information that culminates with a generic, full scale application, feature based demonstration part early for IPT evaluation. These stages (Figure 12-9) are (1) Quick Look assessments, (2) Detailed assessments, and (3) Validation assessments. The first stage rapidly assesses potential show stopper issues that may be encountered with a new material when fabricating components. Stage 2 assesses the producibility details of a new material to establish a producibility knowledge base for specifications, part quality and part producibility assessments. Stage 3 validates that producibility parameters and limits are acceptable for component certification. These three stages correspond to the stages of qualification and certification in the overall program

The Approach for Producibility Item Assessment Provides……………

Activity	Stage 1 Quick Look	Stage 2 Detailed Assessments	Stage 3 Validations
Purpose	Define Item Variable Parameters	Define Item Parameter Limits	Validate Item Parameters
Feature Based Parts	• Flat Panel • Ramped Panel • Generic Full Scale Part	• Multi-Thickness Panels • Ramped Panel • Generic Part Element	• Full Scale Generic Application Component

……………..Knowledge for Qualification and Certification Along with Knowledge for Part Producibility Assessments

Figure 12-9 Producibility Item Assessments in Three Stages with Feature Based Parts

Producibility is a subset of the overall AIM-C approach and directed at capability for qualification and certification. A comparison of the overall AIM-C approach and producibility approach is shown in Figure 12-10.

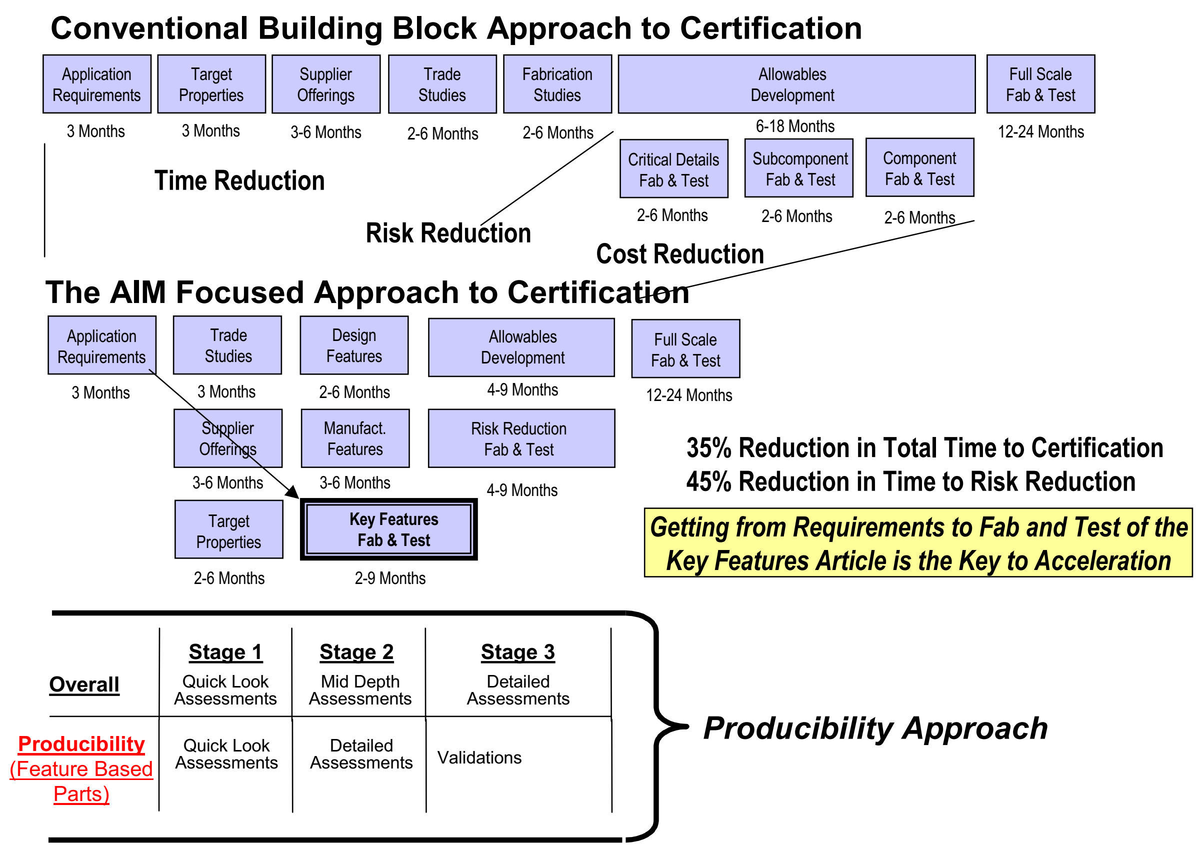


Figure 12-10 AIM Focused Approach for Qualification and Certification

Producibility knowledge generation for accelerated insertion follows the overall process of Problem Statement-Application Requirements, Conformance Planning, Knowledge Generation-Conformance Activities, and Conformance Assessments (Figure 12-11). The generated producibility knowledge for a new material or process is added to the general producibility knowledge base for specific part producibility assessments. These specific part producibility assessments are aimed at answering the questions of (1) Can the part be made? (2) What will be the quality of the part? (3) What are the tooling options for the part?

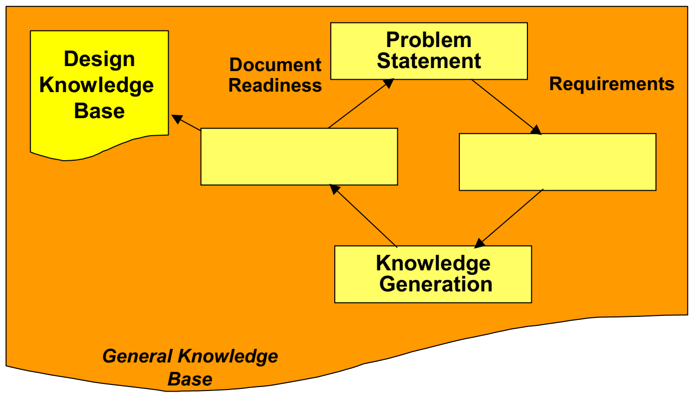


Figure 12-11 Overall AIM-C Process for Material/Process Insertion

For producibility, the process is to identify requirements within the problem statement, establish conformance planning documents, obtain knowledge base information and use it for part producibility assessments. This process is shown in Figure 12-12 going from the problem statement through use of the information.

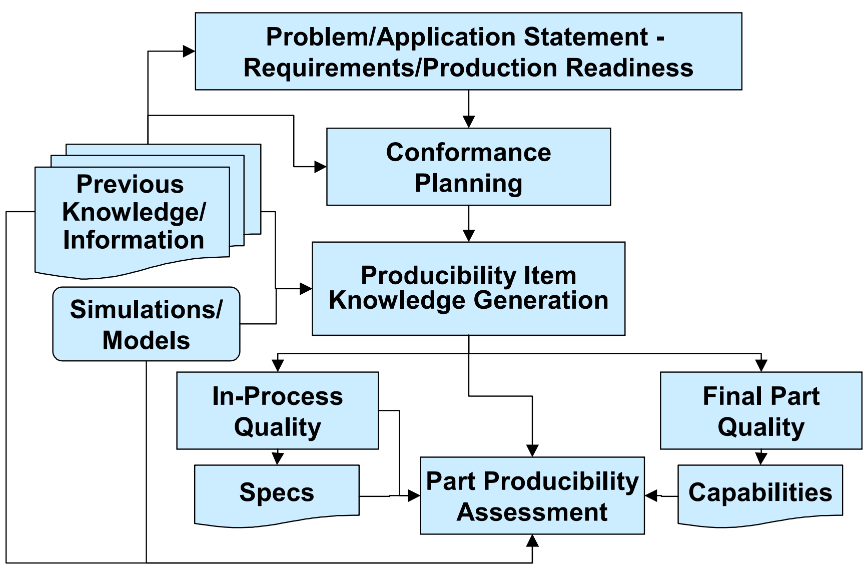


Figure 12-12 Overall Producibility Process

12.1.1 Benefits of This Producibility Methodology

The following chart (Figure 12-8) summarizes the features and benefits of the producibility approach and process. There are two primary payoffs from the producibility approach and process. First is early show-stopper identification. Second is evaluation of the broad producibility picture for the application thereby minimizing the potential rework because of encountering it during actual part fabrication late in the certification process.

Feature	Benefit
Qualification + Certification	Full Identification of Why Producibility Activities are being Conducted Relative to the Problem/Application Statement
Production Readiness	Unique Addition to Requirements
Producibility Knowledge Generation and Part Producibility Assessment As Two Different Producibility Activity Types	Enables Establishing and Using Producibility Knowledge for General and Part Specific Needs
Producibility Item Knowledge Generation With In-Process and Final Part Quality	Enables Guideline/Specification Generation and Part Quality Capabilities With Substantiated Data
Feature Based Application Part Assessment	Generically Applicable to All Applications
Defined, Generic Process	Flexible to Allow Various User View Points
Problem Statement + Requirements + Conformance + Usage	Gives Complete Producibility Picture of Why, What, When, and How

Figure 12-13 Features and Benefits from Producibility Approach/Process

12.2 PROBLEM STATEMENT – REQUIREMENTS

Component requirements flow down to the TRL chart for specific exit criteria according to categories of disciplines or areas. Figure 12-14 highlights Producibility/fabrication exit criteria going from a TRL of 1 through 10 and is primarily based on successful part fabrication. For new material insertion, the primary producibility TRL goal is 4. This essentially means that stability has been demonstrated with multiple parts and that final process specification exist. The intent for this stability is to enable generation of design allowables, subcomponents and components for certification. Previous experience has shown that stability has not been achieved for applications with scale up and this necessitated significant rework because of being a potential show stopper. For this reason, the TRL exit criteria for levels 2 and 3 address application featured generic elements, subcomponents and full-scale components to minimize risk at the time of actual application component fabrication.

TRL	1	2	3	4	5	6	7	8	9	10
Application Risk	Very High	High	High - Med	Med - High	Medium	Med - Low	Low	Low - Very Low	Very Low	Negligible
Application Maturity	Concept Exploration	Concept Defintion	Proof of Concept	Preliminary Design	Design Maturation	Component Testing	Ground Test	Flight Test	Production	Recycle or Dispose
Certification	Certification Elements Documented	Certification Plan Documented	Certification Plan Approved	Preliminary Design Allowables	Subcomponent Testing	Full Scale Component Testing	Full Scale Airframe Tests	Flight Test	Production Approval	Disposal Plan Approval
Design	Concept Exploration/ Potenital Benefits Predicted	Concept Defintion/ Applications Revised by Lamina Data (Coupons)	Applications Revised by Laminate Data (Coupons)/ Design Closure	Applications Revised by Assy Detail Test Data (Elements)/ Preliminary Design	Applications Revised by Subcompnent Test Data/ Design Maturation	Applications Revised by Component Test Data/ Ground Test Plan	Applications Revised by Airframe Ground Tests/ Flight Test Plan	Production Plan	Production Support	Disposal Support
Assembly	Assembly Concept	Assembly Plan Defintion	Key Assembly Detail Defintions	Key Assembly Details Tested	Subcomponents Assembled	Components Assembled	Airframe Assembled	Flight Vehicles Assembled	Production	Disassembly for Disposal
Structures	Preliminary Properties-Characteristics	Initial Properties Verified by Test	Design Properties Developed	Preliminary Design Allowables	B-Basis Design Allowables	A-Basis Design Allowables			Flight Tracking/ Production Spport/ Fleet Support	Retirement for Cause
Materials	Lab Prototype Materials	Pilot Production Materials	Pre-Production Materials	Production Materials/ Material Specs			EMD Material Supplied	LRIP Material Supplied	Production Material Supplied	Support for Recycle or Disposal Decisions
Fabrication	Unfeatured-Panel Fabrication	Feature Based Generic Small/Subscale Parts Fabricated	Property-Fab Relationships Tested/ Target Application Pilot Production of Generic Full Size Parts	Process Specs/ Effects of Fab Variations Tested/ Elements Fab'd/ Production Representative Parts Fab'd	Subcompnents Fab'd	Full Scale Components Fabricated	EMD Fabrication	Low Rate Initial Production (LRIP)	Production	Recycle or Disposal
Cost Benefits	Cost Benefit Elements ID'd & Projected	ROM Cost Benefit Analysis	Cost Benefit Analysis Reflect Size Lessons Learned	Cost Benefit Analysis Reflect Element and Production Representative Part Lessons Learned	Cost Benefit Anlysis Reflect Subcomponent Fab & Assembly Lessons Learned	Cost Benefit Anlysis Reflect Component Fab & Assembly Lessons Learned	Cost Benefit Anlysis Reflect EMD Lessons Learned	Cost Benefit Anlysis Reflect LRIP Lessons Learned	Cost Benefit Anlysis Reflect Production Lessons Learned	Cost Benefit Anlysis Reflect Disposal Lessons Learned
Supportability	Repair Items/Areas Identified	Repair Materials & Processes Identified	Repair Materials & Processes Documented	Fab Repairs Identified	Fab Repair Trials/ Subcomponent Repairs	Component Repairs	Production Repairs Identified	Flight Qualified Reapirs Documented	Repair-Replace Decisions	Support for Recycle or Disposal Decisions
Intellectual Rights	Concept Documentation	Patent Disclosure Filed	Proprietary Rights Agreements	Data Sharing Rights	Vendor Agreements	Material and Fabrication Contracts	Production Rate Contracts	Vendor Requal Agreements	Post-Production Agreemtns	Liability Termination Agreements

Figure 12-14 Requirement Flow Down to the TRL Chart for Producibility/Fabrication

The feature based part fabrication approach is for knowledge generation and is compatible with the exit criteria at TRL level 1 through 4. Two issues arose when establishing the producibility methodology/process using the readiness level concept with specific exit criteria.

1. Producibility subdivides into the manufacturing operations/processes of cutting, layup, debulking, bagging, cure, tooling, and NDE where each could be at a different maturity level and not be captured correctly at the upper TRL level.

2. Production readiness for each of the operations/processes in producibility is not captured.

Producibility for fabrication is comprised of several areas or items. These are cutting, layup, debulking, bagging, cure, tooling and non-destructive evaluations (NDE). These would form individual technology readiness level sheets for producibility one level below the top level summary sheet for readiness. Specific exit criteria would be established for each area or item maturity going from concept definition through qualification and into certification.

This readiness level concept then leads to the question of how can production readiness be incorporated into requirements for qualification. Production readiness has a series of generic evaluation categories that have to be addressed, regardless of the technology (materials, processing, producibility, etc.). These are shown in Figure 12-15.

Material	**Final Product Quality**
Processes	**Application Maturity**
Equipment	**Cost Benefit Analysis**
Tooling	**Supportability**
Variability	**Regulatory**
In-Process Quality	**Intellectual Property**

Figure 12-15 Production Readiness Categories

By combining the production readiness categories with XRL maturity step numbering, a generic matrix worksheet can be established where individual blocks can be filled in for exit criteria. Figure 12-16 shows a generic example TRL for production readiness and technology readiness requirements that are applicable for composite materials, processing and producibility. The categories include technical requirements and ones associated with production readiness. Being generic, it covers all assessment areas. It should be noted that not all areas or maturity level exit criteria may be specifically applicable to qualification and certification of materials, processing, producibility or answering of the problem statement.

(x)RL Rating	1	2	3	4	5	
					5.0 - 5.4	5.5 - 5.9
MATERIAL	Material ingredients/ combinations never used previously. No industrial base capability available. Constituent properties and compatibility issues unknown.	Material ingredients/combinations made in a laboratory environment. No industrial base capability available. Constituent properties and compatibility issues identified.	Key material ingredient characteristics identified for processing, quality, and application. Potential approaches identified to remedy incompatibilities.	Critical functions/ characteristics of material/ ingredients demonstrated. New material within state-of-the-art. Indirect material requirements identified. Facility requirements identified.	Proof-of-concept completed for production, properties, and scale-up of material under relevant conditions achieved (including resolving of material incompatibilities).	Material requirements/out based on models and/or prototypes and/or pilot pla relavent environment. Ma capacity (e.g., single sour offshore only, pilot plant, e
PROCESSES	Requires technology never used previously. No industrial base capability available. Constituent properties and compatibility issues unknown.	Requires yields/tolerances/ throughput/scale not previously achieved. New process needed requiring state-of-the-art advance. Critical facility or vendor not available. Process compatibility issues identified.	Key characteristics identified for process, quality, and application. Potential approaches identified to remedy incompatibilities.	Critical functions/ characteristics of processing demonstrated. New process operates within state-of-the-art. Facility requirements identified. Indirect materials or process steps identified.	Proof-of-concept completed for production, properties, and scale-up of process achieved under relevant conditions (including resolving of material incompatibilities). One or more requirements only marginally achievable.	Process requirements/out based on models and/or prototypes and/or pilot pla Marginal capacity (e.g., si source, offshore only, etc)
EQUIPMENT	Appropriate equipment does not exist and/or requirements are not known.	Necessary equipment requirements identified including key technology areas.	Key characteristics identified for process, quality, and application. Characteristics applicable to technology areas and individual equipment pieces.	Critical functions/ characteristics of individual equipment pieces demonstrated. Indirect materials and facility requirements identified. Equipment accuracy requirements defined.	Initial proof-of-concept testing completed including critical scale-up issues.	Integration of equipment parts/systems demonstrat
TOOLING	Appropriate tooling does not exist or requirements are not known.	Necessary tooling requirements identified and includes key technology areas.	Key characteristics identified for process, quality, and application. Characteristics applicable to technology areas and individual equipment pieces.	Critical functions/ characteristics of individual tooling pieces demonstrated. Indirect materials and facility requirements identified. Tooling accuracy requirements defined.	Initial proof-of-concept testing completed including scale-up issues.	Integration of tooling parts/details/systems demonstrated.
VARIABILITY	Drivers of variability unknown or not understood.	Some items of variability identified.	Key drivers of variability identified. Methods of measuring identified.	Variabilities roughly characterized.	Variabilities measured with tests on representative samples/items and used as base line capabilities. Proof-of-concept for scale-up variablity issues identified.	Variability requirements O based on models and/or prototypes and/or pilot pla
QUALITY - IN-PROCESS	Requires technology never used in manufacturing previously. No industrial base capability available	Requires Q/A capability levels not previously achieved.	Key quality characteristics identified.	Critical quality functions/characteristics demonstrated. Indirect material and/or process steps identified. Facility requirements identified. Defects identified	Proof-of-concept for quality practices/procedures/techniques successfully demonstrated including scale-up issues.	Quality requirements/outp based on models and/or prototypes. Defects evalu
QUALITY - FINAL PRODUCT	Requires technology never used in manufacturing previously. No industrial base capability available	Requires Q/A capability levels not previously achieved.	Key quality characteristics identified.	Critical quality functions/characteristics demonstrated. Indirect material and/or process steps identified. Facility requirements identified. Defects identified.	Proof-of-concept for quality practices/procedures/techniques successfully demonstrated including scale-up issues.	Quality requirements/outp based on models and/or prototypes. Defects evalu
APPLICATION MATURITY	New technology required; state-of the art advance. One or more requirements may be unachievable.	Relevant unit problems identified, technologies understood and tested at unit level.	Primary functions/characteristics understood and demonstrated.	Critical functions/characteristics demonstrated; physical phenomena understood.	Component/breadboard successfully tested in relevant environments,OR, existing item requiring major modification tested. One or more requirements only marginally achievable.	Generic small-subscale pr parts or engineering mode successfully tested in rele environments, OR, existin requiring significant modif tested.
COST/BENEFIT ANALYSIS	Cost/benfits not known.	High level costs/benefits identified.	Costs/benefits defined.	Key costs/benfits have had a preliminary assessment for quantification.	Key costs/benfits have been shown in a relavent environment with scale-up.	Key costs/benfits have be shown with models and/or prototypes.
SUPPORTABILITY	Requires repair technology never used before. No capability available.	New repair processes requiring state-of-the-art advanced.	Key characteristics identified for repair processes.	Critical repair functions and characteristics demonstrated.	Proof-of-concept completed for repair procedures under relevant conditions including scale-up issues, OR, major modification of proven repair procedure completed.	Repair requirements OK b on models and prototypes significant modification of repair procedures comple
REGULATORY	Potential problems unknown.	Potential regulatory issues identified.	Federal, state, and local applicable regulations identified (i.e. OSHA, NIOSH, EPA, air, water, building, shipping, etc.).	Regulatory issues understood.	Potential approaches identified to eliminate regulatory concerns.	Initial proof-of-concept tes potential approaches succ completed.
Intellectual Property		Proprietary material and process concepts identified.	Patent disclosures based on data drafted. Trademark and potential trade secret issues identified.	Reduction to practice in progress. Strategy to issue patents or preserve technology as trade secret accepted.	Patent Applications drafted. Trade secret practices in place.	Reduction to practice veri

Figure 12-16 Example TRL Worksheet Chart for Production Readiness Requirement Identification

A TRL chart covering detailed requirements/production readiness summary chart covering qualification and certification is established for each of the producibility items shown in Figure 12-17. In other words, each producibility item has its own TRL chart for requirements and production readiness.

Producibility Operations/Processes

- Cutting
- Layup
- Debulking
- Bagging
- Cure
- Tooling
- NDE

Figure 12-17 Producibility Items

The approach used to generate the detailed requirement summary charts is to ask questions from each block of the generic TRL matrix chart worksheet as to whether it applies to the producibility item. If so, in what way does it apply? This approach ties detailed requirements up through top level TRL requirements for component applications relative to conformance activities

Examples of detailed requirement TRL charts for cutting, layup, debulking and cure are shown in Figure 12-18. The individual TRL sheets for producibility areas and items are in Appendix A.

Figure 12-18. Detailed Requirements TRL Charts for Cutting, Layup, Debulking and Cure.

Conformance Planning

The feature based producibility parts are fabricated at different stages or maturity levels and are a metric of producibility maturity. This maturity aspect of the feature based approach is shown in Figure 12-19 where the darkened box indicates the primary activity maturity with the feature based approach. Flat and ramped panels are the basic parts for producibility assessments and comparisons at all maturity levels to ensure that any specific changes to parameters do not impact overall parameter impact on quality. These sheets for producibility parts fabrication establish a check sheet for what has been made and what has to be made. It is established within a multiple discipline environment with participation and concurrence with customers and customer groups.

Producibility Methodology/Process Steps (Feature Based)

Stage 1 Quick Look Assessments | **Stage 2** Detailed Assessments | **Stage 3** Validation

TRL

Area		Application	0.25	0.50	0.75	1	2	3	4	5	6	7
Producibility Evaluations, In-Process Quality, Final Quality	1	Flat Panels (.125)				X	x	x	x			
	2	Ramped Panels				X	x	x	x			
	3	Multiple Thickness Flat Panels (.08, .125, .250, .5)					X	x				
	4	Generic Elements					X					
	5	Feature Based Full Scale Generic Component				x		X				
Other		Effect of Defects				x	X	x	x			

Note: Flat and Ramped Panels Are Re-made When Matl's or Processes Are Changed

Feature Based Producibility is Used to Establish the Producibility Knowledge Base Through Producibility Item Assessments

Figure 12-19 Producibility Maturity Based on Featured Parts

A detailed description of planned producibility evaluations and knowledge generation for the different areas and items are shown in Figure 12-20. This also forms a check sheet of what is to be done and when it is to be done. The darkened boxes are when the primary activities for that activity will be conducted. There are several activities that generate information through the whole maturity cycle and this information is accumulated for the overall producibility knowledge base.

					TRL						
Operation	**Activity**	**0.25**	**0.50**	**0.75**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Hand Cutting	Requirements				x						
	Spool Information				x						
	Indirect Materials ID/Compatability				x	x					
	Tack, Original				x						
	Tack, Out Time				x		x				
	Tack, Freezer Time						x				
	Variability, Dimensions				x						
	Variability, Angle				x						
	Specification, Draft Items/Areas				x	x					
	Specification, Preliminary						x				
	Specification, Final							x			
Hand Layup	Requirements				x						
	Indirect Materials ID/Compatability				x	x					
	Tack, Original (lay down and removal)				x						
	Tack, Out Time (lay down and removal)				x		x				
	Tack, Freezer Time						x				
	Variability, Dimensions				x						
	Variability, Angle				x						
	Specification, Draft Items/Areas				x	x					
	Specification, Preliminary						x				
	Specification, Final							x			
Debulking	Requirements				x						
	Indirect Materials ID/Compatability				x	x					
	Methods, Plies/Times/Temps/Pressures				x	x					
	Limits, Plies/Times/Temps/Pressures					x					
	Specification, Draft Items/Areas				x	x					
	Specification, Preliminary						x				
	Specification, Final							x			
Bagging	Requirements				x						
	Indirect Materials				x	x					
	Edge Gaps, Initial				x						
	Edge Gaps, Limits					x					
	Specification, Draft Items/Areas				x	x					
	Specification, Preliminary						x				
	Specification, Final							x			
Cure	Requirements				x						
	Initial Times/Temps/Pressures				x						
	Material Combinations				x						
	Limits, Times/Temps/Pressures					x					
	Limits, Heat up/Cool Down/Tooling/Equipment				x	x					
	Specification, Draft Items/Areas				x	x					
	Specification, Preliminary						x				
	Specification, Final							x			
Tooling					x	x	x	x			
NDE					x	x	x	x			

Figure 12-20 Producibility Area/Item Maturity Level Activities

In-process quality addresses item variability that is measured/controlled during individual item or operation execution. For composites producibility, in-process quality variability covers the areas shown in Figure 12-21. The investigations and knowledge generation of in-process variability impact is conducted on each individual item during quick look assessments at Stage 1 (TRL=1) and detailed assessments at Stage 2 (TRL=2) as shown in
Figure 12-22

- **Indirect/Support Materials**
- **Ply Angle**
- **Ply Lap/Gap**
- **Out Time**
- **Freezer Time**
- **Cure Time, Temp, Pressure**
- **Heat-up Rates**
- **Cure Abort Conditions**
- **Debulk Time, Temp, Pressure, Methods**
- **Bagging Gaps, Breathers, Bleeders**
- **NDE Standards**

Figure 12-21 In-Process Quality Items

Area	Item	Activity	0.25	0.50	0.75	TRL 1	2	3	4	5	6	7
In-Process Qulaity	Cutting	Times				x						
		Temperatures				x						
		Dimensions				x						
		Angles				x						
		Indirect Manterial Compatability				x	x					
		Limitations					x					
		Specification, Draft Items/Areas				x	x					
		Specification, Preliminary						x				
		Specification, Final							x			
	Hand Layup	Times				x						
		Temperatures				x						
		Pressures				x						
		Indirect Material Compatability				x	x					
		Dimensions				x						
		Angles				x						
		Limitations					x					
		Specification, Draft Items/Areas				x	x					
		Specification, Preliminary						x				
		Specification, Final							x			
	Debulking	Plies				x						
		Times				x						
		Temperatures				x						
		Pressures				x						
		Indirect Material Compatability				x	x					
		Limitations					x					
		Specification, Draft Items/Areas				x	x					
		Specification, Preliminary						x				
		Specification, Final							x			
	Bagging	Indirect Material Compatability				x	x					
		Edge Gaps				x						
		Limitations					x					
		Specification, Draft Items/Areas				x	x					
		Specification, Preliminary						x				
		Specification, Final							x			
	Cure	Times				x						
		Temperatures				x						
		Pressures				x						
		Aborts					x					
		Limitations					x					
		Specification, Draft Items/Areas				x	x					
		Specification, Preliminary						x				
		Specification, Final							x			
	Other	Out Time				x		x				
		Freezer Time						x				

Figure 12-22 In-Process Quality Area/Item Maturity Level Activities

Final part quality addresses accept/reject criteria commonly used for composite parts (Figure 12-23). The investigation and assessments of final part quality impact is conducted on each individual item during quick look assessments at Stage 1 (TRL=1) and detailed assessments at Stage 2 (TRL=2) as shown in Figure 12-24. These evaluations yield capabilities for material and producibility that is then compared to application requirements to see whether these requirements can be met with the capabilities. This information is also used during part producibility assessments.

- **Geometric Dimensions**
- **Thickness**
- **Voids**
- **Porosity**
- **Inclusions**
- **Surface Waviness**
- **Surface Finish**
- **Fiber Volume/Resin Content**
- **In-Plane Fiber Distortion**
- **Out of Plane Fiber Distortion**

Figure 12-23 Final Part Quality Items

Area	Item	Activity	0.25	0.50	0.75	TRL 1	2	3	4	5	6	7
Final Quality	Voids/ Porosity	Debulking				x						
		Bagging				x						
		Cure				x						
		Flat Panels				x						
		NDE Defect Detectability				x	x					
		NDE Defect Detectability Limits				x	x					
		Ramps				x						
		Multiple Thickness Flat Panels					x					
		NDE Thickness Standards					x					
		Hats					x					
		NDE Multiple Material Standards					x					
		Size Scale up				x		x				
		Specification, Draft Items/Areas				x	x					
		Specification, Preliminary						x				
		Specification, Final							x			
	Delaminations/ Inclusions	Indirect Material Detectability				x						
		Indirect Material Detectability Limits					x					
		Multiple Material Separation Detectability					x					
		Specification, Draft Items/Areas				x	x					
		Specification, Preliminary						x				
		Specification, Final							x			
	Thickness	Material Capability				x						
		Producibility Capability				x	x					
		Specification, Draft Items/Areas				x	x					
		Specification, Preliminary						x				
		Specification, Final							x			
	In-Plane Fiber Distortion							x				
								x				
	Out of Plane Fiber Distortion							x				
								x				
	Other	Effects of Defects					x	x	x			

Figure 12-24 Final Part Quality Area/Item Maturity Level Activities

12.4 Knowledge Generation

The approach for producibility knowledge generation is comprised of two steps. First is to generate the producibility knowledge and information at an item level for each item to satisfy qualification and certification requirements. Second is to summarize information from each item as to its impact on either in-process quality or final part quality. This concept is shown in Figure 12-25.

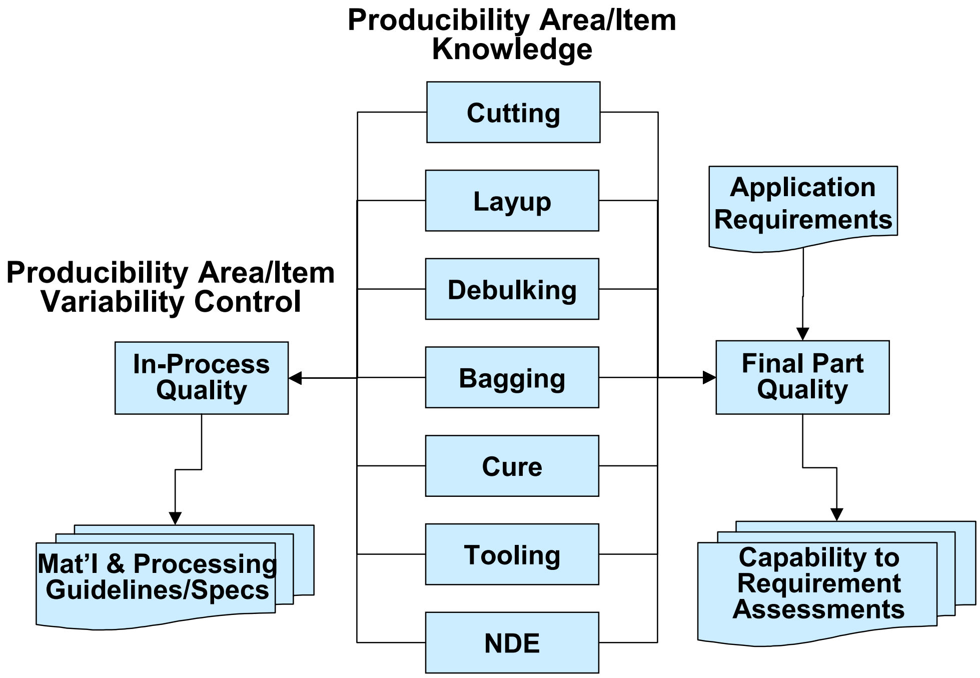


Figure 12-25 Producibility Item Assessment Process

The in-process quality information goes into material and processing guidelines/specification for controls and tolerances. Final part quality information is used for comparisons of capabilities to application requirements as a means of assessing whether the application parts can be made with the materials and producibility operations.

Producibility knowledge generation activities are conducted to establish the knowledge base for qualification and certification using a feature based part approach. This feature based producibility approach is a key aspect of producibility methodology. This approach is based on manufacturing a series of increased complexity parts starting with flat, constant thickness panels going up to full scale generic components based on the application (Figure 12-26). Parameters for producibility areas and items are established using flat and ramped panels. These parameters are then either validated or modified when making multiple thickness flat panels, application elements, and generic full scale components. One of the unique aspects of this approach is that mechanical and physical properties can be obtained during producibility development and utilized for the design knowledge base properties and effects of defects very early in qualification and certification activities. Steps 1, 2, and 3 are applicable to any application that would be considered and evaluation results are used to establish producibility parameters. Steps 4 and 5 are generic components that are based on the application being certified. These parts would contain key features of the application for early producibility evaluations and assessments.

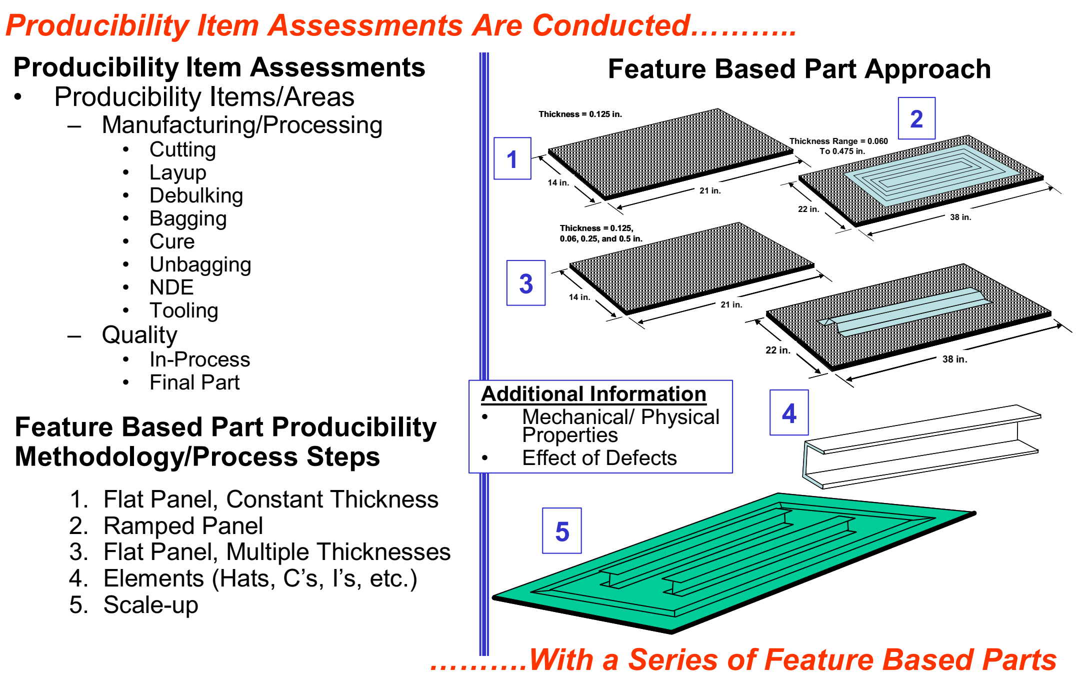


Figure 12-26 Feature Based Producibility Assessment Parts

Producibility knowledge is generated through these different parts at the different maturity levels. Figure 12-27 shows the parts and types of information generated for the knowledge base on producibility at TRL of 1.

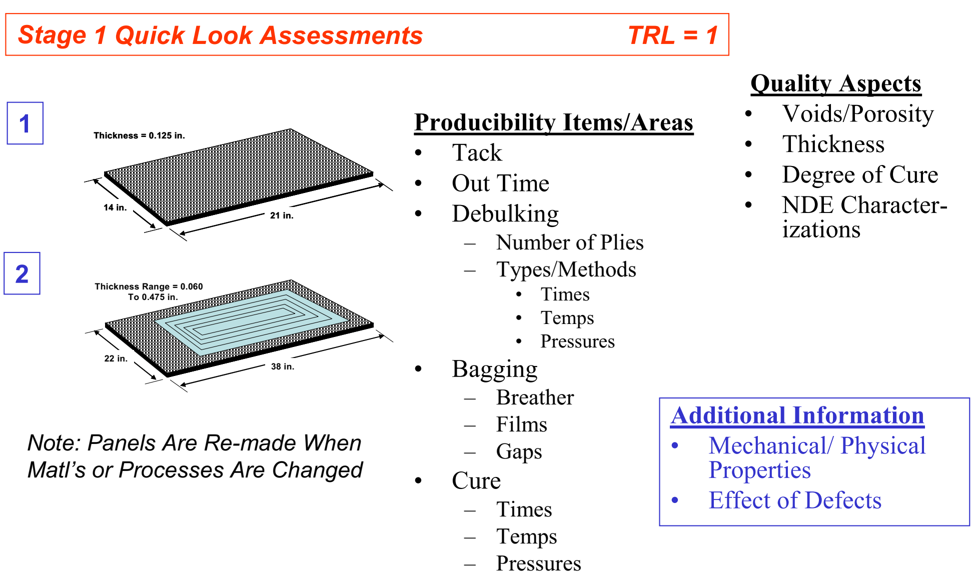
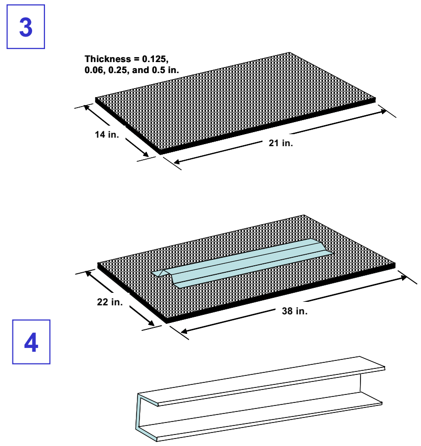


Figure 12-27 TRL = 1 (Stage 1) Parts and Information

Figure 12-28 shows the parts and types of information generated for the knowledge base on producibility at TRL of 2.

Stage 2 In-Depth Assessments TRL = 2



Producibliity Limits
- Tack
- Out time
- Debulking
  - Number of plies
  - Types/Methods
    - Times
    - Temps
    - Pressures
- Bagging
  - Breather
  - Films
  - Gaps
- Cure
  - Times
  - Temps
  - Pressures

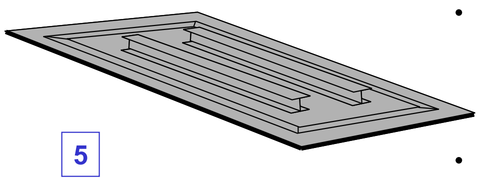
Quality Aspect Limits
- Voids/Porosity
- Thickness
- Degree of Cure
- NDE Characterizations

Additional Information
- Mechanical/ Physical Properties
- Effect of Defects

Figure 12-28 TRL = 2 (Stage 2) Parts and Information

Figure 12-29 shows the parts and types of information generated for the knowledge base on producibility at TRL of 1.

Stage 3 Validation Assessments TRL = 3



Full Scale Generic Application Article for Producibility Evaluations and Structural Evaluations

Producibliity Validation
- Tack
- Out time
- Debulking
  - Number of plies
  - Types/Methods
    - Times
    - Temps
    - Pressures
- Bagging
  - Breather
  - Films
  - Gaps
- Cure
  - Times
  - Temps
  - Pressures

Quality Aspect Validation
- Voids/Porosity
- Thickness
- Degree of Cure
- NDE Characterizations

Additional Information
- Mechanical/ Physical Properties
- Effect of Defects

Figure 12-29 TRL = 3 (Stage 3) Parts and Information

To better understand and describe this feature based approach, an overall process flow chart was established and is shown in Figure 12-30. The different types of symbols are shown in Figure 12-31

A few items to note in this Figure are as follows:

- **A certain amount of material information is required to establish initial producibility parameters**
- **Similar material producibility can be utilized for initial parameters**
- **Lessons learned can also be applied to establish initial parameters**
- **Simulations and modeling can be used for initial parameters and for producibility limits investigations**
- **All panel and producibility results (good and bad) are usable and documented for the knowledge base**
- **Effects of defects are continuously evaluated during all activities.**
- **A full scale component is made very early for quick look assessments and for validation of producibility parameters**
- **The full scale validation component is tested for design property generation/validation too.**
- **Most producibility items are assessed by making parts or with shop trials, but some simulation and models are utilized for their special capabilities**

Process Flow For Feature Based Producibility Assessments …………..

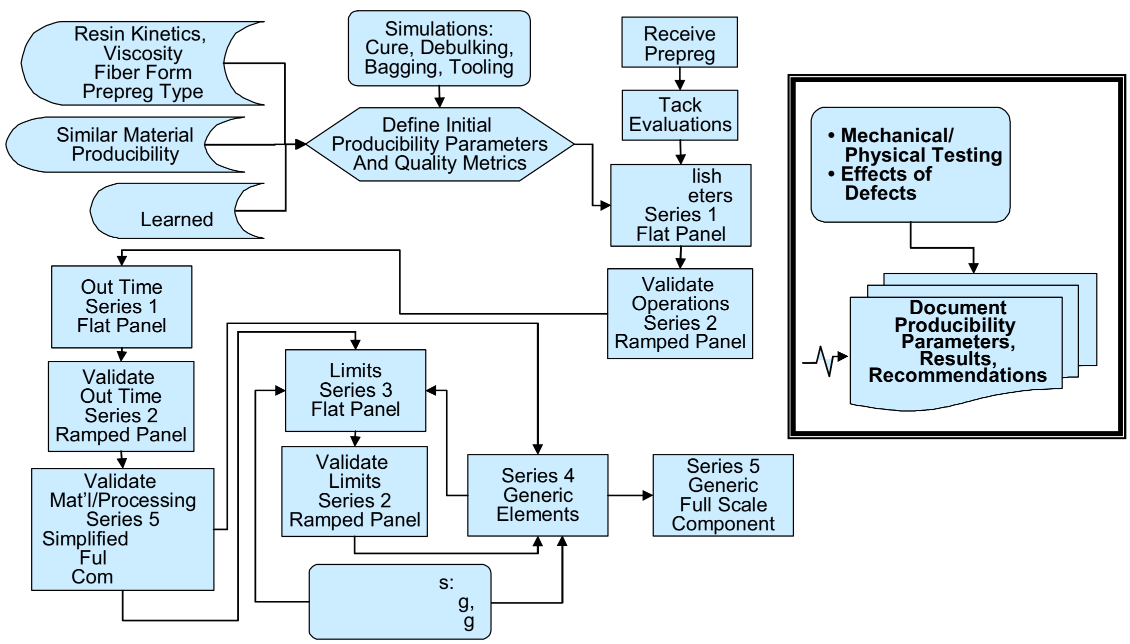


Figure 12-30 Process Flow for Producibility Assessments

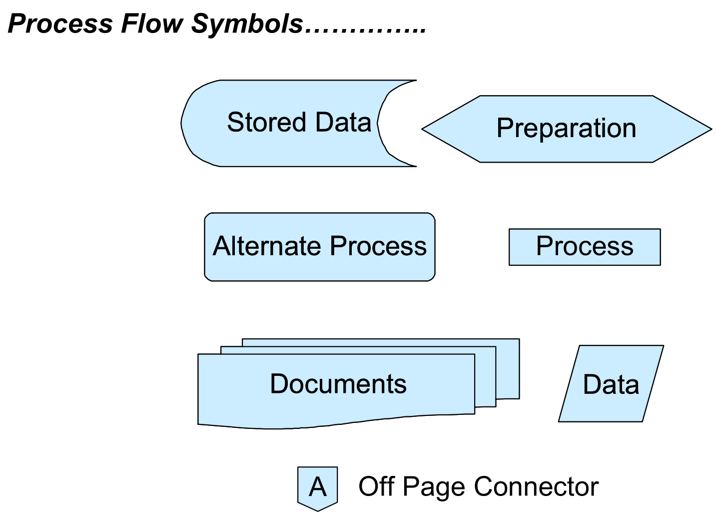


Figure 12-31 Flow Chart Symbols

This overall producibility knowledge generation process flow was broken down into more details at TRL of 1 and TRL of 2. Figure 12-32 shows the TRL 1 activity process flow. Figure 12-33 and Figure 12-34 show the TRL 2 activity process flows.

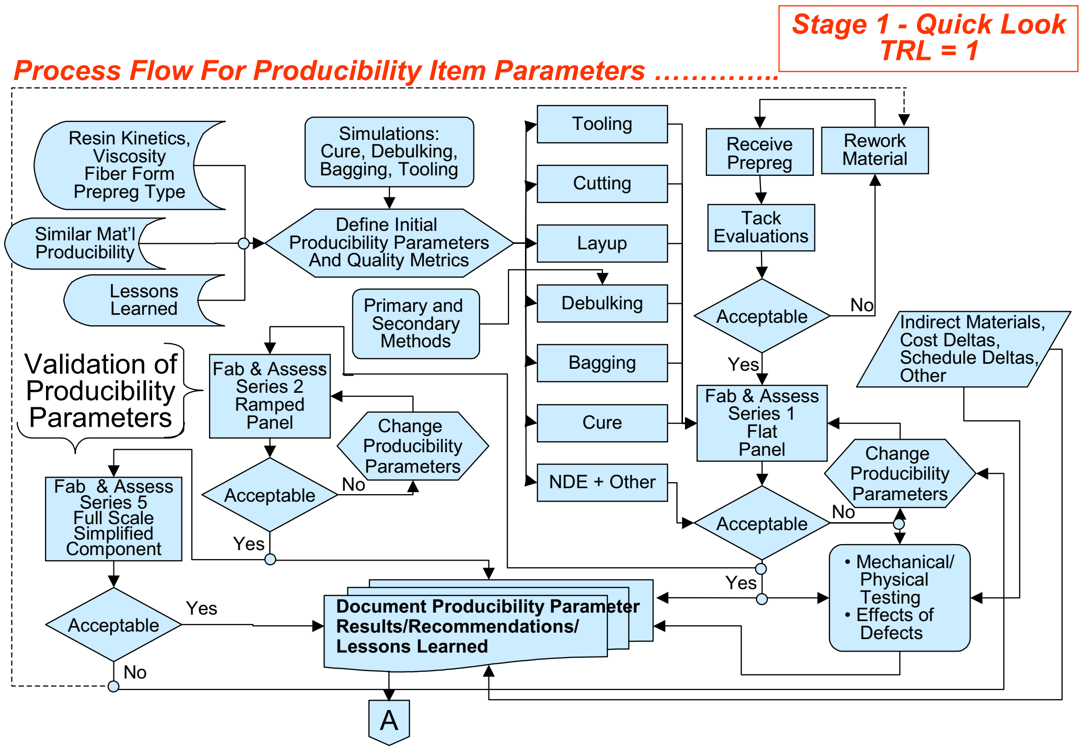


Figure 12-32 Producibility Process Flow for TRL = 1 Activities

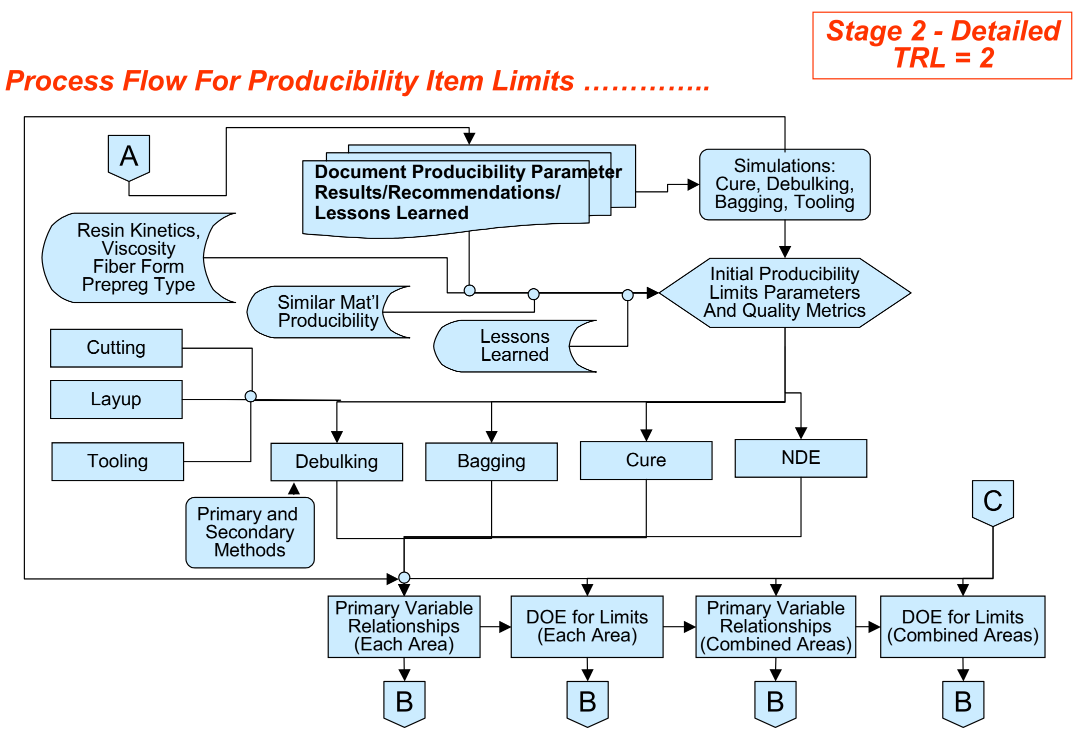


Figure 12-33 Producibility Process Flow for TRL = 2 Activities

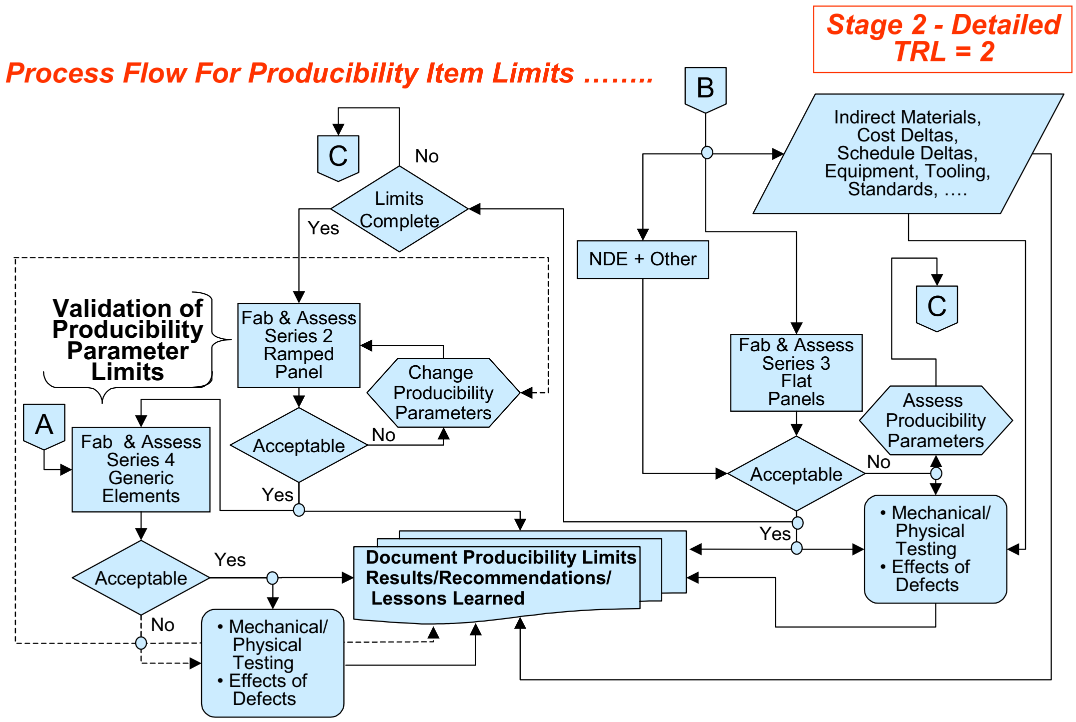


Figure 12-34 Producibility Process Flow for TRL = 2 Activities, Continued

12.5 Part Producibility Assessment

Producibility part assessments are conducted when answering questions about manufacturing application components Figure 12-30. It can be considered as a way of using producibility knowledge base information from producibility item activities, final part quality and other knowledge to answer manufacturing questions in an IPT environment. The size of this is huge relative to application diversity and the needed amount of information is huge.

- **Part Producibility Assessments** Are Conducted When Answering Questions About Manufacturing Specific Components/Articles Using the Knowledge Base

Figure 12-35 Part Producibility Activities

As a step in developing the part producibility assessment methodology, an evaluation was conducted to address producibility information needed at the time of part trade studies on a hat stiffened panel. A review of IPT activities was conducted from a producibility standpoint and results are listed as the seven activities in Figure 12-36. The first three items are from part requirements. Items 4 and 5 are a trade off of manufacturing (final part quality from producibility item assessments) and tooling capabilities (from previous knowledge other than what is generated in the AIM-C process) is compared to requirements. Items 6 and 7 are the producibility operations, in-process quality and final part fabrication.

IPT Activities

1. **ID Defects To Be Minimized**
2. **ID Surface(s) That Need to be Maintained**
3. **ID Acceptable Tolerances**
4. **Define Assembly/ Manufacturing Method**
5. **Define Tooling Approach**
6. **Define Producibility/ Quality Steps**
7. **Make Parts**

Figure 12-36 Integrated Product Team (IPT) Producibility Activities During Trade Studies

By using the feature based part producibility assessment approach, the hat stiffened demonstration (HSD) panel could be broken down into specific features or characteristics as shown in Figure 12-37.

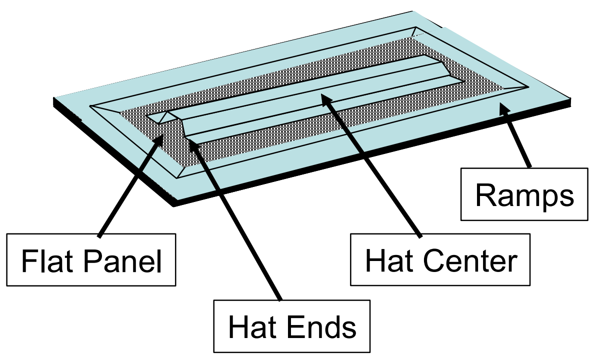


Figure 12-37 Feature Based Part Producibility Concept

When IPT needs were investigated further, what the team really wanted was an identification of part defects and variability relative to tooling options, manufacturing operations and material. The metric that they wanted was dimensions for the different types of variability. Using this information requirement, a six step process was established to utilize the feature based approach for usable producibility information for the IPT during trade studies. These process steps are shown in Figure 12-33. It appears that this is a generic process and can be utilized for any part.

1. Define Configuration
2. Identify Features/ Characteristics
3. Identify Defects Associated With Features/ Characteristics
4. Identify Tooling Options
5. Associate Defects to Tooling, Producibility and Material Areas
6. Quantify Defects Relative to Tooling, Producibility and Material Areas

Figure 12-38 Generic Feature Based Part Producibility Assessment Process

Combining the IPT activities, parts features and feature based assessments gives the overall picture of part assessments in an IPT environment for trade study information. This is shown in Figure 12-34.

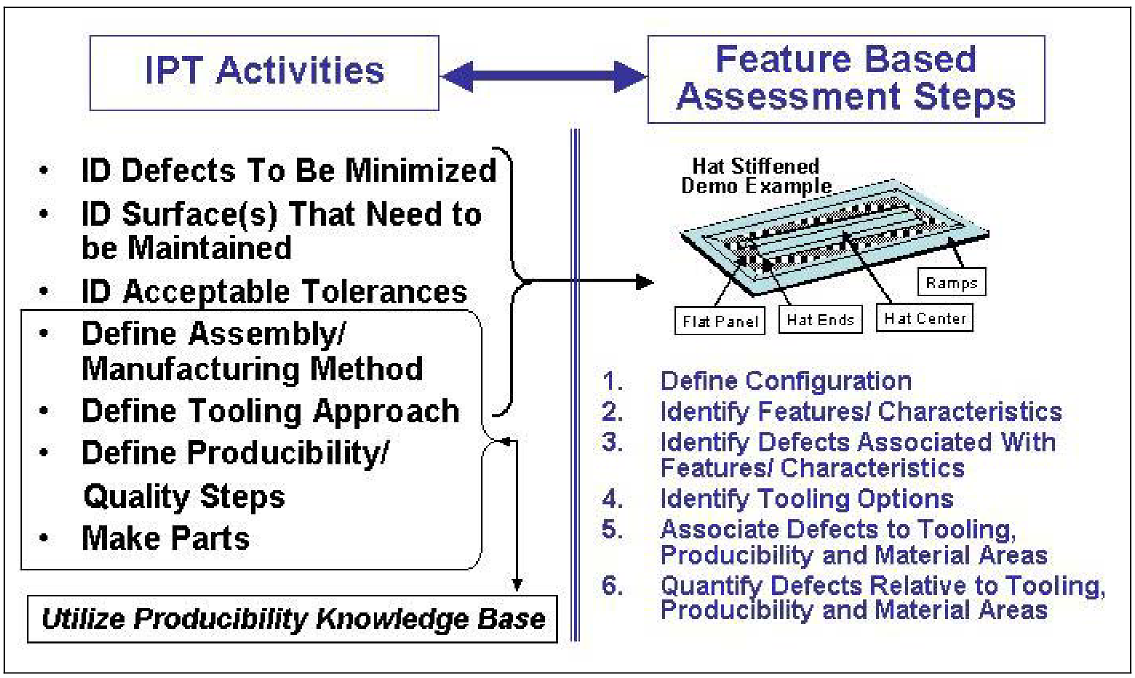


Figure 12-39 IPT Trade Study With Part Producibility Assessment Process

The information or knowledge for assessment steps 2, 3, and 4 comes from previous knowledge or history. Information or knowledge for assessment steps 5 and 6 comes from producibility item assessment results and from previous knowledge or history. One information and history void area is dimensional quantification of defects relative to tooling, producibility and materials. Consequently, results from this part assessment process are very subjective and varies from person to person and company to company according to previous experience and opinion.

12.5.1 Part Producibility Assessment example introduction

The part assessment test case was a hat stiffened panel. This part is shown in Figure 12-40 with the different features identified.

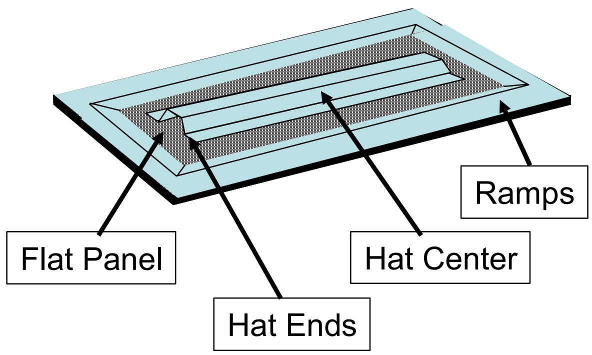


Figure 12-40 Hat Stiffened Part for Part Assessment Activities

The primary part features were flat panels, ramped sections and a hat section with center and end areas. Results from part producibility assessments using the process are described according to the part breakdown into features. The results for these part features are presented in a series of figures that correspond to the assessment steps show in Figure 12-41. Each part feature is evaluated by the process steps. This identifies issues in the overall part by understanding issues at the individual feature level of the part.

1. **Define Configuration**
2. **Identify Features/ Characteristics**
3. **Identify Defects Associated With Features/ Characteristics**
4. **Identify Tooling Options**
5. **Associate Defects to Tooling, Producibility and Material Areas**
6. **Quantify Defects Relative to Tooling, Producibility and Material Areas**

Figure 12-41 Six Step Process for Feature Based Part Assessments

This assessment process uses information from producibility knowledge generation along with overall producibility knowledge. The process itself is generic and applicable to a wide range of parts, but there are several things that need to be noted. Different people with different composites experience and history will come up with different answers. There is no single answer that is correct, but the answers arrived at by following the process will be valid for the individuals or groups using the process and utilizing their overall producibility knowledge.

The following sections cover example assessment results for the part features shown in Figure 12-40

12.5.2Flat Panel Part Feature Assessment Example

The first step for assessment is identification and definition of the configuration. This is shown in Figure 12-37.

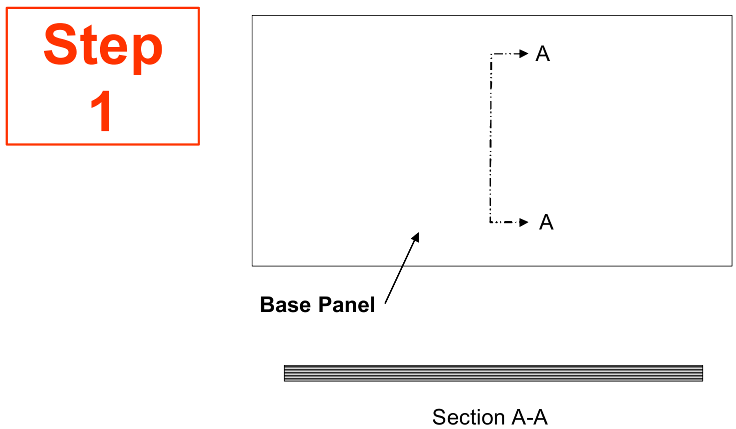


Figure 12-42 Flat Panel Configuration

The second step is identification of features or characteristics associated with the configuration. These are shown in Figure 12-38.

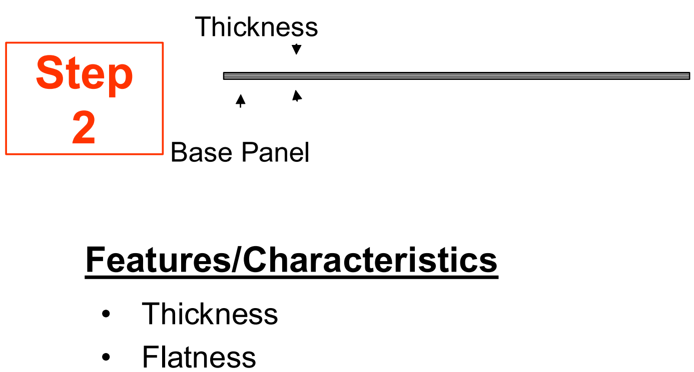
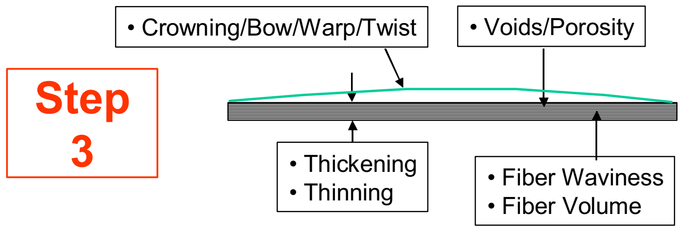


Figure 12-43 Flat Panel Features, Step 2

The third step is identification of defects associated with the configuration or characteristics. These are shown in Figure 12-39.



Defects

- Voids/Porosity
- Thickness
- Flatness
- In-plane Fiber Waviness
- Out of Plane Fiber Waviness
- Resin Content (Fiber Volume)

Figure 12-44 Flat Panel Defects, Step 3

The fourth step is identification of possible tooling options to make the part configuration. These are shown in Figure 12-40.

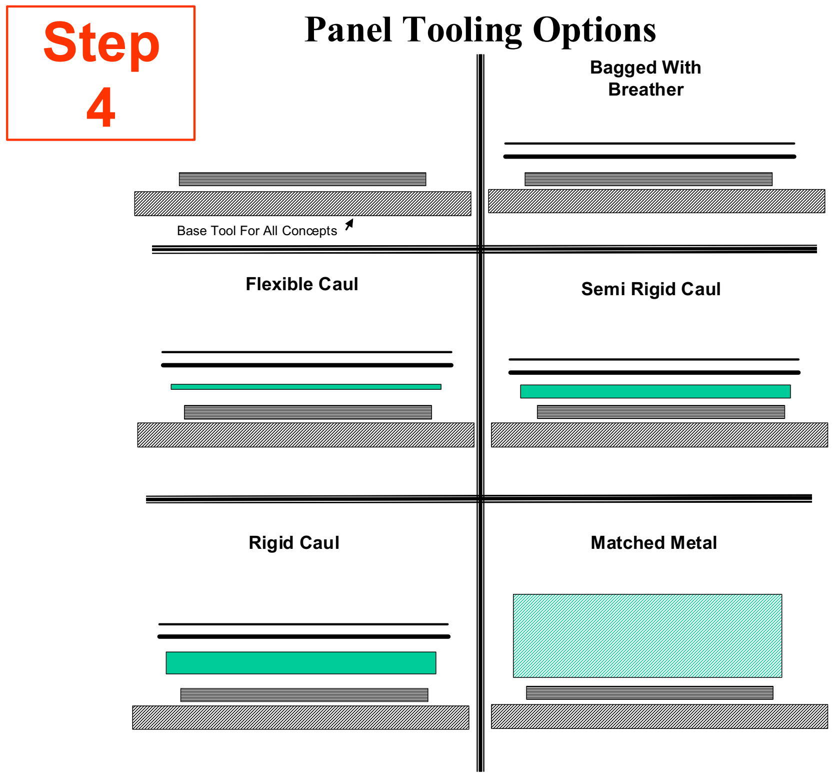


Figure 12-45 Flat Panel Tooling Options, Step 4

The fifth step is association of defects to tooling options, producibility areas and items and material. The matrix of these associations is shown in Figure 12-41.

Step 5 — Panel Defects	Tooling	Cauls				Producibility							Mat'l
	None (Bag)	Flexible	Semi Rigid	Rigid	Matched Metal	Cutting	Layup	Debulking	Bagging	Cure	Unbagging	Trimming	Prepreg
Center Out to Edges													
Thinning	x	x	x					x	x				x
Thickening	x	x	x					x					x
Voids/Porosity								x	x	x			x
Fiber Waviness (Out of plane)	x	x	x	x	x		x	x	x	x			x
Fiber Waviness (In-plane)	x	x	x	x	x		x	x	x	x			x
Surface Finish/Roughness	x	x	x					x	x				
Crowning/Warp/Bow/Twist (Flatness)													
Edges													
SAME AS ABOVE													
Net - (Thinning - Fiber Variation)	x	x	x	x	x	x	x	x	x	x			

Figure 12-46 Flat Panel Defect Mapping to Tooling, Producibility, Material Matrix, Step 5

The sixth step is quantification of the defect associations identified in step five. Figure 12-42 show these quantifications.

Step 6 Panel Defects	Tooling: None (Bag)	Tooling: Cauls: Flexible	Tooling: Cauls: Semi Rigid	Tooling: Cauls: Rigid	Tooling: Matched Metal	Producibility: Cutting	Producibility: Layup	Producibility: Debulking	Producibility: Bagging	Producibility: Cure	Producibility: Unbagging	Producibility: Trimming	Mat'l: Prepreg
Center Out to Edges													
Thinning	<0.015	<0.015	<0.01	<0.003	<0.003			x	x				x
Thickening	<0.015	<0.015	<0.01	<0.003	<0.003			x					x
Voids/Porosity	<1%	<1%	<1%	<1%	<1%			x	x	x			x
Fiber Waviness (Out of plane)	<.015	<.015	<.005	<.005	<.005		x	<.015	<.015	x			x
Fiber Waviness (In-plane)	<.015	<.015	<.005	<.005	<.005		x	x	x	x			x
Surface Finish/Roughness	±.003 to .015	±.003 to .015	<±.010	<±.003	<±.003			±.003 to .015	±.003 to .015				
Crowning/warp/Bow/Twist (Flatness)	Varies According to Layup and Geometry												
Edges													
SAME AS ABOVE													
Net - Thinning	(-20%)	(-20%)	(-10%)	(-2%)	(-2%)	±.020	±.050	-10%	-10%	x			

Figure 12-47 Flat Panel Defect Quantification, Step 6

12.5.3 Ramped Panel Part Feature Assessment Example

The first step for assessment is identification and definition of the configuration. This is shown in Figure 12-43.

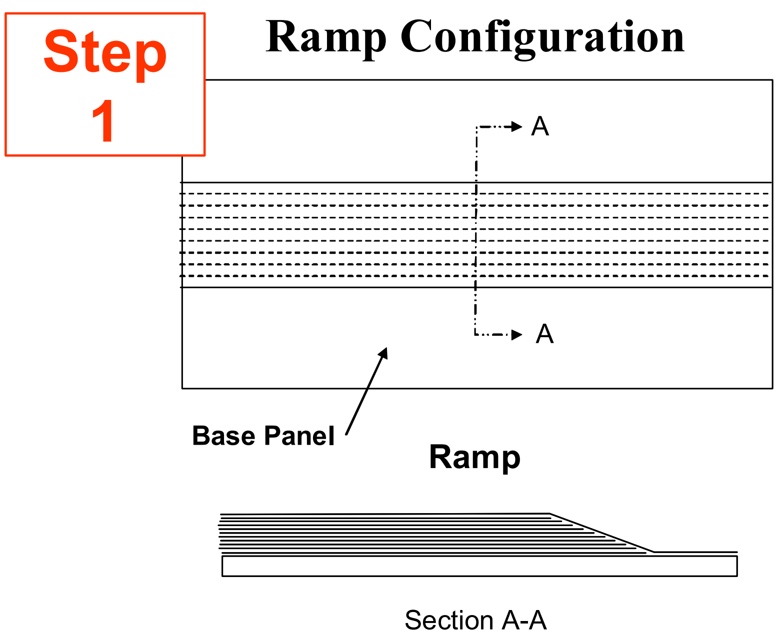
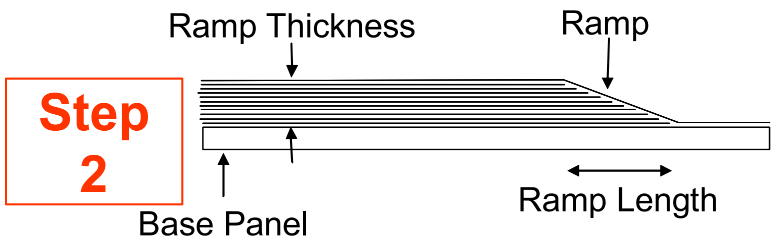


Figure 12-48 Ramp Configuration, Step 1

The second step is identification of features or characteristics associated with the configuration. These are shown in Figure 12-44.

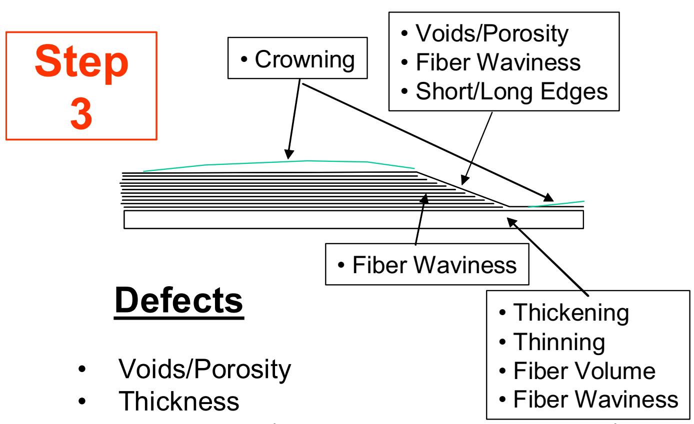


Features/Characteristics

- Ramp Thickness
- Ramp Length to Thickness Ratio
- Edge Terminations
- Base Panel

Figure 12-49 Ramp Features/Characteristics, Step 2

The third step is identification of defects associated with the configuration or characteristics. These are shown in Figure 12-45.



Defects

- Voids/Porosity
- Thickness
- Dimensions (Length, Width, Height, Radii)
- Flatness
- In-plane Fiber Waviness
- Out of Plane Fiber Waviness
- Resin Content (Fiber Volume)

Figure 12-50 Ramp Defects, Step 3

The fourth step is identification of possible tooling options to make the part configuration. These are shown in Figure 12-46.

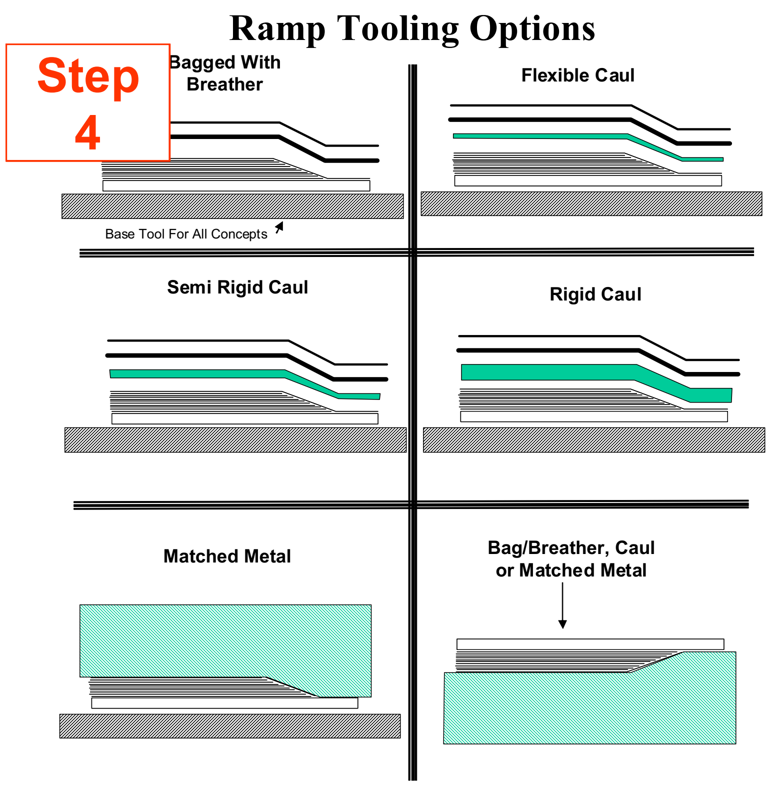


Figure 12-51 Ramp Tooling Options, Step 4

The fifth step is association of defects to tooling options, producibility areas and items and material. The matrix of these associations is shown in Figure 12-47.

Step 5 — Ramp Defects	Tooling	Cauls				Producibility							Mat'l
	None (Bag)	Flexible	Semi Rigid	Rigid	Matched Metal	Cutting	Layup	Debulking	Bagging	Cure	Unbagging	Trimming	Prepreg
Ramp Area													
Long Edges			x	x	x	x	x						
Short Edges			x	x	x	x	x						
Fiber Waviness	x	x					x	x	x	x			
Voids/Porosity								x	x	x			
Surface Finish/Roughness	x	x							x				
Ramp End to Flat Area After Ramp													
Thinning	x	x	x					x	x	x			
Thickening	x	x	x	x	x			x	x	x			
Fiber Waviness	x	x	x				x	x	x	x			
Flat Area Before/After Ramp													
Crowning	x	x	x					x	x				
Surface Finish/Roughness	x	x						x	x				
Thinning/Thickening	x	x	x	x	x								x

Figure 12-52 Ramp Defect Mapping to Tooling, Producibility, Material Matrix, Step 5

The sixth step is quantification of the defect associations identified in step five. Figure 12-48 show these quantifications.

Step 6

Ramp Defects	Tooling					Producibility							Mat'l
		Cauls											
	None (Bag)	Flexible	Semi Rigid	Rigid	Matched Metal	Cutting	Layup	Debulking	Bagging	Cure	Unbagging	Trimming	Prepreg
Ramp Area													
Long Edges			x	x	x	±.02	±.05						
Short Edges			x	x	x	±.02	±.05						
Fiber Waviness	<±.015	<±.015	<±.015	<±.015	<±.015		±.015	±.015	±.015	x			
Voids/Porosity	<1%	<1%	<1%	<1%	<1%			1%-2%	1%-2%	x			
Surface Finish/Roughness	±.003 to ±.015	±.003 to ±.015	<±.005	<±.002	<±.002			±.003 to ±.015	±.003 to ±.015				
Ramp End to Flat Area After Ramp													
Thinning	<.005	<.01	<.005					x	x	x			
Thickening	<.005	<.01	<.01	<.01	<.01			x	x	x			
Fiber Waviness	<.015	<.015	<.005	<.005	<.005		<.005	<.005	<.005	x			
Flat Area Before/After Ramp													
Crowning	<.015	<.015	<.01	<.002	<.002			<.015	x				
Surface Finish/Roughness	±.003 to ±.015	±.003 to ±.015	<±.005	<±.002	<±.002			±.003 to ±.015	±.003 to ±.015				
Thinning/Thickening	<.015	<.015	<.01	<.01	<.01								x

Figure 12-53 Ramp Defect Quantification, Step 6

12.5.4 Hat Stiffener Part Feature Assessment Example

The first step for assessment is identification and definition of the configuration. This is shown in Figure 12-49.

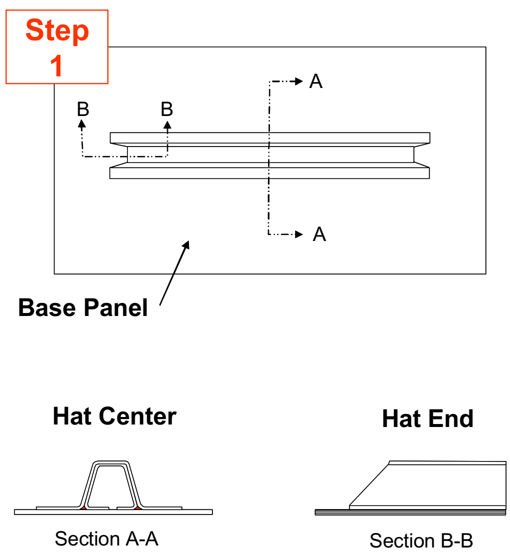
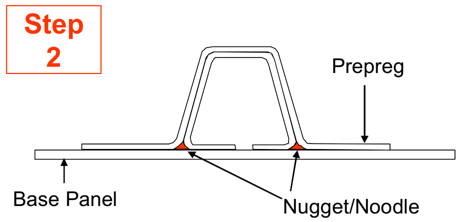


Figure 12-54 Hat Configuration, Step 1

The second step is identification of features or characteristics associated with the configuration. These are shown in Figure 12-50.



Features/Characteristics

- Inside Corners/Radii
- Outside Corners/Radii
- Nugget/Noodle
- Multiple Materials
- Flat Surfaces
- Edge Terminations
- Base Panel

Figure 12-55 Hat Features, Step2

The third step is identification of defects associated with the configuration or characteristics. These are shown in Figure 12-51 and 12-52.

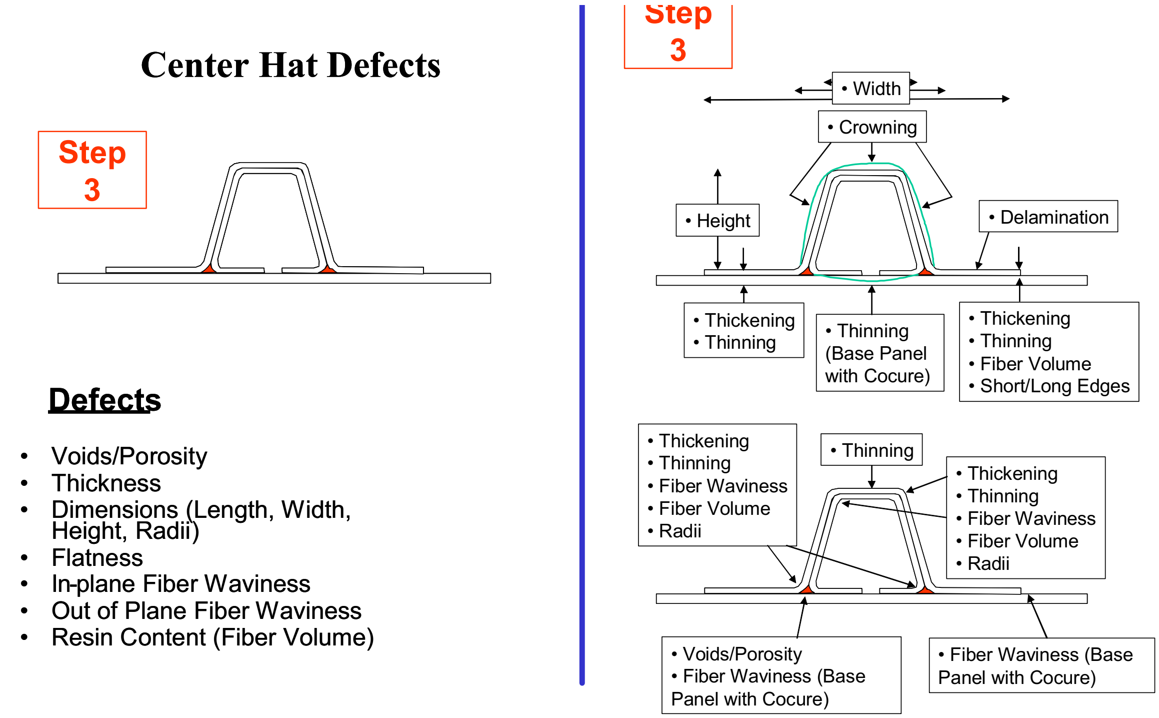


Figure 12-56 Hat Defects, Step 3

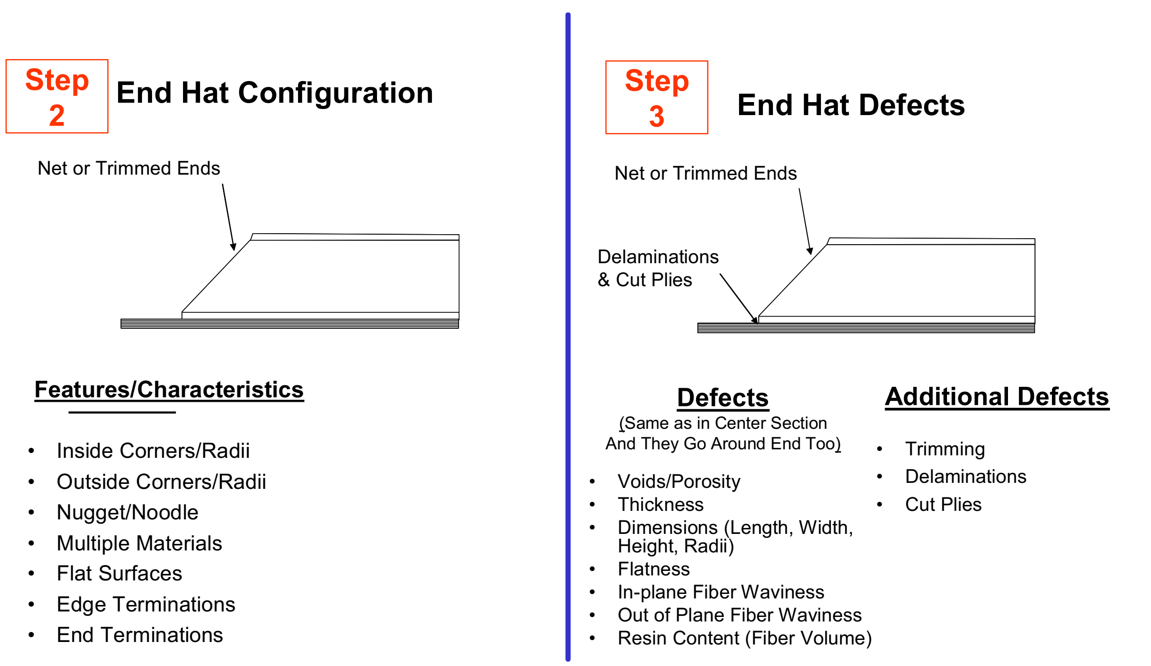


Figure 12-57 End Hat Features and Defects, Steps 2 and 3

The fourth step is identification of possible tooling options to make the part configuration. These are shown in Figure 12-53.

Step
4

Cocured Hat Tooling Options

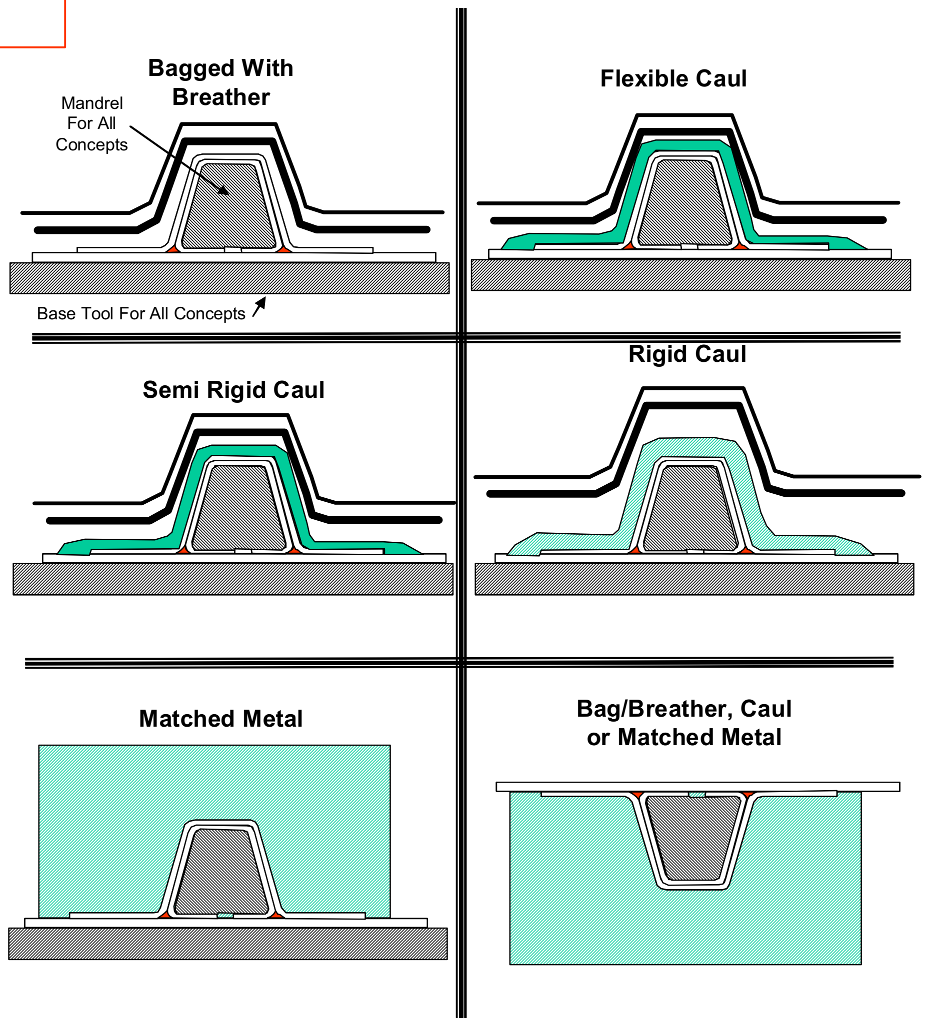


Figure 12-58 Hat Tooling Options, Step 4

The fifth step is association of defects to tooling options, producibility areas and items and material. The matrix of these associations is shown in Figure 12-54.

Step 5 — Hat Defects	Tooling							Producibility							Mat'l
			Cauls												
	Mandrel	None (Bag)	Flexible	Semi Rigid	Rigid	Matched Metal	End Shims	Cutting	Layup	Debulking	Bagging	Cure	Unbagging	Trimming	Prepreg
Center															
Top Crown	x	x	x	x							x	x			
Side Crown	x	x	x	x							x	x			
Top Thinning	x	x	x	x	x	x					x	x			
Bottom Thinning	x			x	x	x						x			
Upper Radii Thickening	x			x	x	x			x	x	x	x			
Upper Radii Thinning		x	x						x	x	x	x			
Upper Radii Fiber Waviness	x	x	x							x	x				
Lower Radii Thickening	x	x	x	x	x	x			x	x	x	x			
Lower Radii Thinning		x	x	x	x	x			x	x	x	x			
Flange Thickening				x	x	x		x	x						x
Flange Thinning								x	x						x
Flange Edge Fiber Volume			x	x				x	x	x					
Flange Edge Fiber Waviness		x	x							x	x	x			
Nugget/Noodle Porosity/Voids									x	x		x			
Nugget/Noodle Fiber Waviness	x	x	x	x	x	x			x	x	x	x			
Surface Finish/Roughness		x	x								x				
Ends															
SAME AS ABOVE															
Net - Fiber Variation		x	x					x	x	x	x	x			
Excess - Cut Fibers														x	
Delamination	x						x						x		
Along Length															
Spacing		x	x	x											
Straightness		x	x												

Figure 12-59 Hat Defect Mapping to Tooling, Producibility, Material Matrix, Step 5

The sixth step is quantification of the defect associations identified in step five. Figure 12-55 shows these quantifications. The text that follows the figure provides an example of how one might use the information provided.

Step 6

Hat Defects	Tooling							Producibility							Mat'l
			Cauls												
	Mandrel	None (Bag)	Flexible	Semi Rigid	Rigid	Matched Metal	End Shims	Cutting	Layup	Debulking	Bagging	Cure	Unbagging	Trimming	Prepreg
Center															
Top Crown	x	< .060	< .060	< .015	<.005	<.005					x	x			
Side Crown	x	< .060	< .060	< .015	<.005	<.005					x	x			
Top Thinning	x	<.015	<.015	<.015	<.015	<.015					x	x			
Bottom Thinning	x	<.01	<.01	<.015	<.015	<.015						x			
Upper Radii Thickening				< .010 (15%)	< .010 (15%)	< .010 (15%)			x	x	x	x			
Upper Radii Thinning	<.01	< .010	< .010						x	<.006	<.01	x			
Upper Radii Fiber Waviness		<.015	<.01							<.006	<.006				
Lower Radii Thickening	<.01	< .010 (15%)	< .010 (15%)	< .010 (15%)	< .010 (15%)	< .010 (15%)			x	<.006	<.006	x			
Lower Radii Thinning	<.01	< .010 (15%)	< .010 (15%)	< .010 (15%)	< .010 (15%)	< .010 (15%)			x	x	x	x			
Flange Thickening					<.01	<.01		x	x						x
Flange Thinning		<.01	<.01	<.005				x	x						x
Flange Edge Fiber Volume			+5%, -60%	+5%, -60%				± .02	± .05	x					
Flange Edge Fiber Waviness		<.03	<.03	<.015						x	x	x			
Nugget/Noodle Porosity/Voids		< 3%, < .5 in2	< 3%, .5 in2	< 3%, < .5 in2	< 3%, < .5 in2	< 3%, < .5 in2			x	x		x			
Nugget/Noodle Fiber Waviness	<.015	<.015	<.015	<.015	<.015	<.015				x	x	x			
Surface Finish/Roughness	<.01	±.003 to ±.015	±.003 to ±.015	<.01	<.002	<.002				±.003 to ±.015	±.003 to ±.015				
Ends															
SAME AS ABOVE															
Net - Fiber Variation		+5%, -60%	+5%, -60%					± .02	± .05	x	x	x			
Excess - Trimming Defects														<.03	
Delamination	x						<.125 in2						<.5 in2		
Along Length															
Spacing		<.125	<.125	<.06	<.06	<.03									
Straightness		<.125	<.125	<.09	<.09	<.09									

Figure 12-60 Hat Defect Quantification, Step 6

The quantified defects for a hat cured using semi-rigid and flexible caul plates are shown in Figure 12-55. There are significantly more defect areas involving this hat due to its greater tooling and processing complexity. Reading down the highlighted columns, the configuration data show an improvement in crowning for the semi-rigid caul plate of 0.015 inch versus 0.060 inch for the flexible caul plate, as the stiffer semi-rigid caul plate reacts better with the thermal expansion of the hat mandrel. A large potential fiber volume decrease, -60%, is seen for both caul plate types. This defect is due to an over-pressure condition during autoclave cure when there is a mismatch between the trim of the hat plies and the caul plate. A large delamination, 0.125 $in^{2,}$ is indicated for an end shim. This value seemed much larger in magnitude than the others and its origin was not clear. Further discussions revealed that the cause of the delamination was the end shim. The qualification of this defect required additional attention and is described in a later paragraph. A 0.5 in^2 delamination caused by unbagging, while also very large by comparison, is due to the skill of the technician. Some data for the configuration and producibility defects still require investigation. The continuation of this process would highlight the location and magnitude of these defects for structural analysis.

Based on a further evaluation of the end shim delamination condition is was determined that a significant hat termination processing feature defect exists.

A review of this feature revealed that the end shim did not exist in the early lay-up of this part but was added later to correct a skin waviness issue. The primary problem was due to the hat mandrel, which extended over the end flange and caused thickness variation, out-of-plane ply waviness (tool mark-off) in the panel flange beyond the hat net trim. A secondary problem was also revealed. During the mechanical trimming operation to achieve the flush hat termination, potential damage to the flange surface plies could occur.

The solution was to add thin end shim (caul plate) in the flange area between the part surface and the hat mandrel that also separated the oversize hat plies from the skin. This may not have been a concern initially because these plies would be trimmed back to the end of the end shim.

The result was a successful improvement to ply waviness problem and protection of the flange laminate during trimming operation.

The unintended consequence was the introduction of another defect between the end of the shim and the trimmed hat laminate. A discontinuity is created at the intersection of the hat termination and the flange laminate as shown in Figure 12-56.

The end shims can create a significant defect that must be included in the analysis of the hat panel. The discontinuity is large (caul plate thickness by hat foot length) it is located at a critical load introduction site for each hat leg and the hat noodles and the discontinuity can occur at both ends of every hat. This evaluation led to a proposed revision to the Feature Based Part Assessment methodology document as shown in Figure 12-57.

Part quality is highly operator/technician skill dependant and could be addressed through awareness training

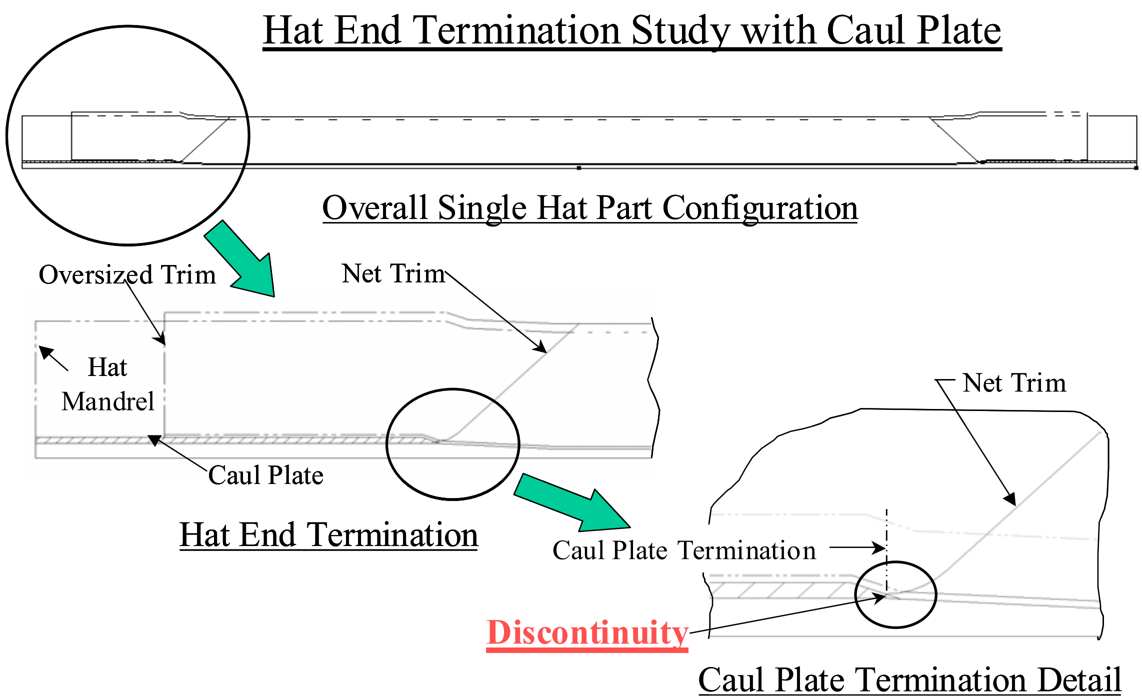


Figure 12-56. Hat End Termination Study with Caul Plate

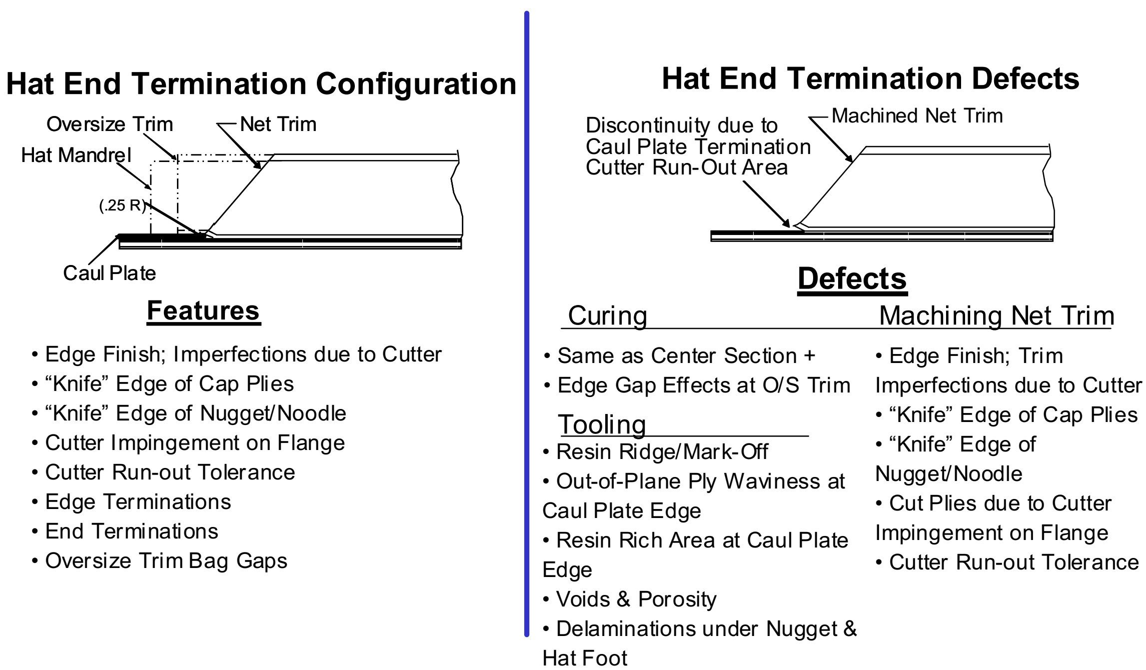


Figure 12-57. Revised Hat End Termination with Caul Plate

13. AIM-C Structures Methodology

This chapter is comprised of four sections. Section 13.1 outlines the general methodology used for the insertion of a new composite material. When a specific AIM-C tool exists to aid this objective it is identified. Section 13.2 discusses the various AIM-C system tools that support generation of preliminary design values. These tools are restricted to those that provide laminate level strength data. Section 13.3 discusses the actual generation of firm design allowables - design allowables being different from preliminary design values. Section 13.4 discusses the Structural Design Process.

13.1 General Methodology to Obtain Preliminary Structural Design Values Using the AIM-C Tool

One may have either a new program in which design values for a new or unused resin/ fiber system is being contemplated or a specific problem which need to be solved in which a new fiber/resin system holds some promise. The steps that follow outline a process or a methodology that may be used in order to obtain preliminary design values using the AIM-C system. When a specific task can be accomplished by the AIM-C system, the AIM-C tool is identified. Once the preliminary design values are obtained it is up to the judgment of the structural engineer in consultation with other design, manufacturing, and processing professionals to use these values directly or to apply a factor(s) to them.

1. **Objective:** Obtain preliminary lamina properties (modulus, etc) so that finite element models of the structure can be built for preliminary analysis. Lamina properties are also needed to predict laminate allowables. Traditionally, lamina properties are obtained from test. However, AIM-C Tools are available to generate these properties given resin and fiber properties.
   TASKS
   1. Enter known data into AIM-C System.
   2. Get material info from Materials (fiber & resin) module.
   3. Check airframe requirements (temperature range, environment, etc).
   4. Run Lamina module to get predicted lamina properties.
   5. Pass lamina properties to IPT's and other AIM-C modules.
   6. Identify additional resin, fiber and prepreg data needed to increase confidence level in predictions for next cycle of allowables predictions (Item 5)

2. **Objective:** Generate preliminary laminate allowables (UNT, UNC, FHT, FHC, OHC, BRG, CSAI) based on nominal parameters. These preliminary allowables will be used to size the structure. Need to include the effects of environment and design features (open vs filled, countersink, hole size, edge distance, etc). Again, this data would all come structural testing. However, AIM-C tools are available to generate some of these properties. Specifically unnotched and open hole tension and compression data (UNT, UNC, OHC, OHT) may be generated for a range of

laminates using the AIMC tool. Some test data is required. At a minimum lamina testing at 10 and 90 degree fiber orientations are required in order to obtain data for the Strain Invariant Failure Theory (SIFT) Method (Template 10). In addition, the point stress method used to generate strength data using Template 21 requires lamina strength data obtained from testing at 0 degree and 90 degree fiber orientations and requires testing of an open hole laminate. The laminate lay up may be common lay up desired for the application but it is best to not use one strongly dominated by +/- 45 degree plies.

TASKS
1. Enter known data into AIM-C System.
2. Get needed info from lamina module.
3. Run Laminate Module or Templates 21 or 10 to get predicted laminate carpet plot data.

3. Preliminary size the part using data generated in previous steps. An AIM-C tool exists for a specific class of structural problem that is the sizing of a hat stiffened panel (Templates 14, 16, and 17).

4. Determine impact of selected materials (components variability, etc.), processes (cure cycle window, etc.), and producibility features (i.e. tooling, part configuration, etc.) on design allowables. Design allowables may need to be refined based on proposed processing, tooling, effects of defects, etc.

5. Pilot batch of material available

First batch of material fabricated using proposed nominal production parameters but on a pilot line.

6. Lamina and laminate tests, including environment, of pilot batch. Number of tests are variable. The objective of these tests is to determine batch variability. This data will be used for extensive structural configuration and sizing exercises by structural designers and engineers.

7. EMD Go ahead

Official start of the Engineering Manufacturing Develop phase. Integrated product teams launch into intense design phase.

8. Update preliminary allowables with pilot batch data

Update previously estimated allowables based on pilot batch data. These allowables will now be available for Concept Layout (CLO). Again, this data will be used for extensive structural configuration and sizing exercises by structural designers and engineers.

9. Production qualification material batches.
The number of batches and testing must be coordinated with Certifying Agency.

10. CLO – Concept Layout
The IPT produces the concept.

11. ALO – Assembly Layout
The IPT produces the initial assembly documentation.

12. BTP – Build To Packages and normal redesign/refinement effort based on coordination with manufacturing

13. Predict in-plane laminate allowables (UNT, UNC, FHT, FHC, OHC, BRG, CSAI). Include environmental impacts.

This task is completed at the beginning of the ALO phase to minimize the amount of redesign because of allowables changes downstream. Need to refine the design allowables based on proposed processing, tooling, effects of defects, etc.

TASKS:
1. Run structures module to update design allowables based on MP2 input.
2. Run durability module to determine impact of fatigue (based on preliminary spectrum)
3. Run materials module to determine impact of fluid resistance, etc.
4. Release updated allowables to IPT's

14. Allowables validation tests (coupon tests)

Validate predicted design allowables from the AIM-C system. Need to do these tests with the production qualification material.

TASKS:
1. Select critical tests to perform first based on risks (cost, schedule, technical) identified by what we know.
2. Tests coupons should be fabricated by the shop that will fabricate the production parts. Use the selected production processes to build in the predicted MP2 parts.
3. Choose proper test methods, test labs, etc.

15. Effects of defects (coupon/element tests)

Based on identified expected defects, determine via tests impact on design allowables. Performed earlier enough in program that design changes can be made to increase robustness and minimize cost.

16. Element Tests, including fatigue

Test critical joints and splices, including fatigue tests. Include defects as required.

17. Allowables modifications, as dictated by tests

Continuously evaluate predicted allowables vs. test data. Update the allowables when differences are identified between prediction and test. Complete this phase before BTP phase is complete.

13.2 Determination of Laminate Strength and Stiffness Properties using AIM-C Tools

The calculation of laminate strength and stiffness properties can be accomplished using AIM-C templates 21 and 10.

Template 21 General non-SIFT analysis of laminated Coupons
Usage Scenario: analysis of laminated coupons, using either a classic point stress or ISAAC analyses, to accurately predict laminate failure including variability.

The template has the ability to predict unnotched or open hole tension or compression strengths. The user is given the option of entering constituent or lamina level properties. The template interfaces with RDCS allowing variability studies and uncertainty analysis. This template provides the capability to compare different methods, failure criteria, laminate types, etc. The generality of the template allows quick "what-if" studies for proposed materials.

Template 10: Generation of Data for Carpet Plots using the Strain Invariant Failure Theory (SIFT) Method

This template uses the SIFT technique to determine final failure stresses and strains for a fixed set of laminates of sufficient quantity to generate carpet plots. The routine does not generate the plot, only the data that to be used by the user to generate the plot. In addition the user may input their own set of layups or simply input a single layup. The default layups are shown below as well as results for open hole tension and compression for an IM7/977-3 coupon test simulation. The coupon size for this simulation was 12.0 inches by 1.50 inches with a 0.25 inch diameter hole located at the coupon centerline.

The data in Figure 13-1 can be plotted into traditional looking carpet plots as shown in Figures 13-2 and 13-3.

				Strength [ksi]	
Layup ID	% 0 Deg Plies	% +/- 45 Deg Plies	% 90 Deg Plies	OHC	OHT
1	20	80	0	-38,623	65,319
2	20	60	20	-50,625	71,918
3	20	40	40	-51,277	71,040
4	20	20	60	-47,543	62,915
5	20	0	80	-38,652	49,548
6	40	60	0	-62,145	100,269
7	40	40	20	-77,553	102,031
8	40	20	40	-75,761	94,191
9	40	0	60	-67,005	87,272
10	60	40	0	-83,100	125,136
11	60	20	20	-95,964	131,863
12	60	0	40	-86,543	118,670
13	80	20	0	-102,432	141,819
14	80	0	20	-104,645	146,353

Figure 13-1 Open Hole Coupon Simulation Laminate Designations and Results

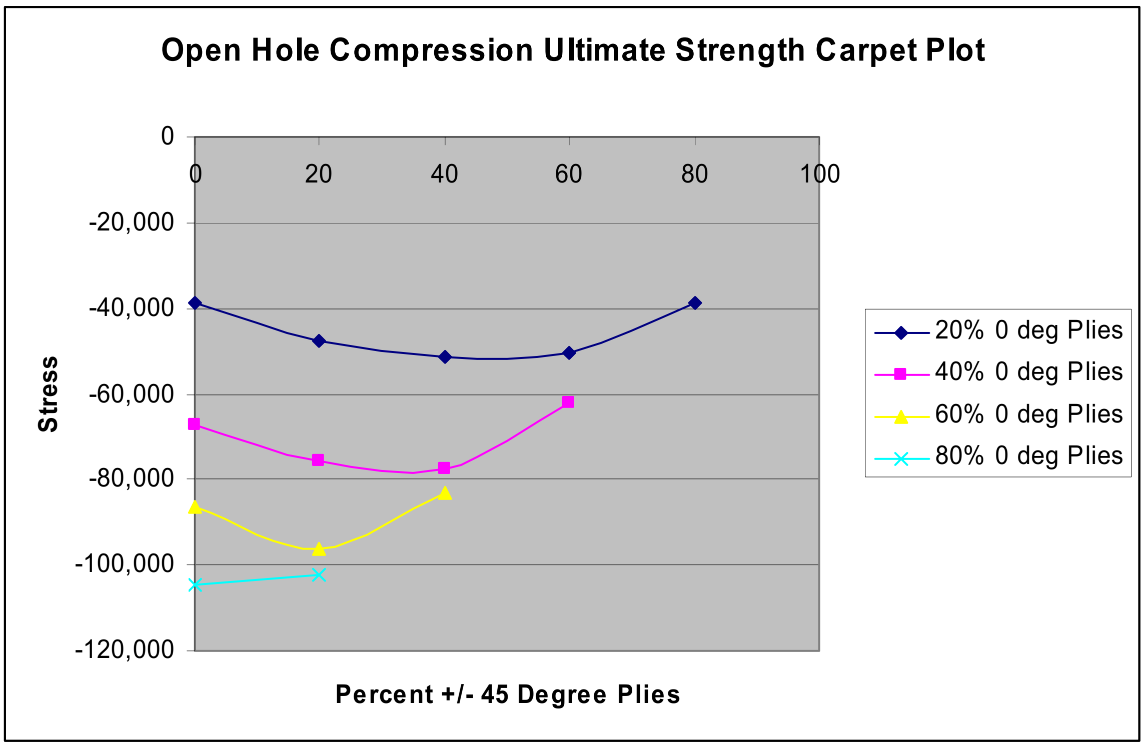


Figure 13-2 Open Hole Compression Strength Carpet Plot

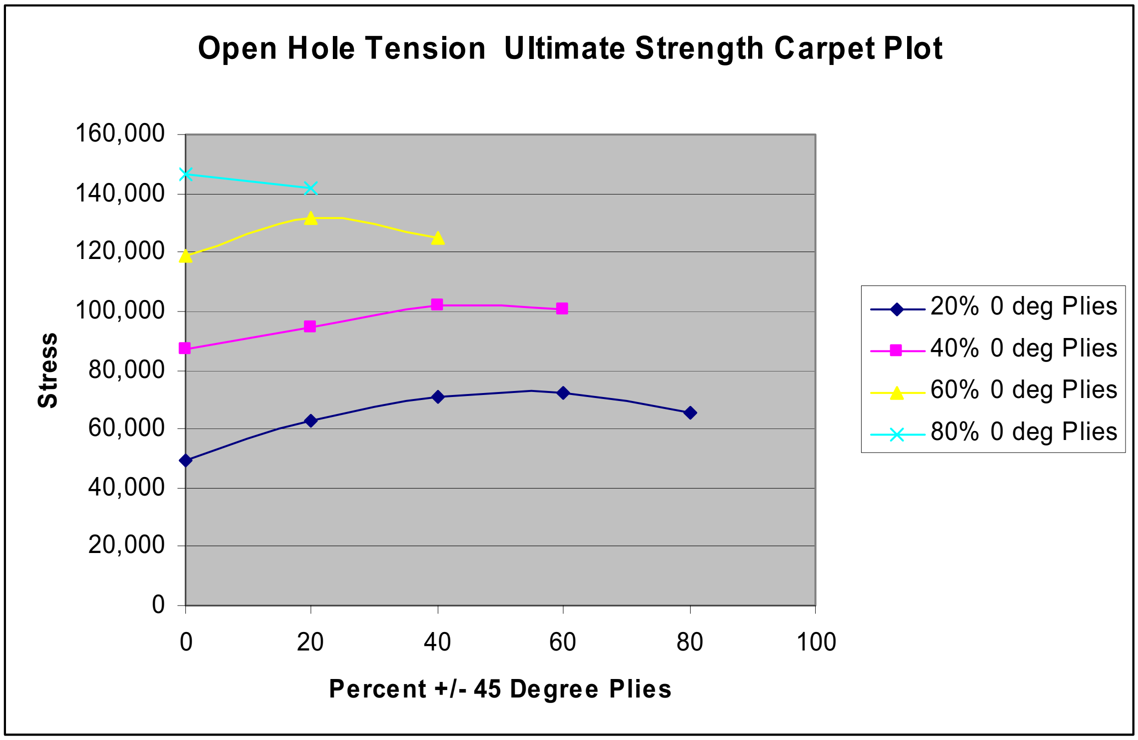


Figure 13-3 Open Hole Tension Strength Carpet Plot

13.3 Generation of Firm Design Allowables

This section contains the test methods for determining the structural mechanical properties of laminates and the methodology to develop allowables. The following laminate tests are outlined.

- Laminate Unnotched Tension
- Laminate Unnotched Compression
- Laminate Open/Filled Hole Tension Test
- Laminate Open/Filled Hole Compression Test
- Laminate Interlaminar Shear Test
- Laminate Pin Bearing Test
- Laminate Compression Strength After Impact (CSAI) Test
- Laminate Flexure Test
- Laminate Interlaminar Tension Test
- Bearing Bypass/Interaction Test

For open hole and filled hole tension and open and filled hole compression testing, gross section width is defined as the width of the specimen including the hole (i.e. the specimen width without the hole diameter subtracted).

Structural (Laminate) Unnotched Tension Test

The objective of this test method is to determine the unnotched tensile strength and modulus of different lay-ups of tape and cloth laminates. A flat rectangular specimen may be used or one with a very gentle radius which provides a minimal stress concentration between the gripped region and the test region. It is recommended to use at least one 0° axial strain gage on one side of the specimen. Both sides may be instrumented to determine if the specimen is experiencing bending stresses.

Laminate Unnotched Compression Test

The objective of this test method is to determine the unnotched compressive strength and modulus of different lay-ups of crossplied tape and cloth laminates. Each specimen should have back-to-back 0° axial strain gages. A lateral stabilization fixture is required to ensure that the specimen does not fail by buckling.

Laminate Open/Filled Hole Tension Test

The objective of this test method is to determine the open/filled hole tension strengths and moduli of different lay-ups of crossplied tape and cloth laminates. The specimen geometry may be identical to that used for unnotched testing provided adequate edge margin exists. Each specimen should have at minimum a single 0° axial strain gage placed on the side without the countersink.

Laminate Open/Filled Hole Compression Test

The objective of this test method is to determine the open/filled hole compression strengths and moduli of different lay-ups of crossplied tape and cloth laminates. The specimen geometry may be identical to that used for laminate open/filled hole tension testing. Back-to-back 0° axial strain gages are required on all compression specimens. A lateral stabilization fixture is required to ensure that the specimen does not fail by buckling.

Laminate Interlaminar Shear Test

The objective of this test method is to determine the interlaminar shear strengths of crossplied laminates. A typical configuration is shown in Figure 13-4.

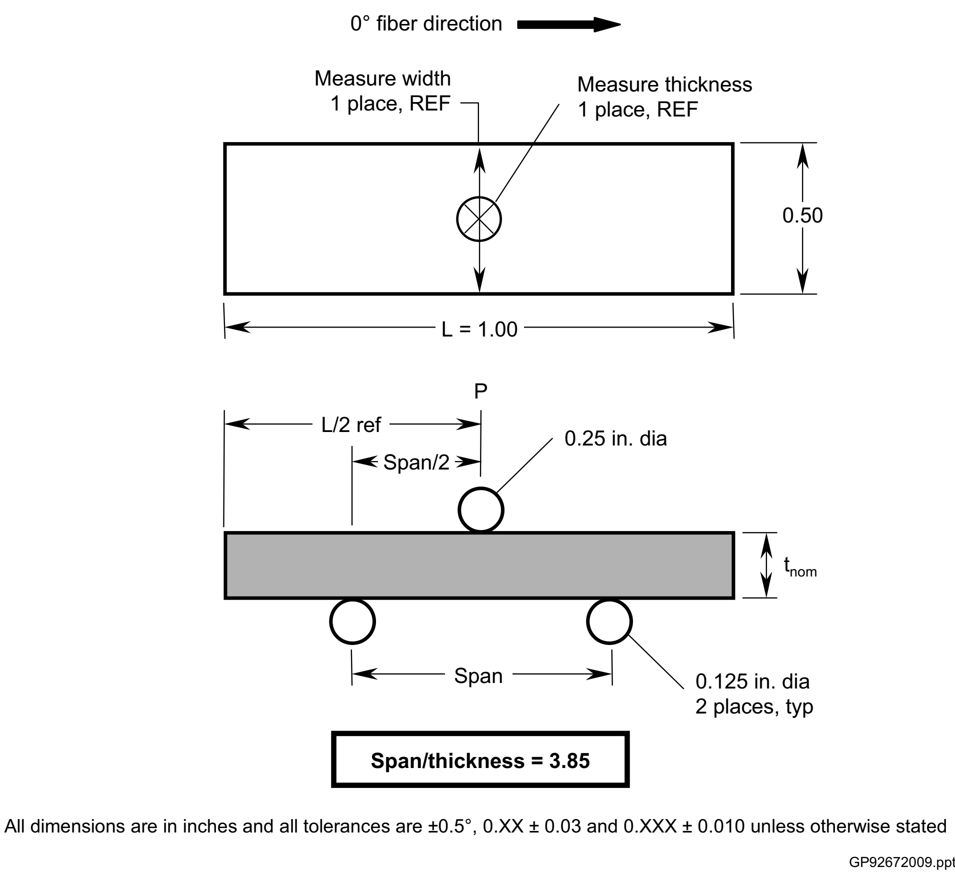
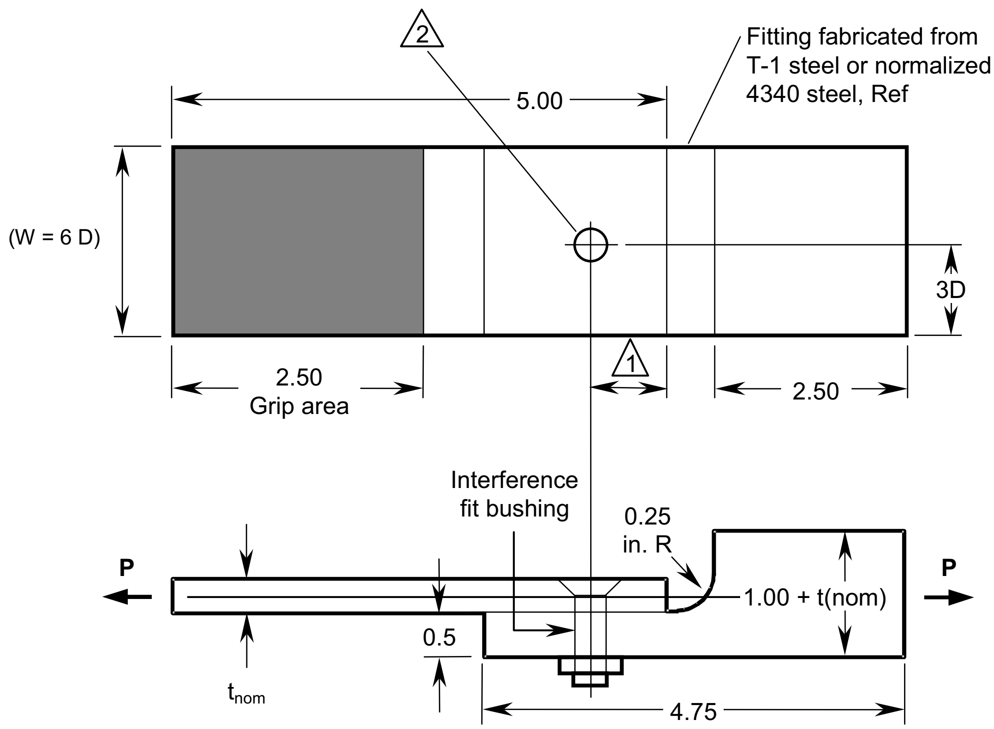


Figure 13-4 Interlaminar Shear Test Configuration

Laminate Pin Bearing Test

The objective of this test method is to determine the static pin bearing strengths of cloth and tape laminates. Typical specimen geometry is shown in Figure 13-5. The reference to TWD, refers to the Test Work Description which could be prepared differently depending on the problem statement and conformance plan. These specimens do not require strain gages. A pin-bearing test fixture is required.



Notes:

1 The edge distance will be per TWD.

2 Hole diameter per TWD.

3 For pin bearing tests, to 10 in-lbs over run on torque.

4 All dimensions are in inches and all tolerances are ±0.5°, 0.XX ± 0.03 and 0.XX ± 0.010 unless otherwise stated

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Figure 13-0-5 Bearing Test Configuration

Compression Strength after Impact (CSAI) Test

The objective of this test method is to determine the compressive residual static strength of composite panels with low velocity impact damage (LVID).   Typical specimen geometry is shown in Figure 13-6. Back-to-back strain gages should be used.

Several trial impact specimens from each configuration should be impacted at various impact energy levels to determine the impact energy level required to produce clearly visible damage at a distance of 5 feet. The trial impact specimens will be impacted in 2 locations per specimen. Due to the lack of a standard for impact testing, the exact number of trial impact specimens required cannot be established with any degree of certainty both technically and programmatically.

After each impact, measure the dent depth of the impact and perform a pulse-echo A-scan or through transmission scan around the damaged and document damage size and location. The dent depth shall be recorded to the nearest 0.001 inch. The required impact depth is 0.01 to 0.02 inches.

Impact all the test specimens in its center at the critical impact energy level determined by the trial impacts. The window should be large enough not to clamp on delaminated areas, but small enough to prevent local laminate buckling (note: delaminations should be still able to buckle). The impact procedures outline above in the trial impact section shall be followed. Attach strain gages and employ the necessary strain recording equipment. The lateral support plates shall have a window large enough so that the damage area is not constrained.

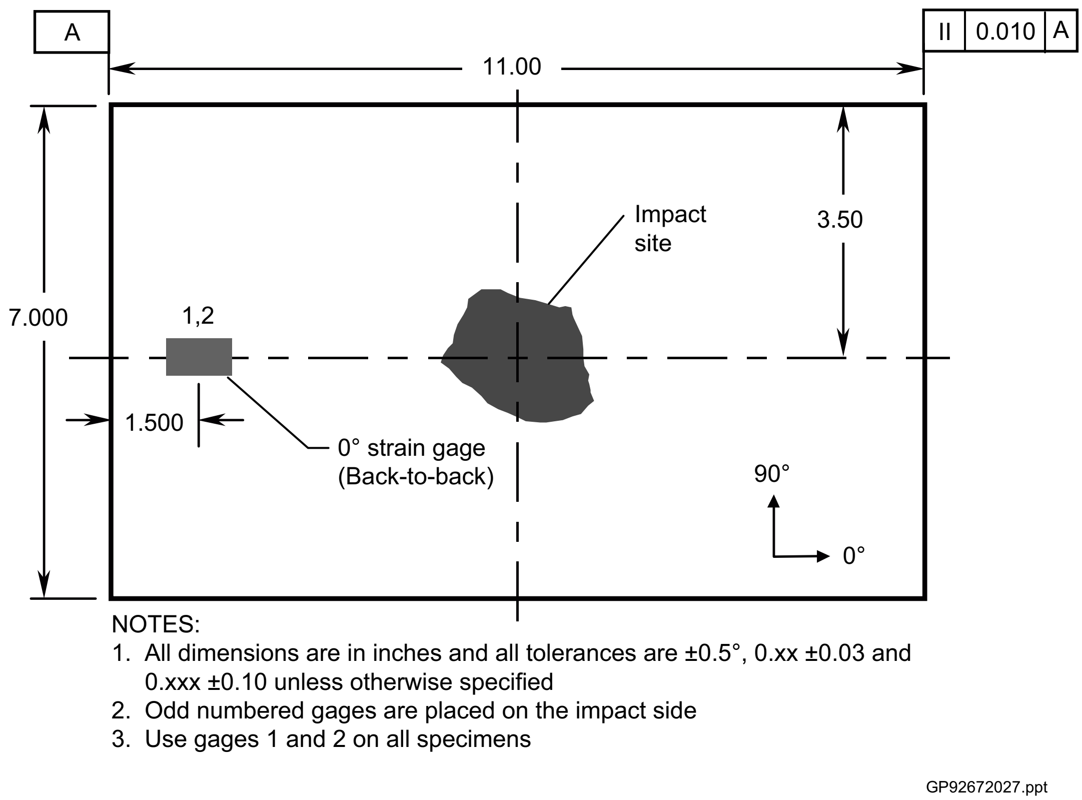

Figure 13-6 Compression Strength After Impact Test Configuration

Laminate Unnotched Flexure Test

The objective of this test method is to determine the flexural strengths of unnotched composite laminates. Typical specimen geometry is shown below. Each specimen requires one set of back-to-back axial strain gages and a displacement transducer. A four-point bending test fixture is required which is illustrated in Figure 13-7.

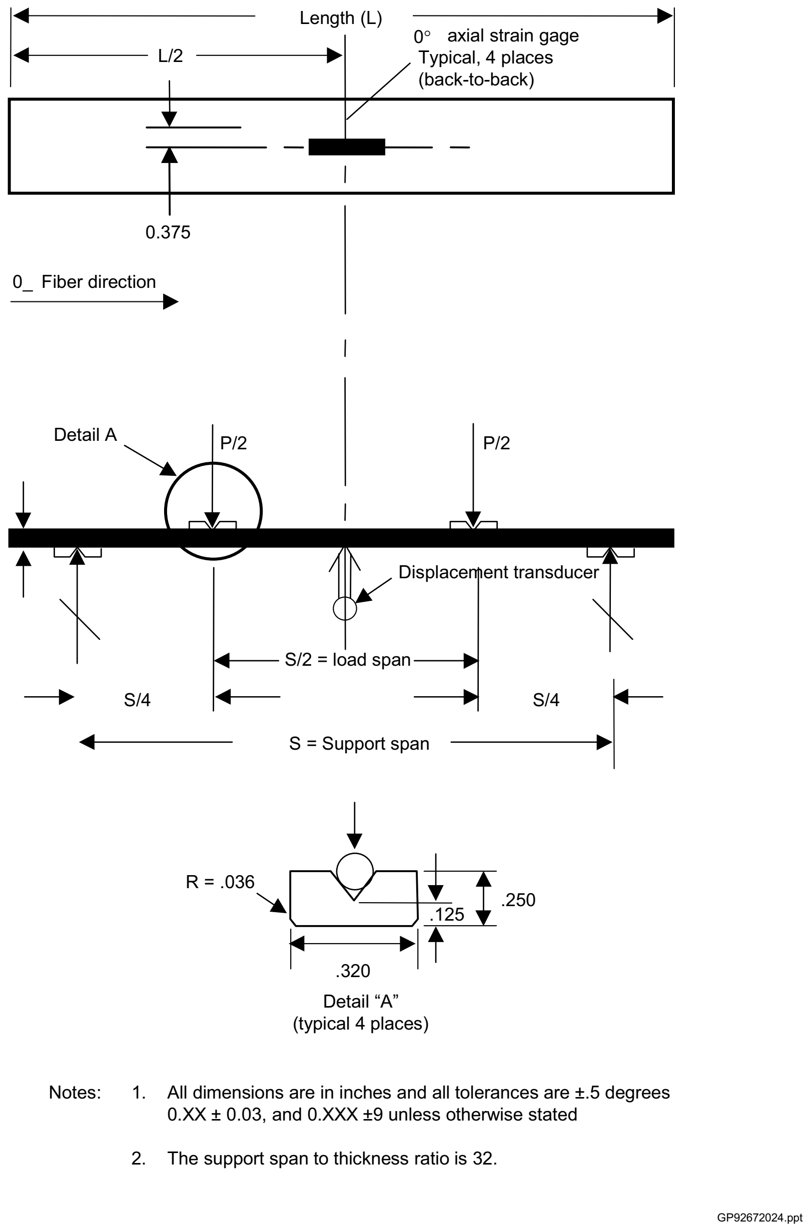

Figure 13-7 Laminate Flexure Test Specimen

Laminate Interlaminar Tension Test

The objective of this test method is to determine the interlaminar tension strength of cross plied laminates. Specimen geometry is shown in Figure 13-8. The specimens do not require any strain gages. (Lfail= momemt arm at failure. Mfail=P(L-Δ).)

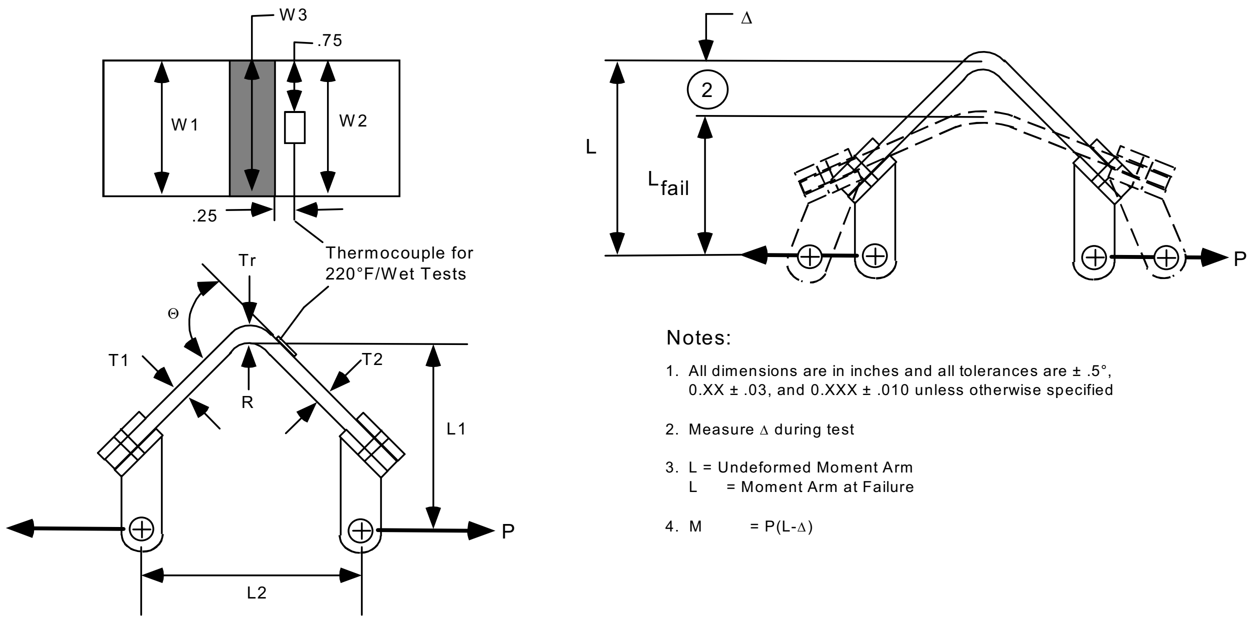

Figure 13-8 Interlaminar Tension Specimen

Bearing/Bypass Interaction Test

The objective of this test method is to determine the static bearing/bypass strengths of cloth and tape laminates. The typical specimen geometry is shown in Figure 13-9. (All units are in inches and all tolerances are +/- 0.5%, 0.XX +/- 0.03 or 0.XXX +/- 0.010 unless otherwise specified.) Each specimen requires back to back axial strain gages. A bearing/bypass test fixture is required. Bearing load (P_B) is applied independently of the tension load (P_T). It should be noted that the bearing load, P_B, is not equal to the load in the strain link but is rather a function of the load in the strain link and the fixture geometry. Apply the initial tensile load (P_{T1}). This load should be equal to the applied bearing load P_B. Apply the bearing load (P_B) at the fastener hole, $P_B = P_{T1}$. While holding the bearing load (P_B) constant, increase the tension load, P_{T1}, to failure.

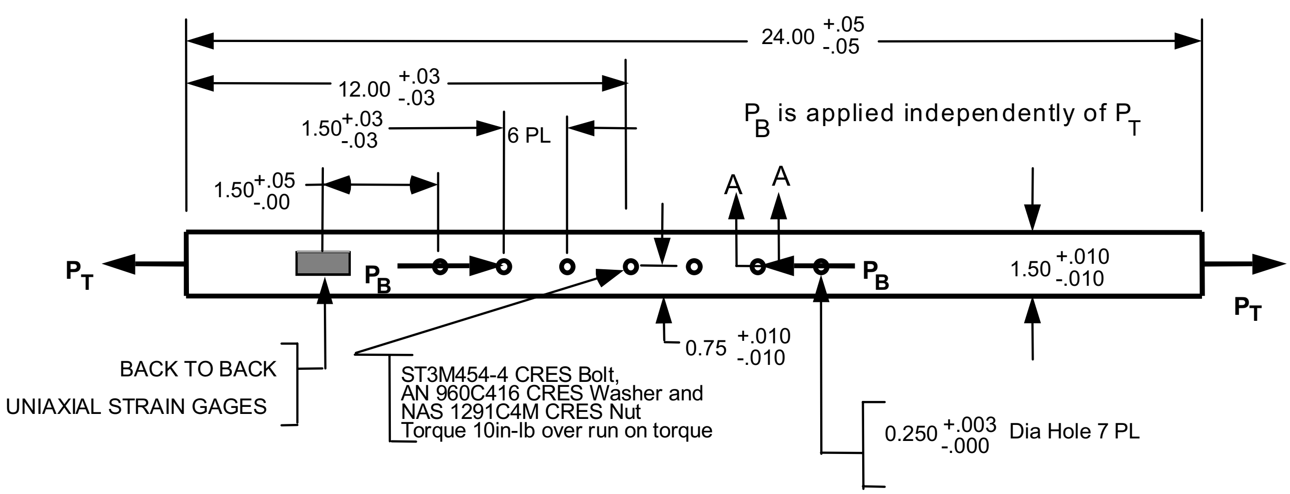

Figure 13-9 Bearing/Bypass Interaction Test Setup

Data Reduction Methodology for Allowables

This section discusses the methodology employed to reduce the test data to generate design allowables. This design allowable approach uses test coupons from representative laminate families. The test configurations are representative of actual aircraft structure; that is, holes, fasteners, etc. are included in the coupons.

It is necessary when developing design allowables to consider how the structural analyst will use the allowables to ensure the structural integrity of the aircraft structural components. The structural analyst typically makes the following assumptions:

1. Finite element and stress analysis assumes the material exhibits a linear elastic behavior.

2. Only one set of lamina elastic constants per environmental condition represents all laminate families.

3. Nominal (theoretical) laminate thicknesses are used in the analysis instead of actual, cured thicknesses.

Tension and Compression Strain Allowables

The end result of a strength analysis is to accurately predict the strength of the part. In determining strain allowables to ensure that the structural part strength is accurately predicted, the following methodology is used:

1. Determine lamina stiffness properties except E_1.

2. E_1 is a best-fit value based on data from a variety of laminates. Classical lamination theory analyses are conducted until an E_1 value is found to best predict the laminate moduli measured during test.

3. Determine a failing strain using the best fit analytical laminate extensional stiffness (same as that used by the analyst) and the nominal failing stress. This ensures that the laminate strength will be correctly predicted during analysis.

4. Determine design allowable strains by reducing the test average failure strains with a B-Basis statistical factor. The B-Basis design allowable implies that composite structure will have this strength or higher 90 percent of the time with 95 percent confidence.

5. Employ the best-fit moduli in the finite element models.

The first step in developing design allowables is to determine the best-fit moduli. The best-fit elastic moduli are determined from a combination of lamina test data and laminate open/filled hole test data. All stiffness properties are determined from the best-fit line of the nominal stress-strain curves from 1000 to 3000 μ-in./in. extensional strain (2000 to 6000 μ-in./in. shear strain), as shown in the figure below This strain range was selected for stiffness determination because a majority of the composite structure does not exceed 3000 μ-in./in. for most flight conditions. The goal for stiffness properties is to most accurately predict deflections for actual flight loads.

Lamina tests are used to establish the lamina stiffness properties E_2, G_{12}, and ν_{12}. Lamina tests can predict these properties with sufficient accuracy, since these lamina properties can be in error by a significant amount and have little effect on the predicted laminate stiffness of a fiber dominated laminate. History and test data developed on the F/A-18 E/F, however, have shown that using 0° moduli from lamina tests in conjunction with classical lamination plate theory, tends to over predict the laminate stiffness. For this reason, the lamina 0° fiber direction stiffness, E_1, as determined from lamina tests, is employed in material acceptance tests but is not used in design. The value of E_1 used in design is instead "backed out" of multidirectional laminate test data.

To determine E_1, the values of E_2, G_{12}, and ν_{12} from the lamina tests and an assumed value of E_1 are input into a classical lamination plate theory analysis to predict the laminate extensional modulus, E_x. This analytically predicted E_x is then compared to the E_x measured in tests. A new value of E_1 is then assumed and the analysis is repeated in an interactive procedure until the analytical E_x is the same as the measured E_x. This procedure is performed for all laminates, loading types, and environmental conditions. Typically, the "backed out" E_1, is 1) lower than the E_1 measured in a lamina test, and 2) varies in value depending upon the percentage of 0° plies in the laminate. The "backed out" E_1 tends to increase in magnitude as the percentage of 0° plies in the laminate increases, which explains why the lamina test value of E_1 is too high to use in design.

To simplify analysis, one value of E_1 is desired for a given load type and environment to predict the laminate stiffness properties for all laminate families. The value of E_1 chosen is from a laminate containing 30% to 35% 0° plies. This E_1 is the middle value from a range of laminates that contains 20% to 50% 0° plies. Figure 13-10 shows typically expected trends of measured laminate modulus versus analytical modulus when E_1 is chosen using this method. As shown, the moduli of "soft" laminates are slightly over predicted while the moduli of "hard" laminates are slightly under predicted.

The goal of the structural analyst is to accurately predict laminate strength, not strain at failure. As illustrated in Figures 13-11 and 13-12, the stress-strain behavior of a laminate as it is loaded to failure is not necessarily linear-elastic, as is assumed in analysis. Due to this inelastic behavior, the predicted laminate strength could be over predicted if the measured failure strain is used with the analytical laminate modulus, as shown in Figure 13-13. To eliminate the potential to over predict laminate strength when designing with strains, all test failure stresses are divided by the analytical laminate modulus to derive analytical failure strains for use in analysis. As illustrated in Figure 13-, by using this methodology the laminate strength will be accurately predicted, but the analytically predicted failure strain may or may not be the same as the actual measured failure strain.

When interpreting full-scale test success criteria, the difference between analytical stiffness and laminate test data must be considered to accurately predict measured failure strains.

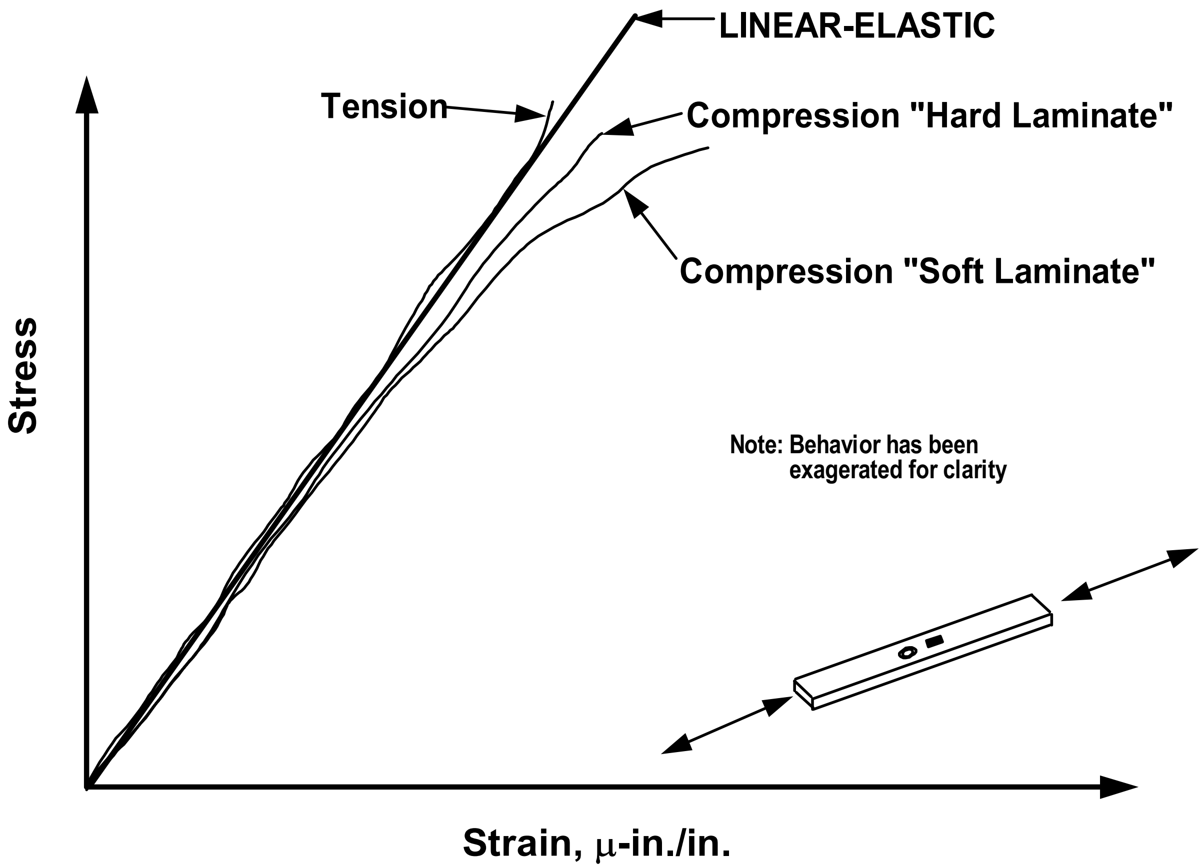

Figure 13-10 Typically Observed Types of Stress-Strain Behavior for Composite

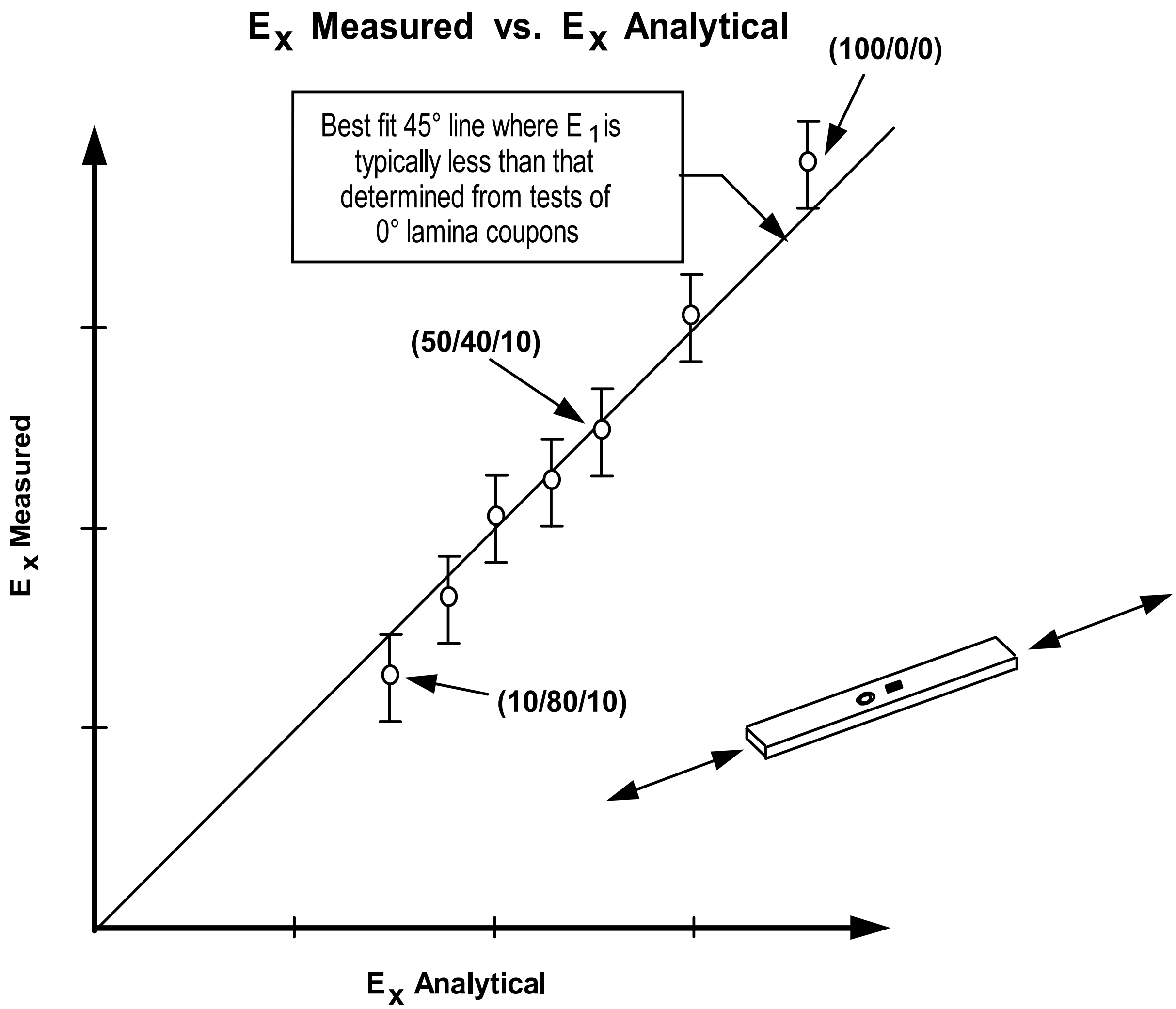

Figure 13-10 Typical Trends of Ex Measured Versus Ex Analytical

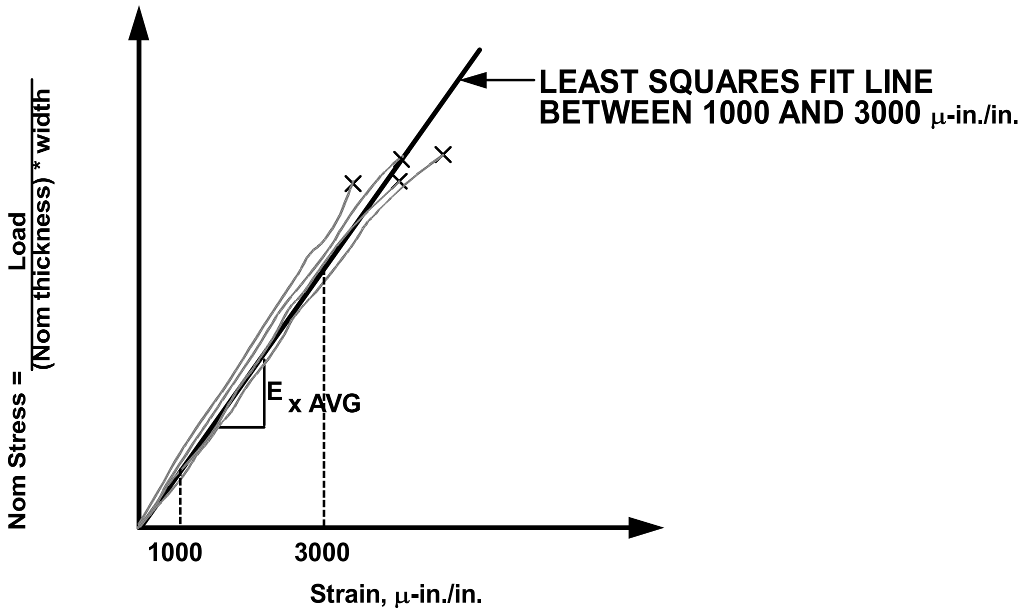

Figure 13-12 Laminate Average Initial Modulus Used for Design

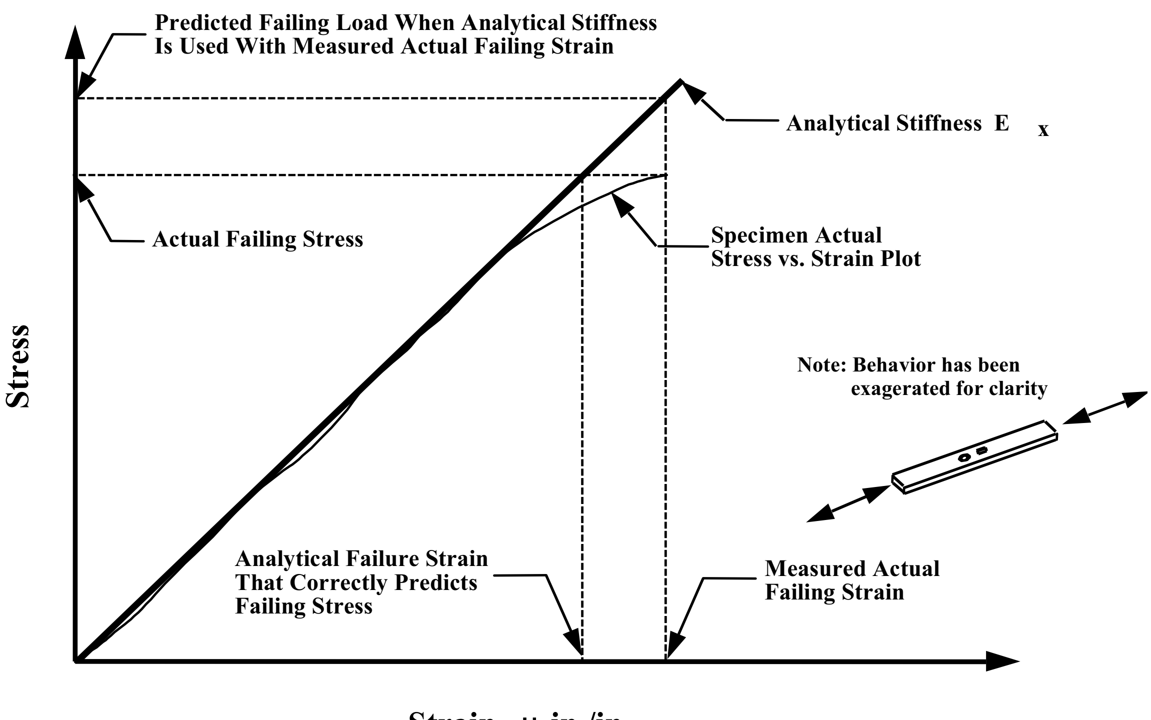

Figure 13-13 Analytical Stiffness Used with Analytical Failure Strains to Correctly Predict Laminate Strength

Pin Bearing Allowables

Pin bearing strength test data is reduced into allowable design data using the methodology of *MIL-HDBK-17E*. The ultimate bearing failure load is defined as the maximum load obtained during a pin bearing test. The bearing yield load is defined as a 4% hole elongation. The design ultimate bearing load was defined as either the ultimate failing load in the test or 1.5 times the test bearing yield load, whichever is smaller. In calculating bearing stress, the nominal thickness and nominal hole diameter are used in the bearing stress equation:

$$F_{br} = \frac{P_{ult}}{Dt}$$

where	F_{br}	=	Ultimate bearing stress
	P_{ult}	=	Ultimate bearing load
	D	=	Nominal hole diameter
	t	=	Nominal laminate thickness

Similarly, the bearing yield stress, F_{bry}, can be calculated using the above equation and substituting the bearing yield load, P_{yield}, for P_{ult}. B-Basis pin bearing allowables are determined using the regression analysis method.

Interlaminar Shear Allowables

The first step in reducing interlaminar shear test data into design allowables is to verify the failure mode is interlaminar shear. The correct interlaminar shear failure mode is illustrated in Figure 13-14. Specimens that show cracks and delaminations near the outer surfaces actually failed in flexure. Test data from interlaminar shear specimens that experienced a flexure failure mode are not used in developing interlaminar shear stress allowables. Interlaminar shear stresses are calculated from the test data using the isotropic beam theory equation:

$$F_{ils} = \frac{V}{bt}$$

where:	F_{ILS}	=	Interlaminar shear stress
	V	=	Out-of-plane shear load in the laminate (P/2)
	b	=	Actual specimen width
	t	=	Nominal specimen thickness

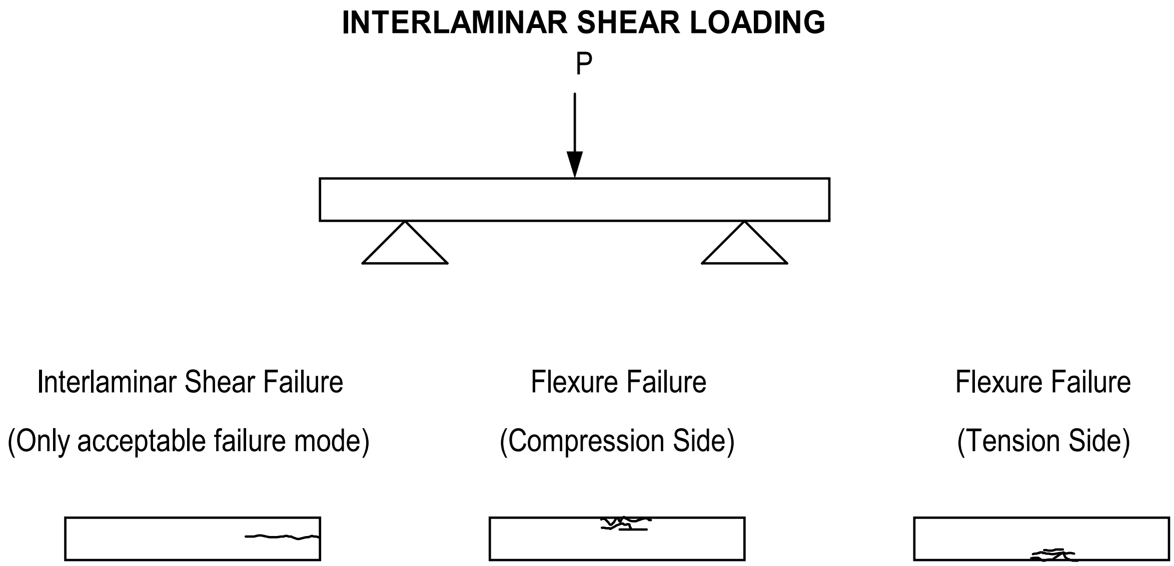

Figure 13-14 Interlaminar Shear Failure Mode Versus Flexure Failure Mode for Interlaminar Shear Test Specimen

In material acceptance tests, interlaminar shear stresses are typically calculated using actual specimen thickness instead of nominal thickness. Actual thickness interlaminar shear calculations are more representative of the true resin interlaminar strength. However, the aircraft is designed using nominal thicknesses. Thus, for design purposes, interlaminar shear stress allowables are based on nominal thickness.

Interlaminar Tension Allowables

The interlaminar tension (ILT) specimen and fixture shown in Figure 13-15 are designed to isolate the maximum interlaminar tensile stress at the center of the curved region. The ILT stress must be computed by hand or via compute program. The interlaminar tensile stress is determined by summing the radial stress induced by the end load and moment. In material acceptance tests, interlaminar stresses are typically calculated using actual specimen thickness instead of nominal thickness. Actual thickness interlaminar tension calculations are more representative of the true resin interlaminar strength. However, the aircraft is designed using nominal thicknesses. Thus, for design purposes, interlaminar tension stress allowables are based on nominal thickness. In addition, using the same analogy, the nominal radius is used in the calculation of the ILT stress.

As a result, the actual moment arm at failure is critical to predicting the ultimate ILT stress. As the specimen is loaded, the moment arm is reduced, thus lowering the actual ILT stress at failure. It is not desirable to use the initial moment arm in the computation of the ILT stress because this over predicts the actual failure ILT stress of the specimen. The reduced moment arm is determined by measuring the lateral displacement of the radius.

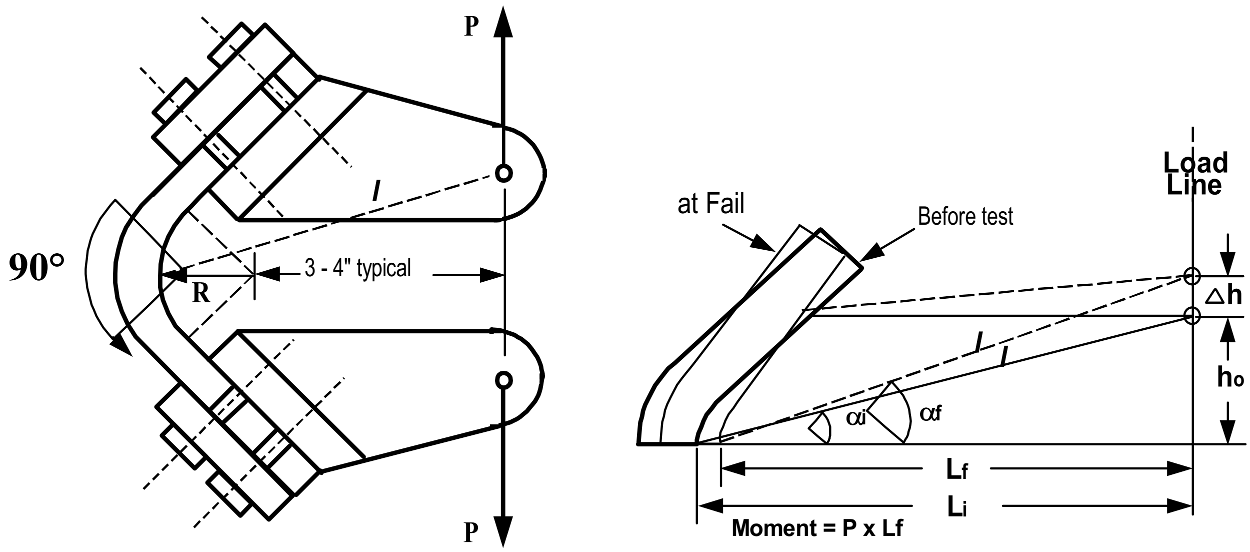

Figure 13-15 Interlaminar Tension Specimen with Reduced Bending Moment Arm

Allowables Development Methods

B-Basis Development Methodology

Composite design allowables are B-Basis values, as a minimum. A B-Basis design allowable, as defined by *MIL-HDBK-5*, is the value, which at least 90 percent of the mechanical property population of values is expected to equal or exceed, with a confidence level of 95 percent.

Design allowables are calculated using one of two procedures described in *MIL HDBK-5*. One procedure is the direct computation of B-Basis allowables from a normally distributed population of a single material property. The other method determines B-Basis allowables by linear regression analysis of a single material property as a function of another parameter.

The direct computation method determines B-Basis allowables for one value of the material property. To calculate the B-Basis allowable for this case, the following equation from *MIL-HDBK-5E* was used:

$$B = X - k_B S$$

where B = B-Basis allowable for the material property
X = Mean (average)
k_B = One side tolerance limit factor, from *MIL HDBK-5E*, Table 9.6.4.1
P = 0.90, 95% confidence and *n* degrees of freedom
S = Sample standard deviation, from *MIL HDBK-5E*, Section 9.2.2.

When a test is run on a set of specimens at two or more different values of the independent variable, the linear regression B-Basis allowables method of *MIL HDBK-5E*, Section 9.2.11, can be applied. For this analysis, the method of least squares is used to best fit a line through the data.
This line is given by:

$$Yo = a + bXo$$

where Yo = The dependent variable
Xo = The independent variable

$$b = \frac{S_{xy}}{S_{xx}}$$

$$a = \frac{\sum y - b\sum x}{n}$$

x = Individual values of the independent variable
y = Individual values of the dependent variable

n = Number of data points used in the regression

A B-Basis allowable can then be determined from the best-fit line using the following equations:

$$B = Y_o - k_B S_y \sqrt{1 + \frac{1}{n} + \frac{\left[X_o - \frac{\sum x}{n}\right]^2}{S_{xx}}}$$

where B = B-Basis allowable for a given value Xo
Yo = Value of the dependent variable for a given value of Xo
k_B = One side tolerance limit factor, from *MIL HDBK-5E*, Table 9.6.4.1, for

P = 0.90, 95% confidence, and n-1 degrees of freedom
Xo = Value of the independent variable
n = Number of data points used in the regression
x = Individual values of the independent variable
S_y = Sample standard deviation

$$S_y = \sqrt{\frac{S_{yy} - \frac{(S_{xy})^2}{S_{xx}}}{(n-2)}}$$

$$S_{xx} = \sum x^2 - \frac{\left(\sum x\right)^2}{n}$$

$$S_{yy} = \sum y^2 - \frac{\left(\sum y\right)^2}{n}$$

$$S_{xy} = \sum xy - \frac{\left(\sum x\right)\left(\sum y\right)}{n}$$

Statistical Tests for Data Normality

The Chi-Square test is used to determine if the data set comes from a normally distributed population. The data must pass this test in order to use the B–Basis methodology discussed above.

To determine if the mechanical property is from a population with a normal distribution, a Chi-Square goodness of fit test is performed on each population. First, the theoretical distribution is divided into several equal slices or intervals centered about the mean. The observed frequencies for these intervals are determined from the test data sample. In the Chi-Square test, the observed frequency distribution is compared to the corresponding values of an expected, or theoretical, distribution.

The Chi-Square statistic, obtained from the above equation, is compared to the 0.95 fractile chi-square for k - m degrees of freedom, where k is the number of terms in the formula for c_2 and m is the number of quantities, obtained from the observed data, that are needed to calculate the expected values. Generally, the number of specimens and the sample standard deviation are used to calculate the expected values, so m = 2.

Data Pooling

Data sets can be combined to increase the population for B-basis calculations. With larger data samples there is increased confidence that the sample variance adequately approximates the population variance. Accordingly, the k_b value decreases with larger data samples. Smaller k_b values give higher B-basis design allowables and lighter weight airframe designs. In general these data must represent the same material, layup, test, etc., before they can be pooled. The data should also come from the same population as can be checked with a t-test.

Some data can be pooled even if the tests were not identical in every way. For example, data sets of the same laminate layup, width to diameter ratio, test temperature, and moisture content can be combined if each data value is divided by the average failure strain at that particular temperature and moisture content. This normalized data can be combined with normalized data from the other test conditions to form a larger pool. The standard deviation of the larger sample is then obtained and used to compute the statistical knockdown factor.

Batch-to-Batch Variation

Composite materials are made in separate batches, so it is possible to encounter batch-to-batch variations in the composite's properties. In fact, this is often the case, although a good, robust manufacturing process will minimize the phenomenon. The goal of all approaches is to determine design allowables at the beginning of the design process that account for any expected batch-to-batch variations.

The simplest and most cost-effective approach is to pool all data together as if no batch-to-batch variation exists and then perform goodness-of-fit tests on the pooled data. Batch-to-batch variability will then be built into the B-basis values. However, this cannot be guaranteed. Engineering judgment must be used to evaluate if the test data has the expected distribution based on the historical performance of similar materials. Important test data are collected from several batches of material to include this batch-to-batch variability and data pooling techniques as shown above are used to include the variability in other tests. During production, acceptance testing is performed on each batch of material to ensure it meets certain minimum requirements so that any excessive batch-to-batch variability is caught before the material is used in production.

Even when all batches of pooled data together pass a goodness-of-fit test for a chosen distribution, however, it does not ensure that batch-to-batch variability is insignificant. Further, one cannot guarantee that B-basis values of structured data computed after pooling and fitting a distribution are always conservative.

13.4 Structural Design Process

Design Goals

In a typical design effort, the primary focus is on

1. meeting the mean structural performance requirements and design constraints
2. meeting the weight target
3. meeting producibility and cost requirements

In the past, this has often been done in a sequential manner, i.e., first find a design that works, then tailor the design extensively to reduce the weight, and finally, pass the design "over the fence" to manufacturing and develop tooling and processing techniques to reduce the cost. It is ASSUMED that the Structure will be consistently built to print.

Even in an IPT environment, where this job is done concurrently with input from all disciplines, the approach is similar. The Structures organization typically defines an initial design and then discussions ensue about how to balance performance, weight, producibility and cost requirements. The primary blind-spots in this approach are: (1) the focus is normally on mean performance, with very little consideration of robustness to defects or material/geometry variation, (2) it is assumed that a defect-free structure can be consistently built, and (3) very little data is available for the Structures and Manufacturing representatives to objectively discuss the effects of potential design and manufacturing trade-offs. As a result, the success of the effort is highly dependent on the experience and knowledge of the IPT members and the available tools and knowledge about the particular concept.

One of the key differences in the AIM-C Design Selection Methodology is the early consideration of design robustness to variation and defects. Another is the availability of a tool set to rapidly assess the criticality of various parameters related to the design, be they geometric parameters or parameters associated with manufacturing effects.

The Design and Selection Process

Structure, be it a detailed part or a complex assembly must meet certain operating objectives if it is to provide satisfactory service. Broken down it a simplistic statement, the basic design philosophy is to create the highest quality product that is feasible, using the best available materials and design and manufacturing techniques. This very broad statement must be considered throughout the design process.

In order to decrease the size of the design space without unduly limiting it is to begin the design process by consulting a "Requirements" or "Design Requirements and Objectives" document. This document is assembled prior to the design of a commercial or military aircraft or platform and includes among other things static and dynamic load factors, margin of safety requirements, criteria to cover buckling and crippling, joint design, fastening requirements, and minimum gage requirements.

With internal and external loads and design criteria in hand the structures engineer may begin the design process. For illustrative purposes a design of a hat stiffened panel will be used as a design example. The following paragraphs detail the design process from this point and discuss how the designer can meet the requirement of "creating the highest quality product that is feasible, using the best available materials and design and manufacturing techniques."

The design process was broken down into the following steps;

(1) Selection of an initial starting point or initial design concept
(2) First Shell Model FEM Runs – Critical Regions and Stability
(3) Initial Cure Cycle and Tooling Selection
(4) Alternate Concepts – Elimination of Critical Defects
(5) Determination of important variables
(6) Interaction with manufacturing
(7) Selection of Tooling Approach
(8) Local Model or Detailed FEM Studies
(9) Defect Sensitivity Studies

Selection of an Initial Starting Point or Initial Design Concept

Perhaps this is the most important step in the process. Often in the design process it is this initial design concept that is used. For this design example a hat stiffened panel was assigned and not "selected." Other designs could have been blade, "J", "I" stiffened or sandwich panel.

To properly perform this study one must accurately assess each design at a level that gives reasonable results and captures trends but also at a level that allows a relatively quick assessment of each concept. Often at this stage a designer may rely upon past experience or may consult company design practices that will give guidance.

First Shell Model FEM Runs – Critical Regions and Stability

In this step shell finite element models are created and reviewed. In all situations involving finite element modeling the designer must look at results with skepticism. Shell element finite element models give accurate results only in regions that are stress concentration free. In addition, any regions where shells intersect at any angle other than zero, the shell results are suspect and other means must be used to determine the state of strain. One must always be aware of the method by which results are obtained in the finite element model. Are results averaged at nodal locations? What domain is used if results are averaged or a maximum number is reported by the finite element code? A myriad of questions must be answered.

Figure 13-16 shows the results of a shell finite element of an initial hat concept. At this load level gross area strains throughout most of the skin are evident. It can be determined that strains in the top of the hat section are quite low. The analyst should also determine if the modeling technique is appropriate. Would those low strains in the stiffener crown increase if a nonlinear analysis is performed? It appears the stiffener run out has the highest strains although that's somewhat difficult to determine. At this point the analyst should look for discontinuities and attempt to rationalize the results of the model. In addition it is always helpful to plot displacements and to animate the displacements, again to determine if the model is behaving as it should. This linear model is sufficient for initial sizing and for trade studies but is inadequate or at least regions of it are inadequate for final strength determinations.

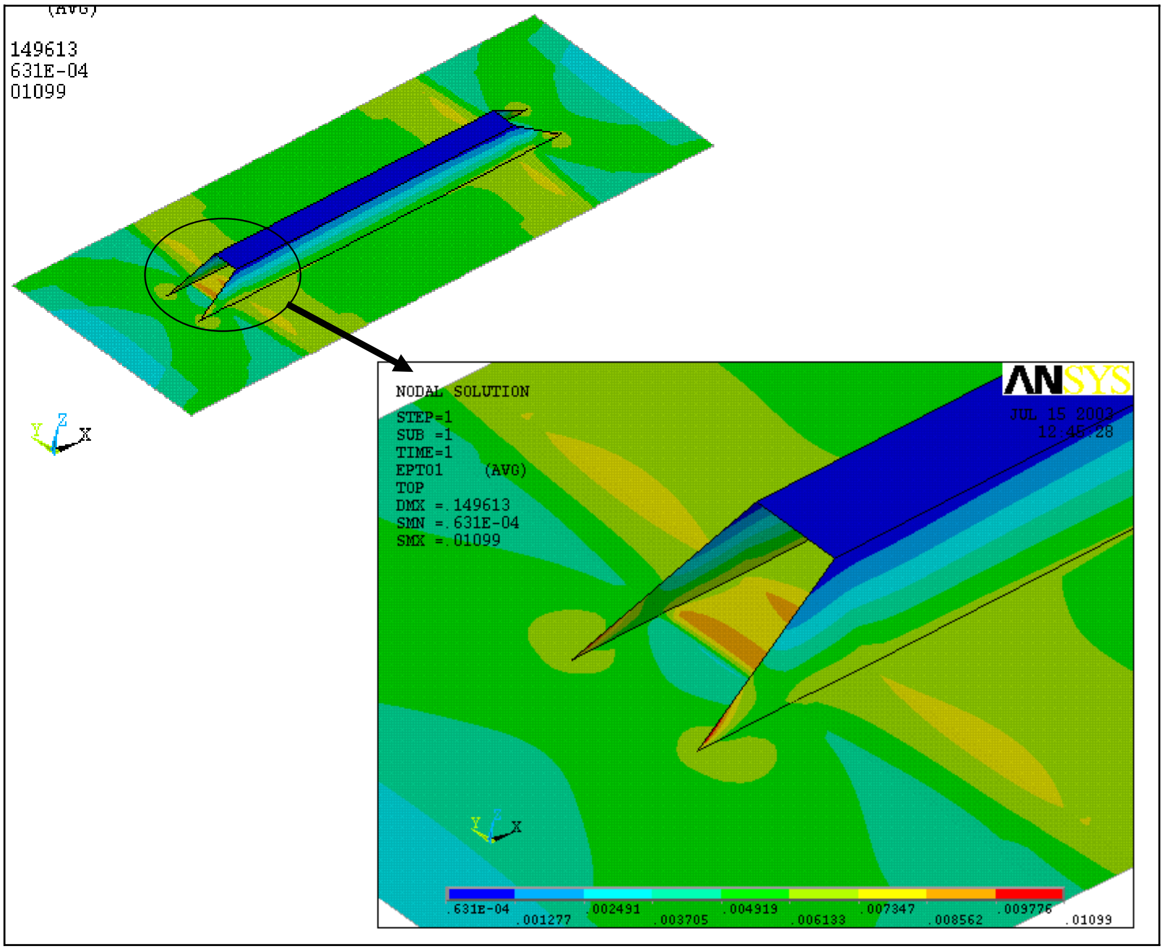

Figure 13-16 Shell Finite Element Model

Initial Cure Cycle and Tooling Selection

With a firm concept defined which includes basic component thickness to a reasonable level of certainty and with knowledge of other basic geometrical parameters the design should be examined to determine appropriate cure cycle and tooling concepts. This step may eliminate some possible variations in downstream design iterations or may lead the design down a different path or variation of the design based on producibility or cost considerations. This exercise is generally beyond the responsibilities of the structures engineer. In depth knowledge of materials and processes is required to accurately determine appropriate methods and interpretation of results of this exercise. Consult the Materials and Process Development and Producibility Sections of this document for further detailed discussion of cure cycle and tooling analysis and selection.

Alternate Concepts – Elimination of Critical Defects

Upon completing the previous steps the design has gained maturity. This does not mean the design cannot be modified. On the contrary, now that the design is determined to be viable, efforts may be expended to make the design better with a high degree of certainty of benefit from these efforts. Many designs have a few critical details that determine overall part strength. If one can eliminate a critical detail – actually eliminate it, one can increase the overall part or assembly strength, or make the part more durable or damage tolerant or perhaps make the part or assembly more easily produced. The hat stiffened panel offers a good example of elimination of a critical detail.

Traditionally the termination of the stiffener foot or flange has been a problem area, often delaminating due to the abrupt stiffness change and requiring the addition of fasteners or requiring fracture based analysis for substantiation. This analysis assumes a defect or delamination at the stiffener termination. Analysis is performed to determine load level at which the crack grows. A large amount of effort and cost is expended attempting to minimize the chance of delamination by tailoring the stiffener flange termination. The cost is highest on the production side by requiring detailed and exacting ply ramp terminations at this location. Figure 13-17 shows this detail and a concept that enables elimination of it.

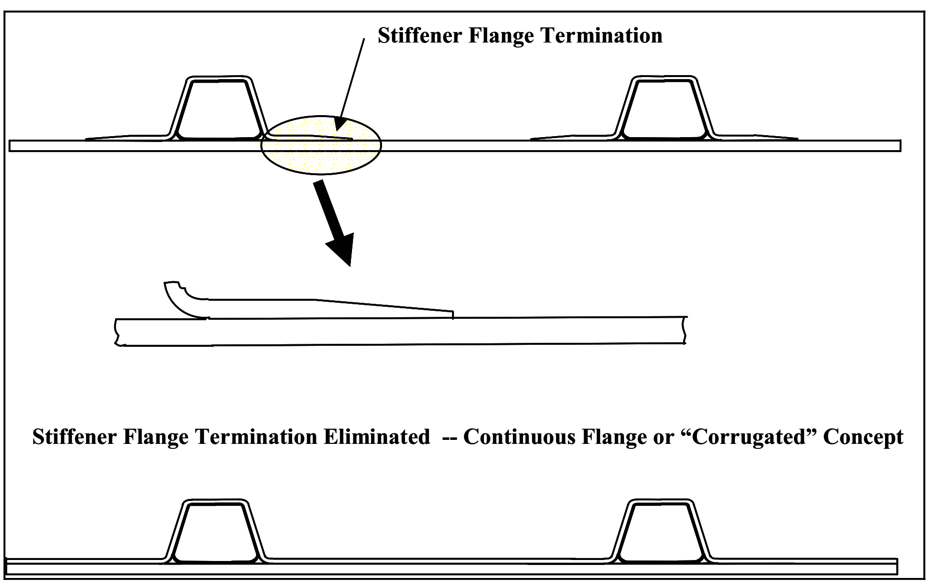

Figure 13-17 Stiffener Flange Termination

For illustrative purposes several of the studies that were done for design of the AIM-C Phase 1 Hat Stiffened Panel Demonstration/Validation are discussed.

Study 8: Corrugated Stiffener/Skin Configuration Study

Due to the relatively small bay width the stiffener foot termination occurs relatively close to the middle of the bay as shown by the sketch below. A concept whereby the stiffener feet common to the skin are extended to meet the adjacent stiffener foot is the focus of this study. The stiffener and wrap detail for a multi stiffener bay assembly would resemble a corrugated sheet, Figure 13-18.

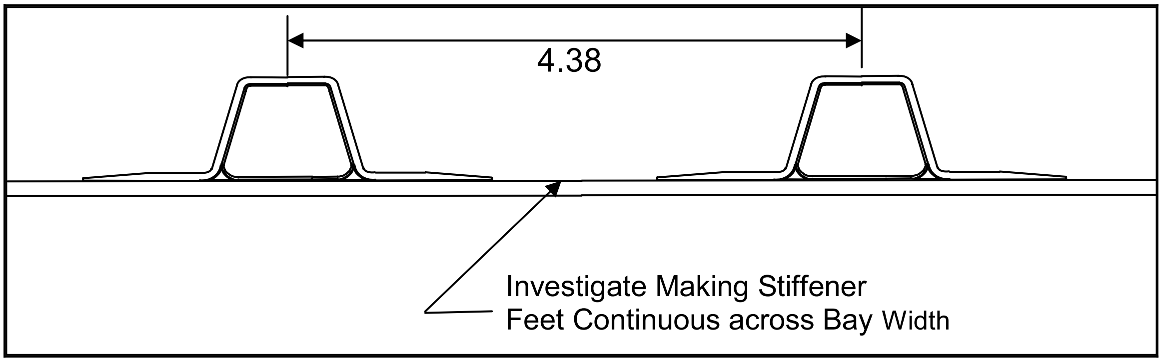

Figure 13-18 Corrugated Study Concept

This can offer advantages of elimination of stress concentrations at the stiffener foot termination, and the elimination of manufacturing defects at the foot. In addition ply waviness at the foot termination, which has been problematic on other stiffened assemblies can be eliminated. The continuous inner skin and outer skin is not new. It is a common arrangement in superplastic/diffusion bonded assemblies. If this concept proves to be weight competitive it can offer a very simple assembly sequence. The inner skin may be easily located on the outer skin by way of tooling tabs. This concept seems to be very simple and therefore relatively easy to assemble.

This study will compare this concept to the conventional concept and determine its weight impact. Determination of the structural efficiency of each concept will also be determined.

Three configurations were studied

1. Separate stiffeners co bonded or cocured to skin
2. Corrugated Stiffener cobonded or cocured to skin
3. Same as 2. Except integral skin plank removed. The skin plank is a local reinforcement in the skin which consist of plies added to the skin below the stiffener

Figure 13-19 details the stain levels in each of the configurations.

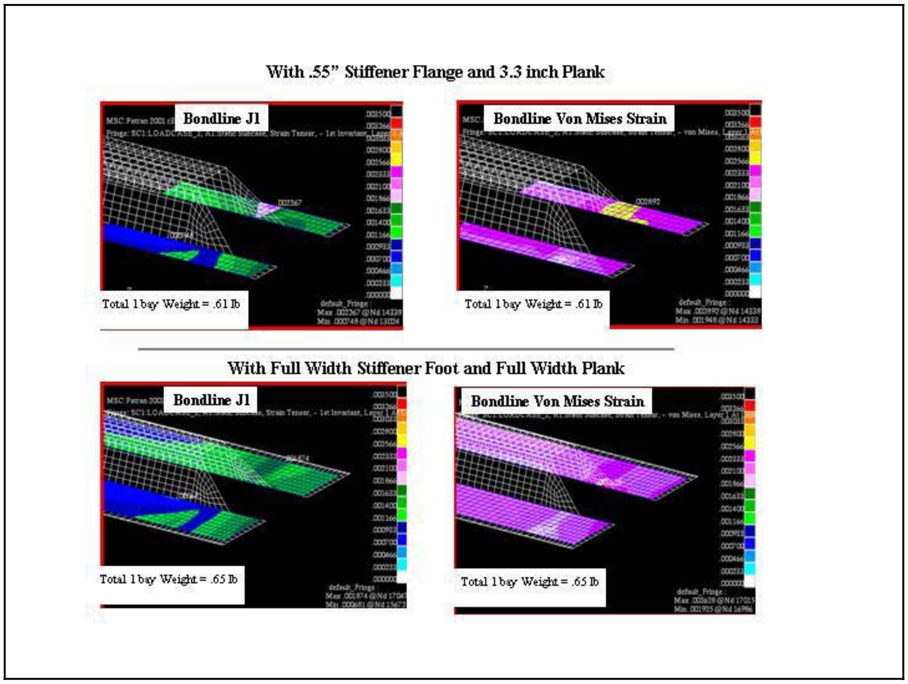

Figure 13-19 Bond Line Strains

Figure 13-19 shows the bond line strains (the strains at the interface of the stiffener flange and the skin) for an assembly with 0.55 inch long stiffener feet and for an assembly with continuous feet. Please note that only a single stiffener bay is shown. Note the strain level in the bond line decreases as the full width stiffener flange is used. The weight of the assembly however also increases.

Figure 13-20 shows the stiffener strains for an assembly with 0.55 inch long stiffener feet and for an assembly with continuous feet. Please note that only a single stiffener bay is shown. Note the strain level in the stiffener decreases as the full width stiffener flange is used. The weight of the assembly however also increases

Figure 13-21 shows the skin strains for an assembly with 0.55 inch long stiffener feet and for an assembly with continuous feet. Please note that only a single stiffener bay is shown. Note the strain level in the skin decreases as the full width stiffener flange is used. The weight of the assembly however also increases

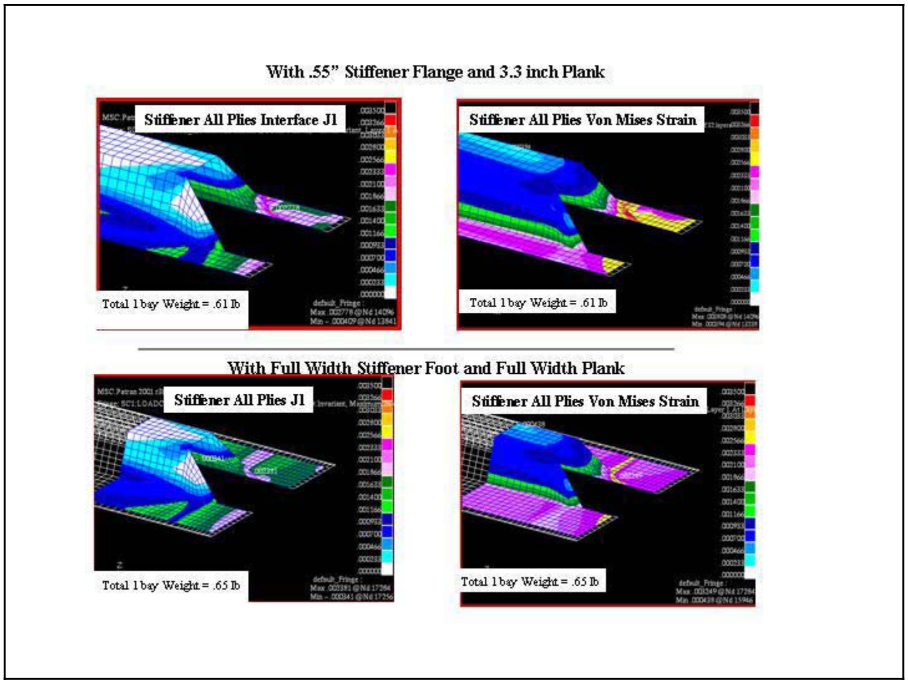

Figure 13-20 Stiffener Strains

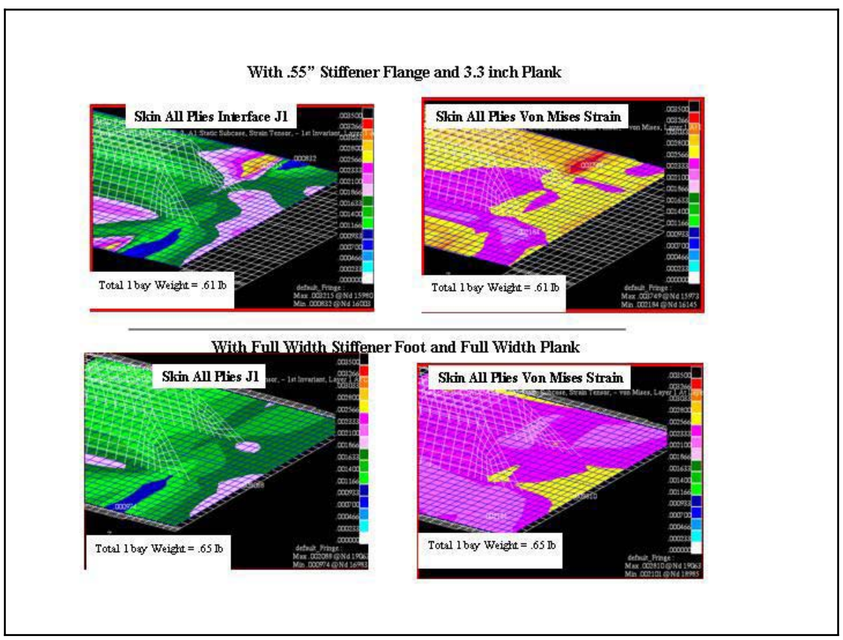

Figure 13-21 Skin Strains

The preceding figures compare the strains for two different assemblies. One with stiffener feet of 0.55 inches and the other with continuous stiffener feet across the bay width. Both assemblies utilized a skin with four 0 degree plank plies located at the skin centerline. The next set of figures will investigate to effect of removing the plank plies thereby reducing the stiffness of the skin.

Figure 13-22 shows the bond line strains for assemblies with full width stiffener feet – the corrugated concept with and without plank plies in the skin. As the skin stiffness is decreased the bond line strains increase. But, of course, the assembly weight decreases as the plank plies are removed

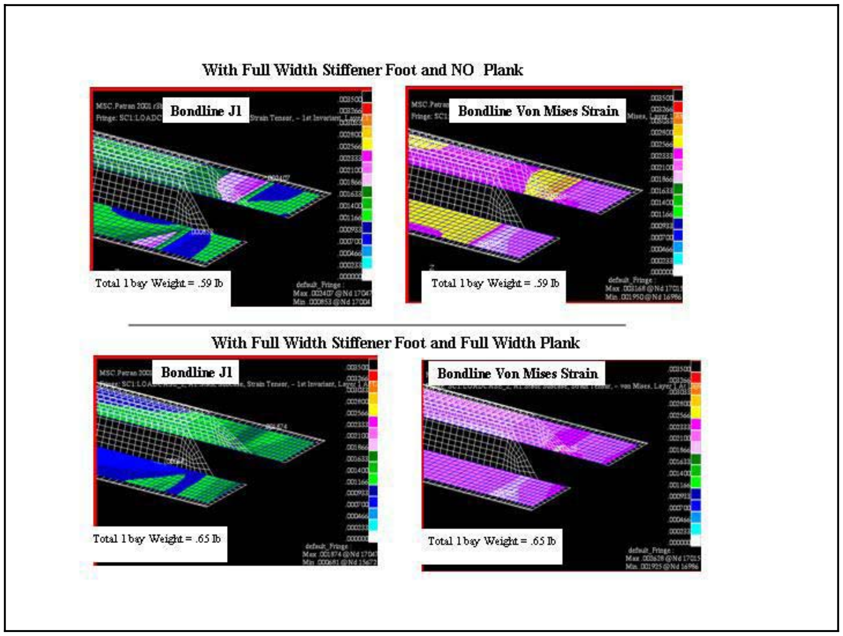

Figure 13-22 Bond Line Strains

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Figure 13-23 shows the stiffener strains for assemblies with full width stiffener feet – the corrugated concept with and without plank plies in the skin. As the skin stiffness is decreased the stiffener strains increase. But, of course, the assembly weight decreases as the plank plies are removed.

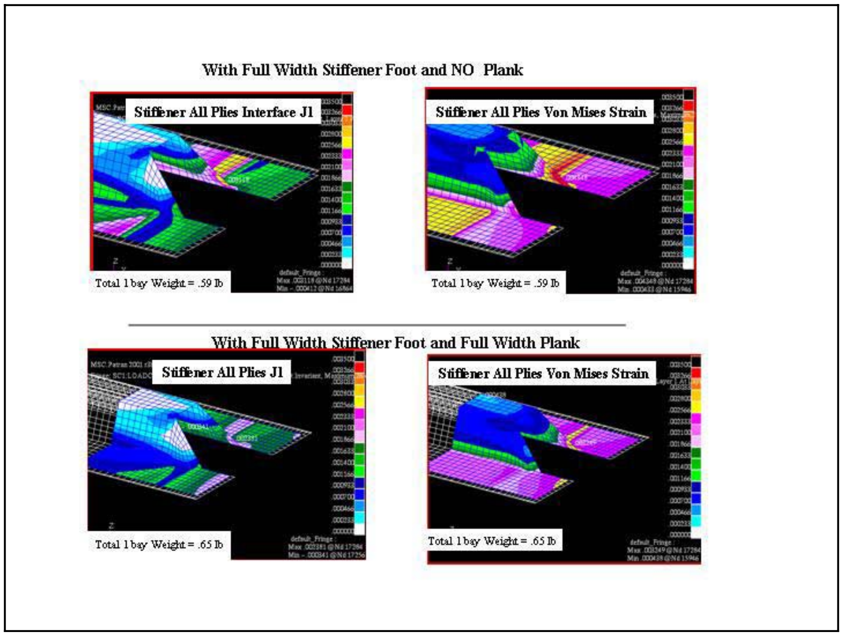

Figure 13-23 Stiffener Strains

Figure 13-24 shows the skin strains for assemblies with full width stiffener feet – the corrugated concept with and without plank plies in the skin. As the skin stiffness is decreased the stiffener strains increase. But, of course, the assembly weight decreases as the plank plies are removed

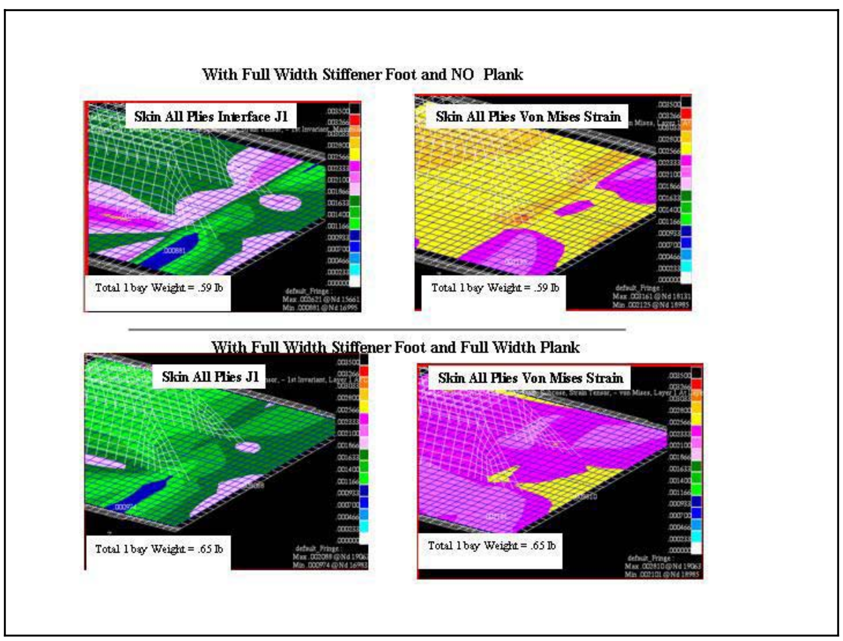

Figure 13-24 Skin Strains

In all cases it was of course shown that strains can increase or decrease as a function of the material thickness – nothing profound about that. How does one determine what design is most appropriate? For this design a concept of structural index was introduced, Figure 13-25. In this case the structural index is defined simply as the strain level multiplied by the assembly weight. One could argue that the exponents should be something other than one for these products but for the sake of this study this simple relationship was used. The structural index for each of the configurations at strain levels seen by each component is given in the figure below. A lower structural index is an indication of a more weight efficient design. Please note in all cases the corrugated design with integral plank plies over 100% of skin has the lowest structural index and is therefore the most weight efficient design.

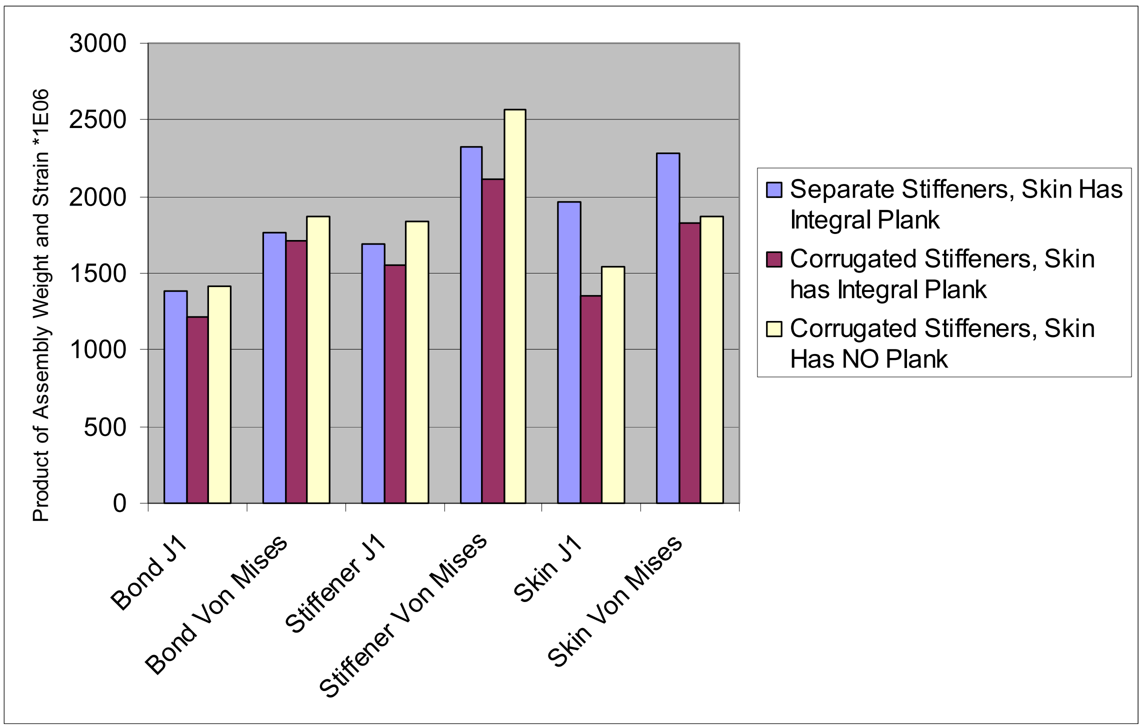

Figure 13-25 Structural Index for Each Configuration (Lower is Better)

The result of this study suggests the corrugated concept is the most weight efficient design studied if plank plies will be utilized for 100% of the skin unlike the existing design which utilized plank plies over approximately 75% of the skin area. The assembly will therefore be made up from a single corrugated hat/ inner skin cobonded to a procured outer skin – both of relatively simple geometry. This design was examined to determine producibility with the corrugated concept shown to be easier to assemble than having separate hats bonded to the skin.

In conclusion, it was determined that the critical stiffener flange termination could be eliminated.

Determination of Important Variables

While it is relatively easy to anticipate the effect of some geometrical parameters on the strength attributes of a detail or assembly it is important to quantify these effects. Some parameters will have profound effects on strength, others will have negligible effect. On the other hand parameters that are unimportant from a strength standpoint may have profound influence on cost and or producibility. If one finds a parameter that is unimportant to strength but is very important to producibility the design parameter may be set by manufacturing and not by structures. It is important to determine the effect of as many parameters as feasible in order to make informed decisions. In an effort to further illustrate these points a study that was performed during the design of the hat stiffened panel is shown here.

Study 7: Stiffener Parameters - Analysis of Variations

In an effort to determine the effect of varying stiffener geometric parameters of height, width and run out or termination angle a full factorial study was done where each of these parameters was varied over a reasonable range. The input parameters are summarized in the table below. It is important to note that the run out angle is not set directly. Rather it is determined by the two parameters H_st, the height of the stiffener and the parameter " once the stiffener height is set, the parameter "run out" which is the distance over which the stiffener crown and webs go from full height to zero. With three independent variables 27 runs separate runs were needed for a full factorial study.

The effect of each variable and the effect of combinations of independent variables, Figure 13-26 is discussed.

Geometric Constants and Other Default Settings

w_st - Stiffener width across flat	**VARY**
H_st - Stiffener height	**VARY**
Lstiff - Stiffener Flange Length	**VARY**
L_st_ramp - Stiffener Flange Ramp	0.2
alpha - Stiffener Leg Angle	15
r1 - Stiffener Upper Radius	0.25
r2 - Lower Radius	0.25
w_p - Plank Width	3.3
adim - Stiffener Bay Size	4.38
wpad - Edge Pad Skin Perimeter	0.08
wpl_l - Plank Ramp	0.2
bdim - Stiffener Spacing	12.5
mdim - Mid Stiffener Length	8.14
runout - Runout Length	**dependent**
stiff2framegap - Stiffener to to Frame Gap	0.2
stiff2framefastener - Stiffener to Frame Fastener	0.57
a_0 - initial crack length	0.08
frame_spacing	14.7
frame_flange_gage	0.125
framewidth	0.53
extend_plank_and_feet 1== Extend Thru Frame	1
plank_integral 1= Plank Integral to Skin	1
mesh_size	0.15

Components

Component	Stacking Sequence T=Tape F=Fabric	t
Skin	[45 -45 0 90 45 -45 0 45 -45]s All IM7 Tape	0.0936
Plank	[0]4 All IM7 Tape	0.0208
	Skin + Plank Thickness	0.1144
Skin at Frame	[45 -45 0 90 45 -45 0 45 -45 0 0 90 0]s 0 All	0.1404
Stiffener	[45]3 AS4 Fabric	0.0420
Crown	[45F 0T 0T 0T 45F 0T 0T 0T 45F] Tape=IM7	0.0732
Wrap	[0 F 45 F] AS4 Fabric	0.0280

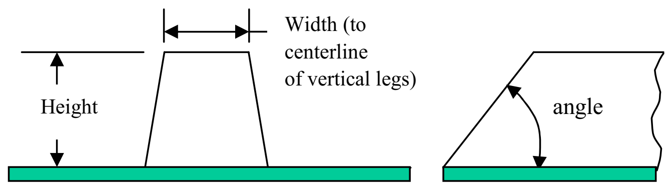

Figure 13-26 Geometric Constraints and Other Default Settings

Fore-Aft Tension dominated load case

- $N_{transvese}$ = 360 lb/in (+)==tension in skin
- $N_{fore/aft}$ =2610 lb/in (+)==tension in skin
- N_{xy} = -1680 lb/in
- Pressure = 4.5 psi (+)==tension in skin compression is stiffener crown

Bond Line Strains

The bond line strains are very important in the determination of the strength of the hat stiffened panel assembly. Past experience has shown delaminations upon assembly and under load are typical and common problems. While the global model by no means has the ability to accurately predict strains in this region it does have the ability to accurately determine trends. The results of the full factorial study are shown in Figure 13-27.

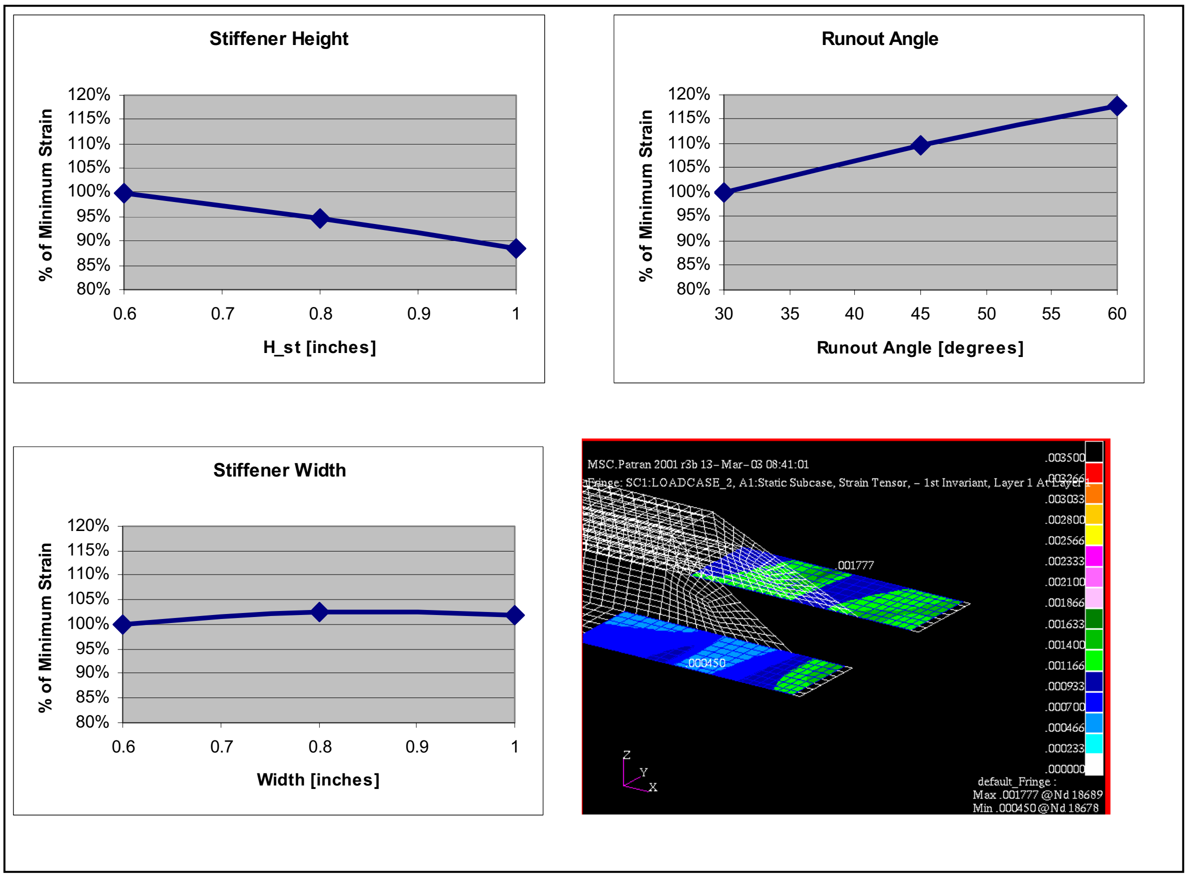

Figure 13-27 Relative Bond Line Strains

Figure 13-27 shows the effect of a single parameter on the bond line strains. These curves were generated by averaging the results from two of the three study parameters and showing the range of the third parameter and its dependent variable, in this case J1 or the first invariant of strain in the bond line. These curves show the strains in the bond line trending downward as the height of the stiffener is increased and as the run out angle is decreased. The effect of the width of the stiffener is relatively minor.

What parameters are the largest contributors to bond line strains? Figure 13-28 shows the relative strengths of each parameter and the effect of parameter combining on the bond line strains.

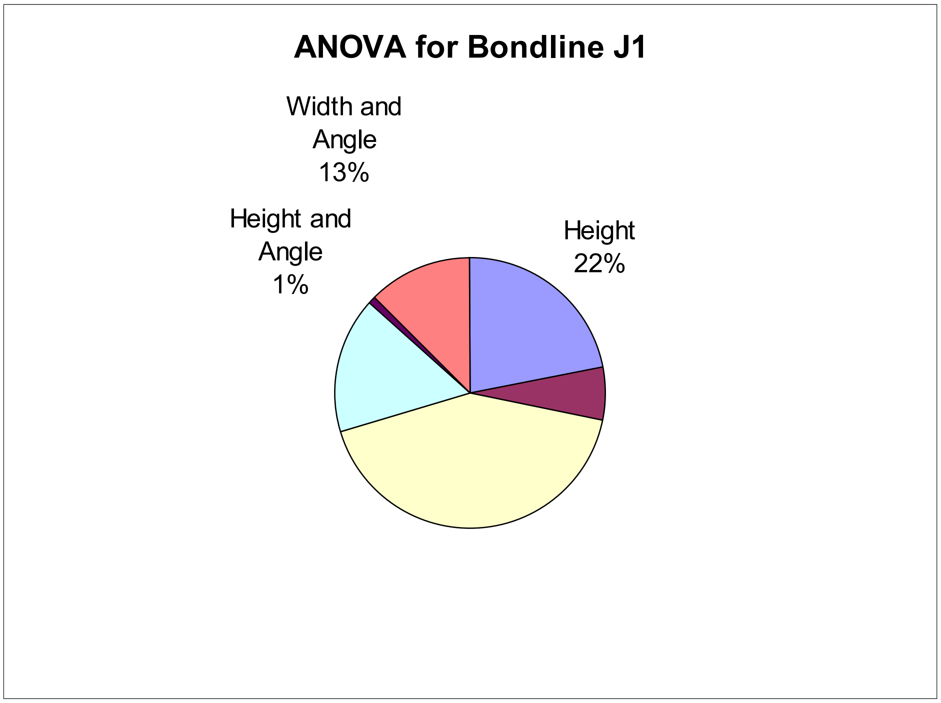

Figure 13-28 Relative Influence of Each Parameter on Bond Line J1

Within the limits of this study, bond line strains were most heavily influenced by the run out angle followed by the height of the stiffener. The width of the stiffener is of relatively minor importance. This study therefore suggests running out the stiffener at a relatively low angle in the range of 30 degrees or so.

Figure 13-29 plots the two strongest influencing parameters as a response surface. This figure strongly shows the influence of stiffener height and run out angle on bond line strains.

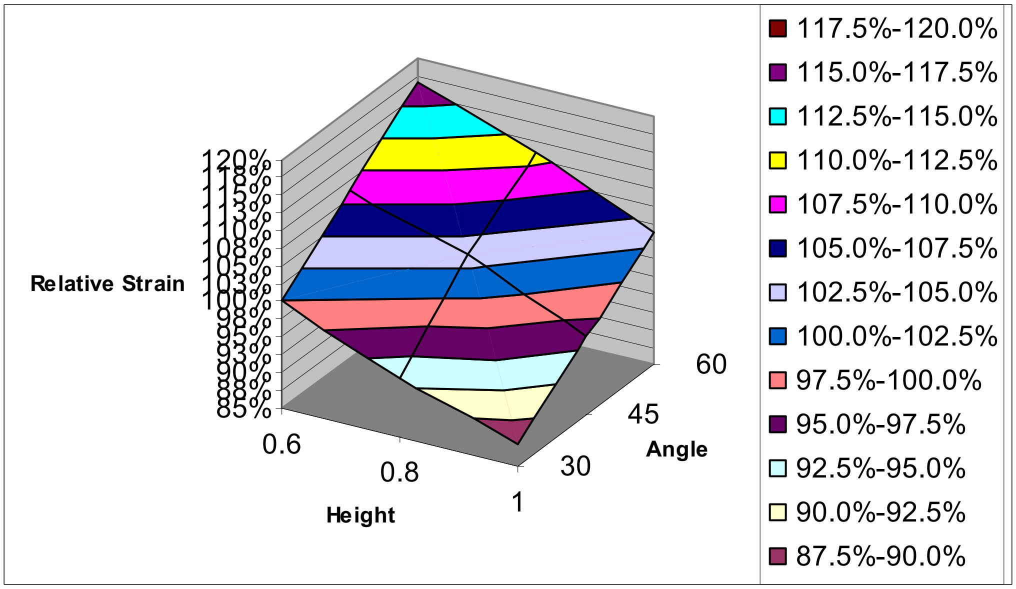

Figure 13-29 Influence Stiffener Height and Run Out Angle on Bond Line J1

What has not been considered in this study is the effect that the above parameters have on the buckling capability of the assembly. Very shallow run out angles will decrease the buckling capability. This study, like all others cannot be used as an ends. Other failure modes must also be considered. However the very strong influence of run out angle and stiffener height as they affect bond line strains must not be ignored and must be weighted very heavily on the determination of the final design configuration.

Stiffener Strains

The stiffener strains are probably of less importance from an assembly strength determination viewpoint than bond line strains. Stiffeners function to add buckling capability to the skin and are generally not highly stressed in most applications. They are not however unimportant. Inattention to any component in an assembly can render the assembly incapable of carrying design loads or of being highly sensitive to design imperfections. No assembly is stronger than its weakest member. The stiffener strains from the full factorial study are shown in Figure 13-30.

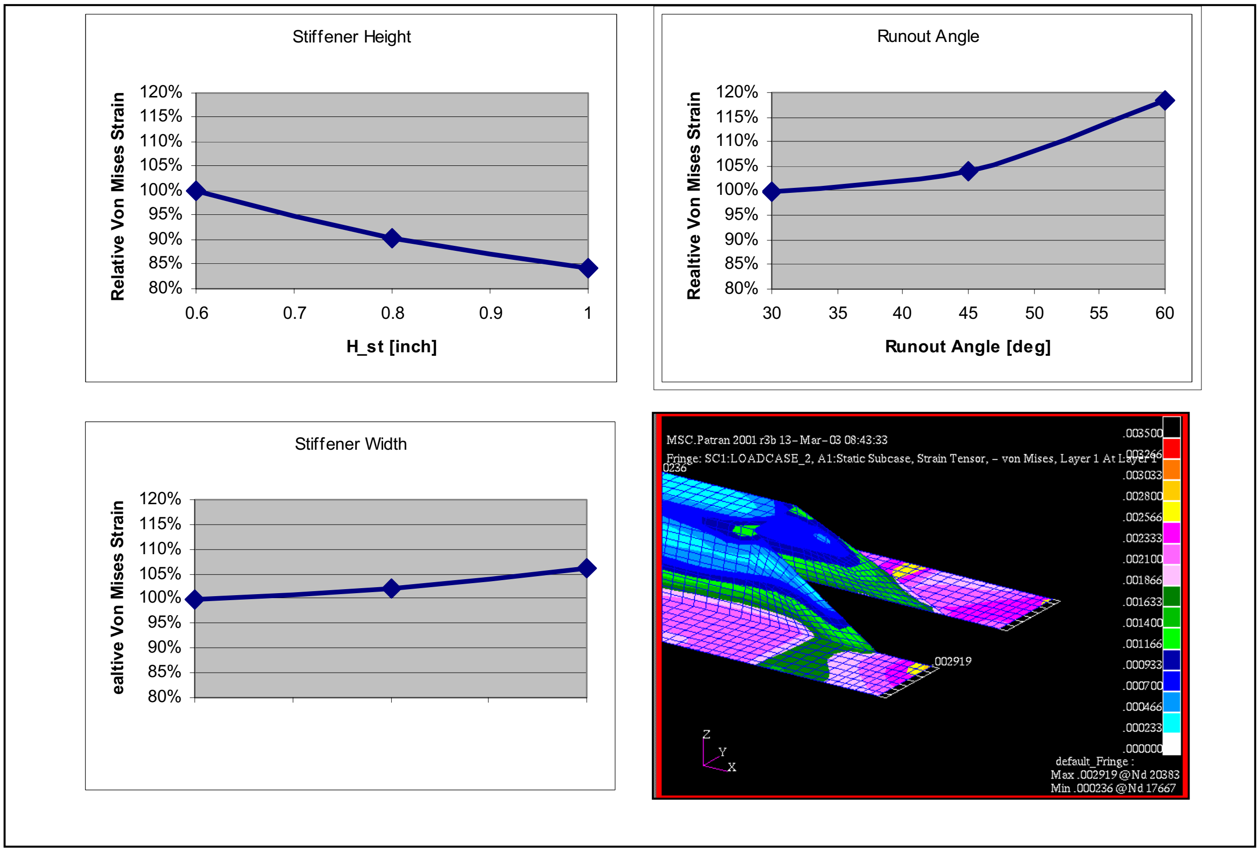

Figure 13-30 Relative Stiffener Von Mises Strain

These curves show the strains in the stiffener trending downward as the height of the stiffener and width are increased and as the run out angle is decreased. These are similar trends as those shown at the bond line. What parameters are the largest contributors to stiffener strains? Figure 13-31 shows the relative strengths of each parameter and the effect of parameter combining on the stiffener strains.

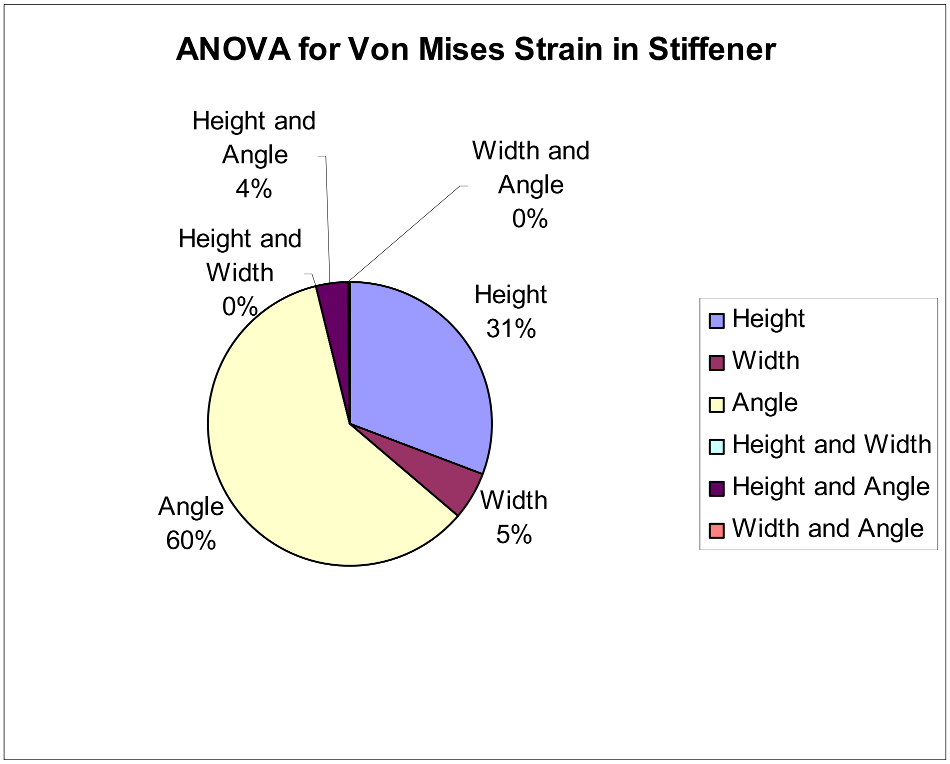

Figure 13-31 Relative Influence of Each Parameter on Von Mises Strain in Stiffener

Within the limits of this study, stiffener strains were most heavily influenced by the run out angle followed by the height of the stiffener. The width of the stiffener is of relatively minor importance. Again, as with the previous bond line study, this study therefore suggests running out the stiffener at a relatively low angle. Say in the range of 30 degrees or so.

Figure 13-32 plots the two strongest influencing parameters as a response surface: the influence of stiffener height and run out angle on the stiffener strains. Also shown in the figure is given a run out angle, one can see the effect of the stiffener height. For instance, one can see that for a 30 degree run out angle strain reduction is most pronounced as the stiffener height is increased from 0.60 inches to 0.80 inches. As the stiffener height increases from 0.80 to 1.0 inches the benefits are less pronounced. This strongly suggest a stiffener height of approximately 0.80 inches for a 30 degree run out is optimal.

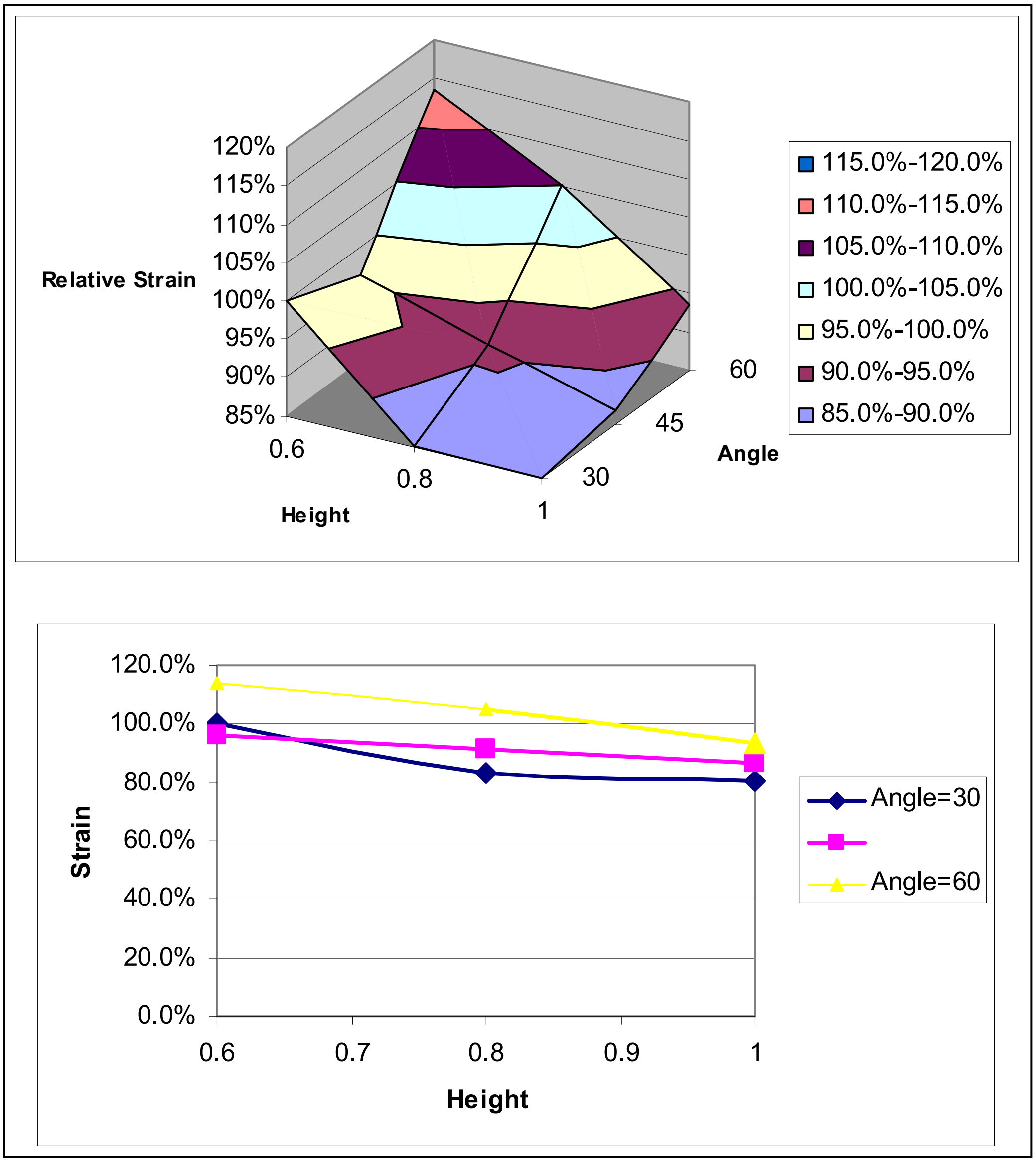

Figure 13-32 Influence of Stiffener Height and Run Out Angle on Stiffener Strain

Skin Strains

The strains in the skin near the frame interface and stiffener run out are of particular concern due to their relatively high level. All configurations show a marked increase in strain level at this location as loads are transferred from the stiffener into the skin and frame. Because the stiffener crown and webs terminate, a very high stiffness change results as one passes from the full height stiffener through the run out and eventually into the frame interface. This is an inherent problem in all configurations of this sort. The skin strains from the full factorial study are shown in Figure 13-33.

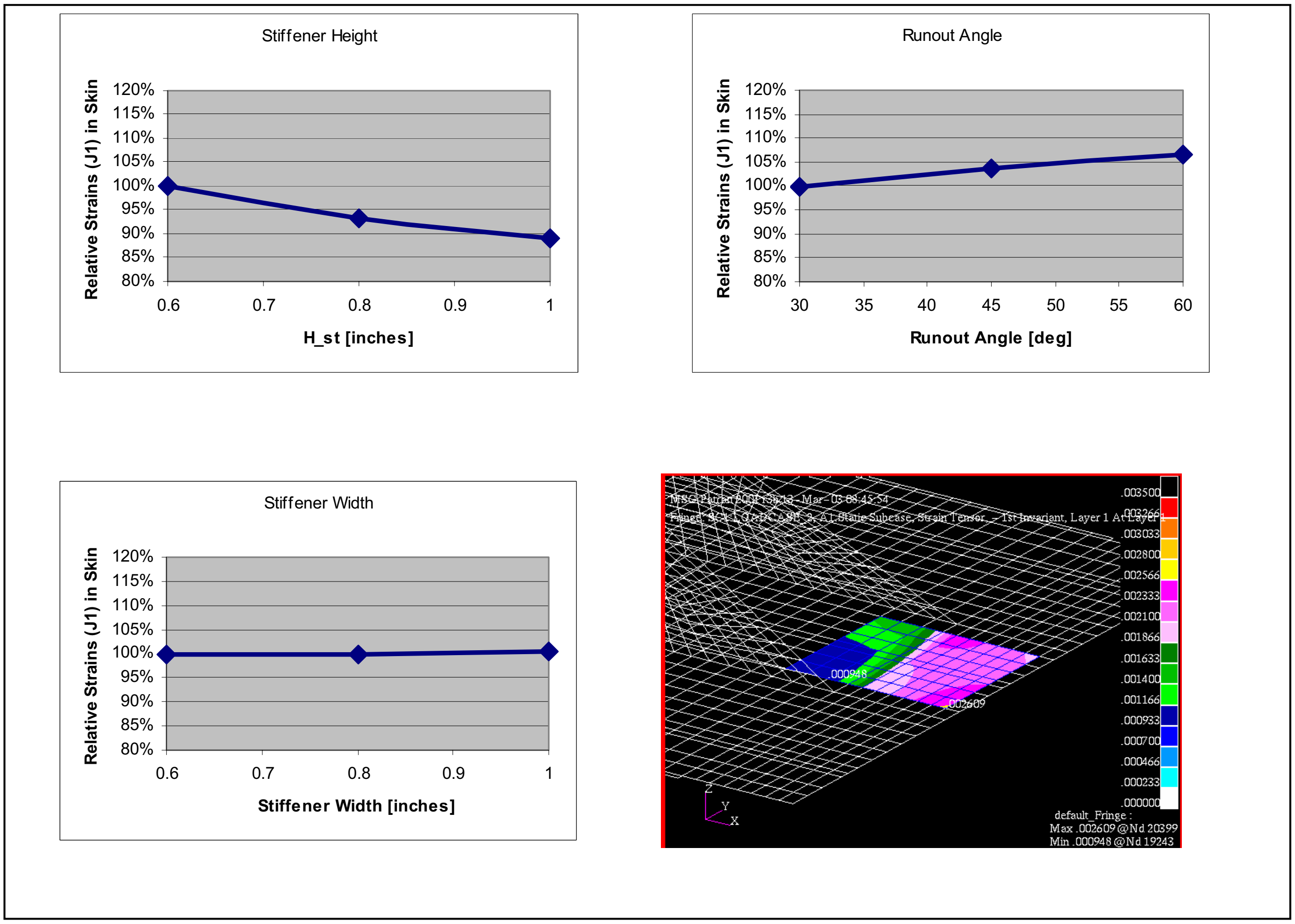

Figure 13-33 Relative Skin Von Mises Strain

These curves show the strains in the skin trending downward as the height of the stiffener is increased and as the run out angle is decreased. Stiffener width has little affect. These are similar trends as those shown at the bond line. What parameters are the largest contributors to skin? Figure 13-34 shows the relative strengths of each parameter and the effect of parameter combining on the skin strains. The plot shows the height of the stiffener is by far the most important parameter influencing the strains in the skin at the stiffener run out. Again, the reader is cautioned that the results are for a set of unchanged skin, stiffener, and wrap thicknesses, material, and stacking sequence groups. In no way does this study discount those very important parameters. This study simply shows the effect of stiffener geometric parameters for a fixed set of skin, stiffener, and wrap thickness, material and stacking sequence parameters and can be used to identify and quantify contributions from the parameters that were varied.

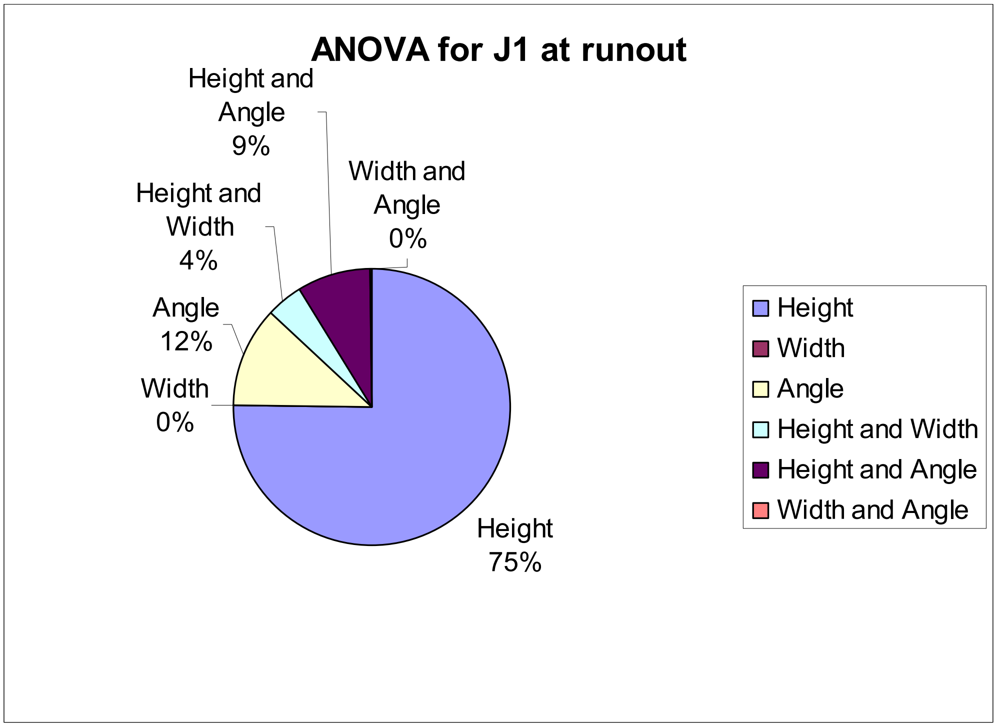

Figure 13-34 Relative Influence of Each Parameter on J1 in Skin at Stiffener Run Out

Within the limits of this study, skin strains were most heavily influenced by the height of the stiffener with taller stiffeners yielding lower skin strains. The width of the stiffener is of relatively minor importance.

Figure 13-35 plots the two strongest influencing parameters as a response surface. This figure strongly shows the influence of stiffener height and run out angle on the skin strains.

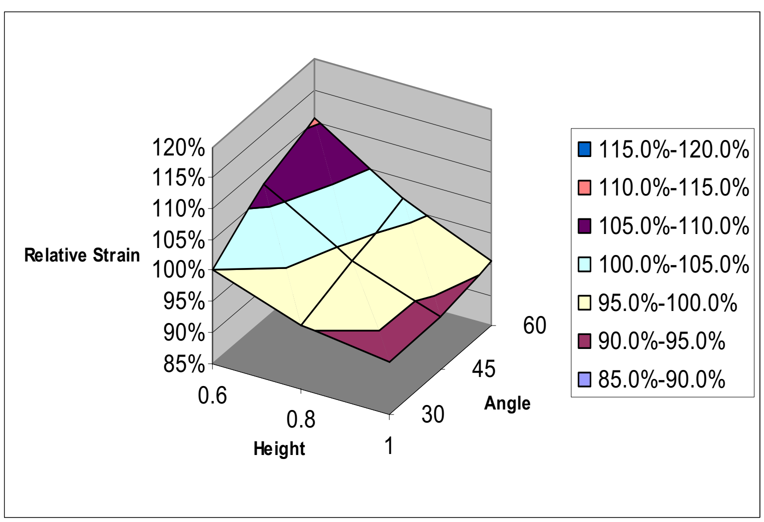

Figure 13-35 Influence of Stiffener Height and Run Out Angle on Skin Strains

The conclusions drawn from this study tended to strongly drive the design concept for the hat stiffened panel. The run out angle was set to 30 degrees which without exception will tend to lower the strains in all components. Buckling capability will be assessed in another study. Stiffener height was firmed up more as the result of this study. In addition it was determined the original design used a very appropriate hat height. The final design of the hat stiffened panel was set to 0.85 inches – only slightly higher than the previous design.

Interaction with Manufacturing

On going coordination with manufacturing allows important information to freely pass between manufacturing and the design group decreasing the possibility of unpleasant surprises upon drawing release.

Selection of Tooling Approach

At this point in the design process the final configuration is very close to being fully defined. A final tooling approach may now be determined. Due to the continuous interaction between the design group and manufacturing this decision has been ongoing and need only be formalized at this point.

Local Model or Detailed FEM Studies

As discussed earlier, there are regions of the shell finite element model that are inadequate for the determination of strength. This section details the use of solid fem submodels used to deal with this.

Figure 13-36 shows a solid finite element model (FEM) laid over the shell model. The detailed solid model must be built using the proper coordinates such that it interfaces exactly with the shell model. A two step solution process is used. The first step is the solution of the shell model. Step two takes the displacements from the shell model and applies them to the solid model at the shell model to shell model interface.