CHAPTER 4 BUILDING BLOCK APPROACH FOR COMPOSITE STRUCTURES

4.1 INTRODUCTION AND PHILOSOPHY

When composites are to be used in structural components, a design development program is generally initiated during which the performance of the structure is assessed prior to use. This process of substantiating the structural performance and durability of composite components generally consists of a complex mix of testing and analysis. Testing alone can be prohibitively expensive because of the number of specimens needed to verify every geometry, loading, environment, and failure mode. Analysis techniques alone are usually not sophisticated enough to adequately predict results under every set of conditions. By combining testing and analysis, analytical predictions are verified by test, test plans are guided by analysis, and the cost of the overall effort is reduced while reliability is increased.

An extension of this synergistic analysis/test approach is to conduct analysis and associated tests at various levels of structural complexity, often beginning with small specimens and progressing through structural elements and details, sub-components, components, and finally the complete full scale product. Each level builds on knowledge gained at previous, less complex levels. This substantiation process, using both testing and analysis in a program of increasingly complex levels, has become known as the “Building Block” approach. The building blocks are integrated with supporting technologies and design considerations as depicted in Figure 4.1(a). One major purpose of employing this approach is to reduce program cost and risk while meeting all technical, regulatory, and customer requirements. The philosophy is to make the design development process more effective in assessing technology risks early in a program schedule. Cost efficiency is achieved by designing a program in which greater numbers of less expensive small specimens are tested and fewer of the more expensive component and full scale articles are required. Using analyses in place of tests where possible also tends to reduce cost.

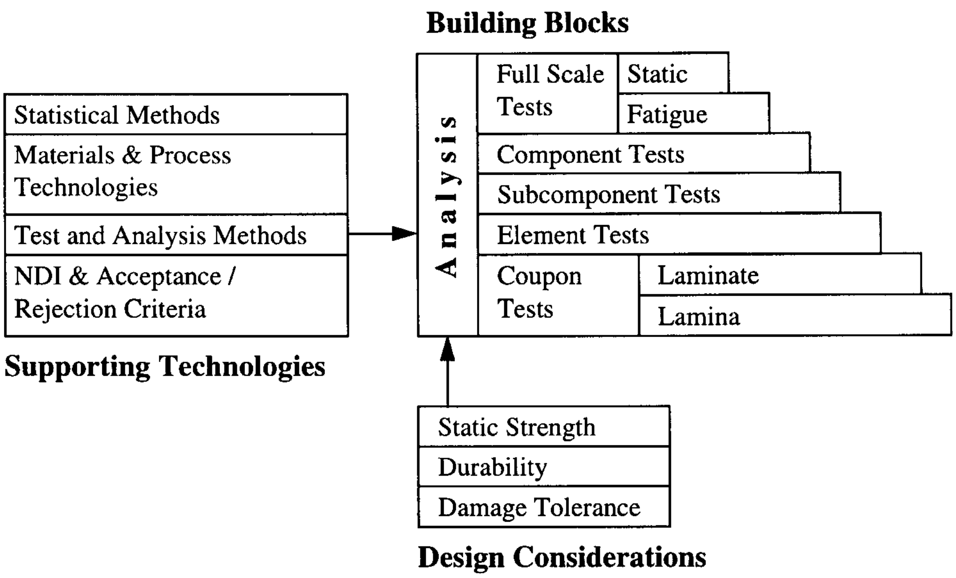

FIGURE 4.1(a) *Building block integration.*

Although the concept of the Building Block approach is widely acknowledged in the composites industry, it is applied with varying degrees of rigor, and details are far from universal. In its simplest form, it represents a method of risk mitigation (both technical and financial) in that testing at the various levels reduces the probability that significant surprises will materialize near the end of a program. In a more elaborate implementation it can be a highly structured and carefully planned effort which addresses many factors in detail, and which may attempt to quantify statistical reliability associated with the process.

Regardless of the details of a specific Building Block program, each level or block takes the general form idealized in Figure 4.1(b) (except for the lowest level). Knowledge gained from analyses and tests in a previous level is combined with structural requirements and used to define and perform the next level of design and analysis. If an acceptable analytical result is not obtained, a structural redesign and/or analysis modification is made until the result is favorable. Once an acceptable analytical result is achieved, it is verified by test. If the test results do not meet the expectations predicted by analysis, the test may be redesigned if an erroneous mode was detected, or the design and/or analytic method may be modified. Additionally, tests or analyses in a previous level may be repeated for verification. The appropriate actions are taken until test results verify an acceptable analytical prediction. When this has been accomplished, the program has advanced to the next level of complexity. It is important to recognize that, since different programs have varying needs, requirements, and constraints, not all building block approaches use the same number of complexity levels or define these levels in the same way.

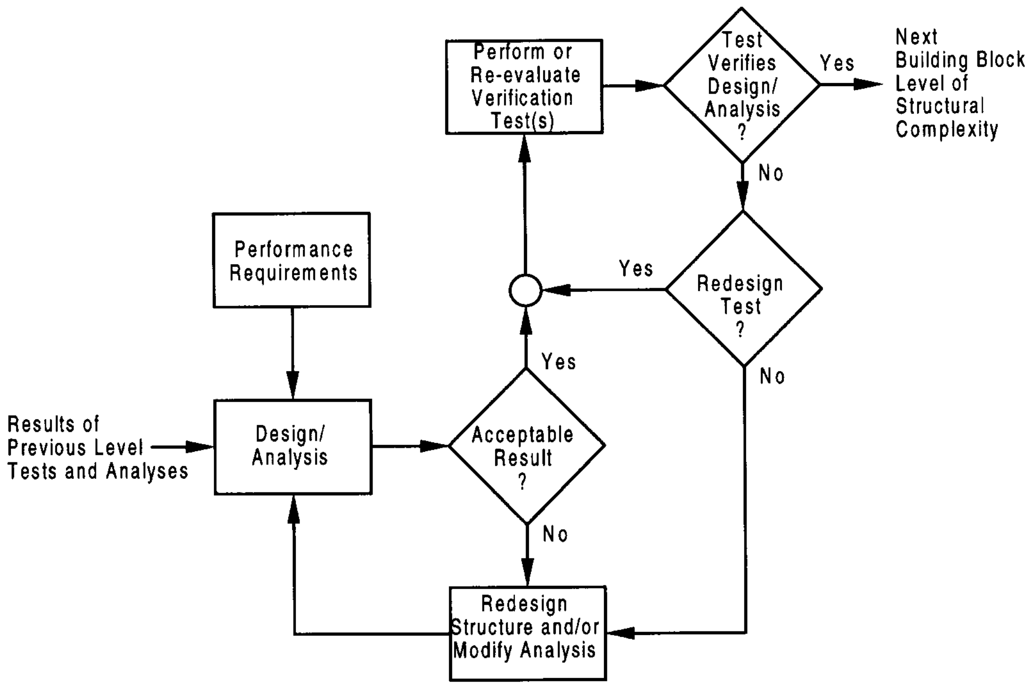

FIGURE 4.1(b) *Idealized general building block schematic (one level).*

Figures 4.1(a) and 4.1(b) and related discussions convey the idea that the Building Block process is a series of steps that progress neatly in order from one block to the next. While this is a convenient way to idealize the Building Block concept, the process is not quite so linear in practice. In reality, program schedules and availability of resources may be such that portions of various blocks overlap in time, and may even occur in parallel. Figure 4.1(c) shows one example of a typical Building Block program flow. The discussion of Building Block levels that follows relates to the idealized model for simplicity.

At the lowest Building Block level, small specimen and element tests are most widely used to characterize basic unnotched static material properties, generic notch sensitivity, environmental factors, material operational limit (MOL – see Volume 1, Chapter 2, Section 2.2.8), and laminate fatigue response. In the case of this first level, testing is used for starting the Building Block process by providing data for first iteration design and analysis. Analysis at this level generally consists of developing material scatter factors and material allowables, evaluation of specimen failure modes, and preliminary laminate analysis. At the same time, external loads for the structure are being defined and initial sizing is being performed.

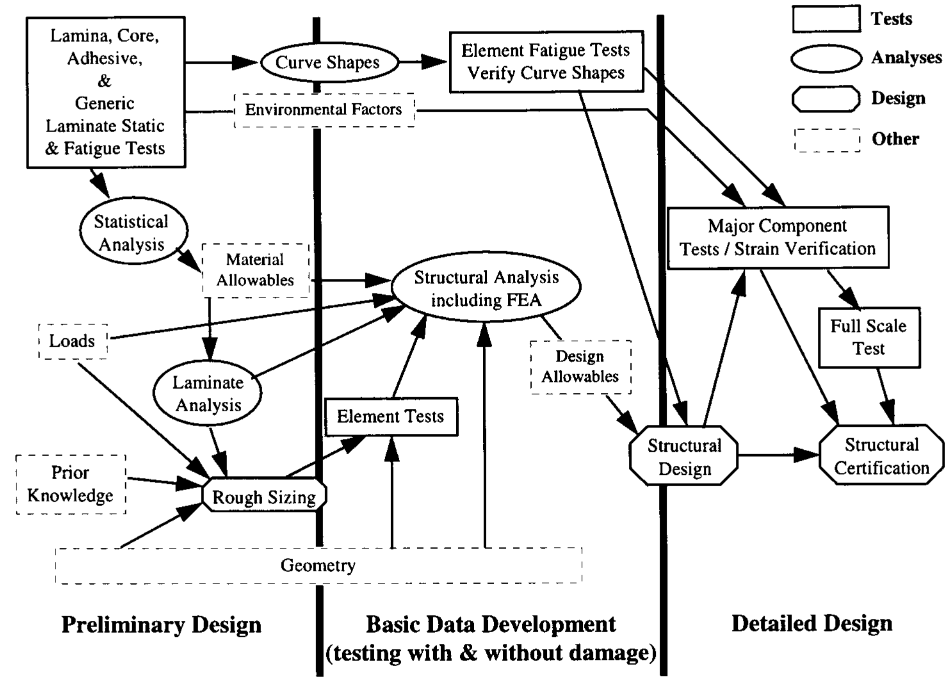

FIGURE 4.1(c) *Typical building block program flow.*

Analysis in the second level uses the basic information obtained at the first level to calculate internal loads, identify critical areas, and predict critical failure modes. More complex element and sub-component tests are designed to isolate single failure modes and verify analysis predictions. At subsequent levels, even more complex static and fatigue loadings are analyzed and verified, with particular attention directed toward assessing out-of-plane loads and identifying unanticipated failure modes. Variabilities introduced by scale-up and response of the structure as a whole are also addressed. The final Building Block level involves full scale static and fatigue testing (as required). This testing validates predicted internal loads, deflections, and failure modes of the entire structure. It also serves to verify that no significant unpredicted secondary loads have appeared.

During the entire Building Block process, manufacturing quality is continually monitored to assure that properties developed early in the program remain valid. One aspect of this activity might include process cycle surveys to verify that larger components experience process histories similar to those of smaller elements and specimens. Also, non-destructive inspections, such as ultrasonic testing, are generally used to assess laminate quality with respect to porosity and voids. Destructive tests might also be used to verify fiber volumes, fiber alignment, and the like.

As noted earlier, the details of applying the Building Block approach are not standardized. While relationships between numbers of specimens and material basis values are well defined for specimen tests at the lowest level (see Volume 1, Chapter 2, Section 2.2.5), the numbers of specimens used at higher levels of complexity are somewhat arbitrary and largely based on historical experience, structural criticality, engineering judgment, and economics. Thus, there is currently no standardized methodology for statistically validating each level of the process, though some attempts have been made to develop models that relate specimen quantities to overall reliability (Reference 4.1). Also, there is no universal approach to the types of analyses or tests, as these may be highly dependent upon particular design details, loadings, and structural criticality.

While it is certainly desirable to standardize the Building Block approach and to develop methods for assigning statistical reliability to the process, these goals are viewed as fairly long term, given the current body of work and diversity of individual approaches. The purpose of this chapter is to summarize the most prevalent and widely accepted methodology, and to present examples of Building Block programs for various applications and material forms.

This section has presented an introduction to the concept of a building block approach. The rationale and assumptions required in developing a building block approach are described in Section 4.2. The general methodology of such an approach is described in Section 4.3. An example describing the use of the building block approach for EMD and production aircraft, processed using autoclave cure of prepreg, is presented in detail in Section 4.4. Section 4.5 includes the use of the building block approach for other applications with general descriptions and references to the more detailed example. The implications of using other types of processing and material forms are discussed in the final section.

4.2 RATIONALE AND ASSUMPTIONS

The Building Block approach has been used in aircraft structures development programs long before the application of composites. However, this approach is more crucial for the certification of composite structures because of issues such as sensitivity to out-of-plane loads, their multiplicity of potential failure modes, and their sensitivity to operating environment. The combination of these issues and an inherent defect sensitivity of the composites, which are best classified as quasi-brittle, has resulted in a lack of analytical tools to predict the behavior of full-scale structure from the lowest level material properties.

The multiplicity of potential failure modes is perhaps the main reason that the Building Block approach is essential in the development of composite structural substantiation. The many failure modes in composite structures are mainly due to the defect, environmental and out-of-plane sensitivities of the materials.

The low interlaminar strength of composites makes them sensitive to out-of-plane loads. Out-of-plane loads can arise directly or be induced from in-plane loads. The most difficult loads to design and analyze for are those loads which arise insidiously in full-scale built-up structures. Analysis tools currently available for structural engineers often assume these loads as secondary loads and they are usually simulated with lower degrees of accuracy. Therefore, it is very important to simulate all potential out-of-plane failure modes and obtain experimental data through a well planned Building Block testing program.

Simulation of the correct failure modes plays an important role in a Building Block testing program. Since failure modes are frequently dependent on the test environment and defects present (manufacturing, bad design detail, or accidental damage), it is important to carefully select the correct test specimens that will simulate the desired failure modes. Special attention should be given to matrix sensitive failure modes. Following selection of the critical failure modes, a series of specimens is designed, each one to simulate a single failure mode. These specimens will generally be lower complexity specimens.

Ideally, if structural analysis tools are fully developed and the failure criteria fully established, the structural behavior would be predictable from the constituent properties. Unfortunately, the capability of the state-of-the-art analysis methods are limited. Thus, lower level test data can not always be used to accurately predict the behavior of structural elements and components with higher levels of complexity. The accuracy of the analytical results are further complicated by the material property variability, the inclusion of defects, and the structural scale-up effects. Therefore, step-by-step building block testings are required to:

1 Uncover failure modes which do not occur at a lower level tests.

2 Verify or modify analysis methods which has been already verified at a lower level.

3 Allow inclusion of the defects in configured structure, which often do not take the same form in specimens and elements (e.g., accidental damage caused by impact).

This approach is based on the assumption that the structural/material response to applied load in test specimens with lower levels of complexity is directly transferable to specimens at higher levels of complexity. For example, fiber strength at the specimen level is the same as the fiber strength in the component. It is also implied that their variability is transferable upward. Thus, a statistical knockdown determined from coupon tests (allowables) provides the same level of confidence at the structural component level.

In a successful Building Block testing program, therefore, specimens can be designed so that failure modes at the lower level of structural complexity would be eliminated at the more complex specimens, by using verified design/analysis methods. Thus, the new failure modes at the next higher level of structural complexity can be isolated. The results of the more complex tests would be used to further modify/verify the analysis methods. Finally, an adequate analysis of methodology is verified and final design can be achieved.

4.3 METHODOLOGY

In Section 4.1, Introduction and Philosophy, the Building Block Approach is introduced and the philosophical framework behind it are discussed, whereas, the Rationale and Assumptions in Section 4.2 provide a logical framework to guide the use of this approach while providing the key assumptions used. However, the Methodology used in performing a building block composite structure development program can spell success or failure in the effort. This section will discuss such Methodology, providing guidelines for its selection and use. The following discussion will present and discuss the methodology used in “building block composite structures development” for various vehicle applications. While there are some differences in methodology among these vehicle types, much of it is similar.

4.3.1 General approach

The methodology used is shown in a generally logical, chronological order, but, during an actual vehicle “building block composite structure development” program, the start and completion of the methodology stages may overlap or not be in the order discussed herein. In such development programs in the real world, preliminary design/analysis of parts and elements and subcomponents may be accomplished using preliminary or estimated allowables. Element and/or subcomponent testing may be started or completed before “design-to” allowables are available. But, “design-to” allowables should be completed before full-scale component testing starts.

The first step is to plan and initiate a suitable composite materials design allowables specimen test program on each composite material to be used. The number of material lots and the number of replicates required per type and environment will depend on whether the vehicle being developed is a prototype, intermediate development (EMD), or production. In addition, the vehicle’s structure criticality within its vehicle category (for instance, Aircraft, Spacecraft, Helicopter, Ground Vehicle, etc.) will affect the number of material lots and specimen replicates per test type and environment.

The materials receiving inspection and acceptance requirements and the Materials & Processes specification requirements will be a function of the structure criticality of the various parts of the selected vehicle. The number and kind of physical, mechanical, thermal, chemical, electrical and process properties tests on the composite material will be a function of this structure criticality.

The amount and level of quality assurance required on the test elements and subcomponents, as well as on the actual parts for the vehicle, is a function of the structure criticality of those parts and defect considerations for structural substantiation and maintenance. In addition the type of tests selected, the number of replicates, and instrumentation needed is a function of the part's structure criticality.

Customer requirements and costs as well as safety and durability concerns may dictate the full scale testing requirements in addition to analytical prediction verification. Such full-scale testing could be proof loading to critical design limit load at RTD conditions, proof loading at various environmental conditions, static test to Design Limit Load (DLL) and Design Ultimate Load (DUL) at RT with or without load enhancement factors to simulate elevated temperatures, and of course static loading to failure, in some cases. In addition, damage tolerance testing is often required to ensure safety for flight critical structure. Durability (fatigue) testing is sometimes required in severe environments and may be required to prove-out long term acceptable economic lifetimes.

The individual methodologies discussed above are, in many cases, available within the companies doing the development work, or, are readily available at a specialty subcontractor. It is usually a matter of organizing such methodologies in a rational manner to achieve an acceptable vehicle composite structure building block development program. Such methodologies are defined and organized in more detail in the individual vehicle type subsections listed below.

4.4 CONSIDERATIONS FOR SPECIFIC APPLICATIONS

4.4.1 Aircraft for prototypes

A detailed description of the allowables and building block test effort needed for acceptable risk and cost effective DOD/NASA prototype composite aircraft structure is presented in the following sections. Section 4.4.1.1 presents the PMC composite allowables generation for DOD/NASA prototype aircraft structure. In Section 4.4.1.2, the PMC composites building block structural development for DOD/NASA prototype aircraft is detailed. And, finally, a summary of allowables and building block test efforts for DOD/NASA prototype composite aircraft structure is given in Section 4.4.1.3.

4.4.1.1 PMC composite allowables generation for DOD/NASA prototype aircraft structure

Allowables generation is needed to support the building block test program depicted in Figure 4.4.1.1, Part A consists of five steps:

1. Experimentally generate ply level static strength and stiffness properties including the testing of 0° or 1-axis tension and compression, 90° or 2-axis tension and compression and 0° or 12-axis in-plane shear specimens with stress/strain curves utilizing, to the extent possible, ASTM D 3039, D 3410, and D 3518.

2. Experimentally generate quasi-isotropic laminate level, static strength and stiffness properties including the testing of x-axis plain and open hole tension, compression, and in-plane shear specimens and tension and compression loaded double shear bearing specimens per ASTM D 3039 for tension and compression and bearing specimens per other standards, respectively, that are currently under development in the ASTM D-30 Committee.

3. The test data generated will be reduced, statistically, to obtain allowable type values using the B-basis value (90% probability, 95% confidence) approach or the 85% of mean value approach if the test scatter is too high. The higher of the two values should be used. This approach was first presented by Grimes in Reference 4.4.1.1.

4. Develop input ply allowables for use in analytical methods that are used in design/analysis. In general the lower of the ultimate or 1.5 x yield strength reduced value should be used for tension, compression, and in-plane shear strength critical allowables. When in-plane shear strength is not critical the reduced ultimate shear strength (a high value) should be used.

5. Laminate design should be fiber-dominated by definition, i.e., a minimum of 10% of the plies should be in each of the 0°, +45°, -45°, and 90° directions. For tape and fabric laminates, always input the 0° or 1-axis strength allowable values in both the 1- and 2-axis slots in the analytical methods for tensile and compressive loads. Shear inputs will be as described above. This approach will ensure fiber dominated failure and was first presented by Grimes in Reference 4.4.1.1. All laminates should be balanced and symmetric.

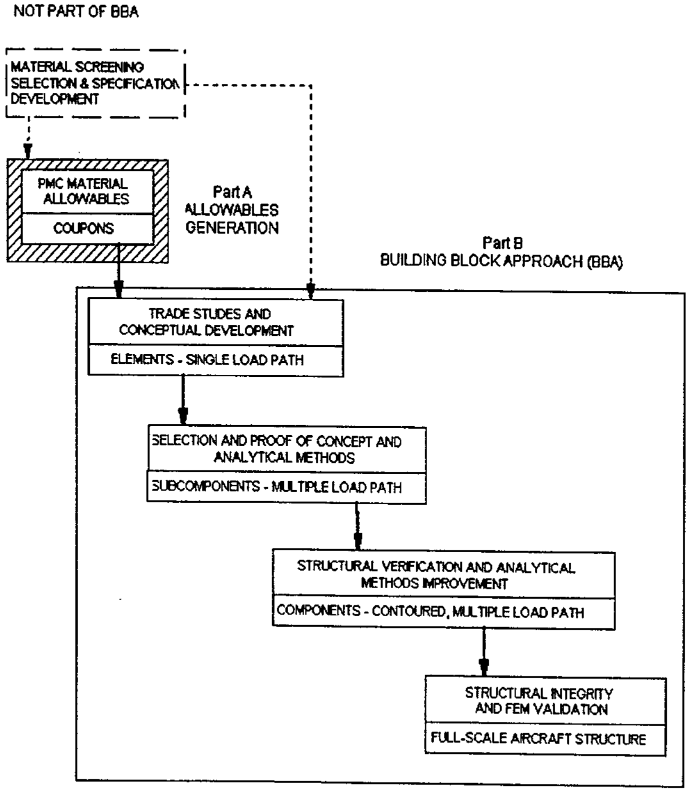

FIGURE 4.4.1.1 *Aircraft structural development goals using building block approach (BBA).*

A structure classification/allowables chart which defines the relationship between aircraft structure criticality and the allowables requirements for prototypes is presented in Table 4.4.1.1(a). In Table 4.4.1.1(b) structural classification vs. physical defect maximum requirements are given so that the acceptable physical defect size parameter varies indirectly with the aircraft structure criticality. Thus, aircraft structure criticality controls the reliability of the data (allowables) and the material and parts quality that are necessary to support it.

TABLE 4.4.1.1(a) *DOD/NASA aircraft structure classification vs. PMC allowables data requirements for prototypes (Reference 4.4.1.1)*.

PART A
(From Figure 4.4.1.1)

Aircraft Structure Classification		Allowable Data Requirements for Prototype Design	
Classification	Description	Preliminary (Tape/Fabric)	Final (Tape/Fabric)
PRIMARY • Fracture critical (F/C)	CARRIES PRIMARY AIR LOADS • Failure will cause loss of vehicle	Based on 1. Estimates using data on similar materials and experience	1 - lot materials testing: 5 to 8 replicates per test type (static)
• Noncritical (N/C)	• Failure will not cause loss of vehicle	2. Vendor Data 3. Journals, magazines and books	1 - lot materials testing: 4 to 6 replicates per test type (static)
SECONDARY • Fatigue critical (FA/C) & economic life critical (EL/C)	CARRIES SECONDARY AIR & OTHER LOADS • Failure will not cause loss of vehicle but may cause cost critical parts replacements	Based on 1. Estimates using data on same or similar materials	1 - lot materials testing: 3 to 4 replicates per test type (static) plus fatigue testing
• Noncritical (N/C)	• Failure will not cause loss of vehicle • No cost or fatigue critical parts	2. Vendor data 3. Journals, magazines and books	Use legitimate, verified data bases
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure replacement of parts causing minor inconvenience, not cost critical	Based on 1. Estimates using data on similar materials, or 2. Vendor data, or 3. Journals, magazines and books	Estimates using data on similar materials, or Vendor data, or Journals, magazines and books

TABLE 4.4.1.1(b) *DOD/NASA aircraft structure classification vs. PMC physical defect minimum requirements for prototypes (Reference 4.4.1.1).*

PART A AND B
(From Figure 4.4.1.1)

Aircraft Structure		Physical Defect Maximum Requirements for Parts: Carbon or Glass Reinforced PMC Example	
Classification	Description	Tape	Fabric
PRIMARY • Fracture critical (F/C)	CARRIES PRIMARY AIR LOADS • Failure will cause loss of vehicle	≤3% porosity over ≤10% of area. Delaminations over ≤1% of area. No edge delaminations allowed (including holes).	≤5% porosity over ≤10% of area. Delaminations over ≤1% of area. No edge delaminations allowed (including holes).
• Noncritical (N/C)	• Failure will not cause loss of vehicle		
SECONDARY • Fatigue critical (FA/C) & economic life critical (EL/C)	CARRIES SECONDARY AIR & OTHER LOADS • Failure will not cause loss of vehicle but may cause cost critical parts replacements	≤3% porosity over ≤15% of area. Delaminations over ≤2% of area. No edge delaminations allowed (including holes).	≤5% porosity over ≤15% of area. Delaminations over ≤2% of area. No edge delaminations allowed (including holes).
• Noncritical (N/C)	• Failure will not cause loss of vehicle • No cost or fatigue critical parts		
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure replacement of parts causing minor inconvenience, not cost critical	≤4% porosity over ≤20% of area. Delaminations over ≤3% of area. Repaired edge delaminations ≤10% of edge length or hole circumference are allowed.	≤4% porosity over ≤20% of area. Delaminations over ≤3% of area. Repaired edge delaminations ≤10% of edge length or hole circumference are allowed.

4.4.1.2 PMC composites building block structural development for DOD/NASA prototype aircraft

Part B of the flowchart in Figure 4.4.1.1 defines the building block test effort in the general categories of:

1. Trade studies and concept development (element-single load path),
2. Selection, proof of concept, and analytical methods verification (sub-component-multiple load paths),
3. Structural verification and analytical methods improvement (contoured composite-multiple load path), and
4. Structural integrity and FEM validation (full-scale aircraft structure testing).

The allowables shown in Figure 4.4.1.1 Part A and in Table 4.4.1.1 (a) logically flow into Part B, building block testing. Table 4.4.1.1(b) on physical defect requirements applies to both Parts A and B. The Part B building block test effort is delineated in Table 4.4.1.2(a) in accordance with the part's structural classification. The four categories, above, are defined in detail for each structural classification, with the higher the structural classification, the more testing and analysis required. The key point here is that these are guidelines for structural development testing. The actual structural testing needed for a specific classification of structure could be more or less, depending on the vehicle's mission and whether it is manned or unmanned. Knowing the structural part classification, the aircraft's purpose and mission, risk analysis can be applied to minimize testing cost and risk. FEM and closed form composite analysis methods utilizing proper mechanical and physical properties and allowables input data will be necessary every step of the way. Failure modes and loads (stresses) as well as strain and deflection readings must be monitored and correlated with predictions to assure low risk. The use of FEM or other analysis methods alone (without testing) or with inadequate testing that does not properly interrogate failure modes, stresses (strains), and deflections for comparison with predictions can create high risk situations that should not be tolerated.

Another risk issue for composite structure is quality assurance (QA), a subject that applies to both Parts A and B. Table 4.4.1.2(b) presents the nominal QA requirements for the categories of

1. Material and process selection, screening, and <u>material specification</u> qualification,
2. Receiving inspection/acceptance testing,
3. In-process inspection,
4. Non-destructive inspection (NDI),
5. Destructive testing (DT), and
6. Traceability

The QA requirements in each of these categories vary with the structural classification, with the higher the classification, the more quality assurance required. By following the procedure outlined in this table, the amount of QA necessary to keep risk at an acceptable level can be ascertained. Again the amount of QA needed and the risk taken will be a function of the aircraft type and mission and whether it is manned or unmanned. Risk and cost are inversely proportional to each other for composite structural parts in each classification, so the determination of acceptable risk is necessary to this building block test program for prototypes.

TABLE 4.4.1.2(a) *DOD/NASA aircraft structure classification and goals vs. PMC building block development tests for prototypes (Reference 4.4.1.1)* (continued on next page).

PART B (From Figure 4.4.1.1)

Aircraft Structure		Building Block Structural Development Test Effort	
Aircraft Structure Development Goals		Trade Studies and Conceptual Development Analysis	Selection and Proof of Concept Testing and Analytical Methods Development
Classification	Description	Element - Single Load Path	Sub-Component - Multiple Load Paths (Including Joints)
PRIMARY	CARRIES PRIMARY AIR LOADS	Concept and analytical methods development - static and fatigue test (optional)	Proof of concept and analytical methods - static and fatigue test (residual strength)
• Fracture critical (F/C)	• Failure will cause loss of vehicle	3 - each stiffening configuration 3 - each joint configuration	1 box beam/cylinder: static ultimate 1 box beam cylinder: fatigue and residual strength
• Noncritical (N/C)	• Failure will not cause loss of vehicle	1 - each stiffening configuration 1 - each joint configuration	1 box beam/cylinder: static ultimate
SECONDARY • Fatigue critical (FA/C) & economic life critical (EL/C)	CARRIES SECONDARY AIR & OTHER LOADS • Failure will not cause loss of vehicle but may cause cost critical parts replacements	Concept and analytical methods development - static and fatigue test 2 - each stiffening configuration 2 - each joint configuration	Proof of concept and analytical methods - static (DLL/fatigue/ residual strength test) 2 box beam/cylinder: static (DLL/fatigue/residual strength test)
• Noncritical (N/C)	• Failure will not cause loss of vehicle • No cost or fatigue critical parts	1 - each stiffening configuration 1 - each joint configuration	No testing required - proved by element tests
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure/replacement of parts causing minor inconvenience, not cost critical	Concept development/static test/ analytical methods check 1 - each most critical configuration	Proof of concept: element testing plus analysis No testing required - proved by element tests and analysis

TABLE 4.4.1.2(a) *DOD/NASA aircraft structure classification and goals vs. PMC building block development tests for prototypes (Reference 4.4.1.1)* (concluded).

PART B

Aircraft Structure		Building Block Structural Development Test Effort	
Aircraft Structure Development Goals		Structural Verification Testing for Analytical Methods	Structural Integrity testing for FEM Validation
Classification	Description	Component with True Contours - Multiple Load Paths	Full Scale Aircraft Structure: Simulated Air Loads & Load Paths
PRIMARY	CARRIES PRIMARY AIR LOADS	Structural verification: static and durability and damage tolerance tests	Structural integrity validation - static strain survey & proof test; static test to DUL/failure or fatigue test depending on budget and schedule requirements
• Fracture critical (F/C)	• Failure will cause loss of vehicle	1 large structural section: static damage tolerance to DUL/failure 1 large structural section: damage tolerance and durability plus residual strength	1 proof test - critical flight load condition: strain/deflection survey and fatigue and residual strength to DLL, to DUL and failure if required
• Noncritical (N/C)	• Failure will not cause loss of vehicle	1 large structural section: static and durability critical damage tolerance to DLL, then take to DUL/failure for residual strength test	1 proof test - critical flight load condition: strain/deflection survey and static test to DLL, durability testing and static residual strength to DUL and failure if required
SECONDARY	CARRIES SECONDARY AIR & OTHER LOADS	Structural verification and analytical methods improvement: static and durability and damage tolerance tests (DUL/failure)	Structural integrity validation - static strain survey & proof test; static test to DUL and failure if required
• Fatigue critical (FA/C) & economic life critical (EL/C)	• Failure will not cause loss of vehicle but may cause cost critical parts replacements	1 large structural section: static damage tolerance to DUL/failure	1 proof test: - critical flight load condition: strain/deflection survey and static test to DLL, to DUL if required
• Noncritical (N/C)	• Failure will not cause loss of vehicle • No cost or fatigue critical parts	No testing required - proved by element tests and analysis	No testing required – proved by element tests
NONSTRUCTURAL	NON- OR MINOR LOAD BEARING	Structural verification by proof test/analysis	Structural integrity validation by previous tests and analysis

TABLE 4.4.1.2(b) *DOD/NASA aircraft structure classification vs. PMC quality assurance requirements for prototypes (Reference 4.4.1.1)* (continued on next page).

PART A and B

Aircraft Structure		Quality Assurance Requirements		
Classification	Description	M&P Selection, Screening, and Qualification	Receiving Inspection/Acceptance Testing*	In-Process Inspection
PRIMARY • Fracture critical (F/C) • Noncritical (N/C)	CARRIES PRIMARY AIR LOADS • Failure will cause loss of vehicle • Failure will not cause loss of vehicle	Preliminary physical, mechanical, & process variable evaluation & 1-sheet specification development; record evaluate, select & store test data	Per preliminary 1-sheet M&P specifications - minimum physical, mechanical, & process property requirements - test for acceptability; engineering accept/reject decision; store test data	Per preliminary 1-sheet process specification & drawing - inspect/ record for conformance & use engineering judgment for accept/reject decision; store test data
SECONDARY • Fatigue critical (FA/C) & economic life critical (EL/C) • Noncritical (N/C)	CARRIES SECONDARY AIR & OTHER LOADS • Failure will not cause loss of vehicle but may cause cost critical parts replacements • Failure will not cause loss of vehicle • No cost or fatigue critical parts	Preliminary, but limited, physical, mechanical, & process variable evaluation & 1-sheet specification development; record, evaluate, select & store test data	Per preliminary, but limited, 1-sheet M&P specifications - minimum physical, mechanical, & process property requirements - minimal tests for acceptability; engineering accept/reject decision; store test data	Per preliminary, but limited, 1-sheet process specification & drawing - inspect/ record for conformance and use engineering judgment for accept/reject decision; store test data
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure replacement of parts causing minor inconvenience, not cost critical	Limited physical property tests; use vendor recommended process; store data	Vendor certification	Worker self-inspection per vendor process

* May be done at material vendors plant to 1-sheet specification after M&P approval.

TABLE 4.4.1.2(b) *DOD/NASA aircraft structure classification vs. PMC quality assurance requirements for prototypes (Reference 4.4.1.1)* (concluded).

PART A and B

Aircraft Structure		Quality Assurance Requirements		
Classification	Description	Non-Destructive Inspection (NDI)	Destructive Testing (DI)	Traceability
PRIMARY • Fracture critical (F/C)	CARRIES PRIMARY AIR LOADS • Failure will cause loss of vehicle	100% area; engineering accept/ reject decision based on defect standard (defect panel or lead tape); store data	Preliminary physical and mechanical property testing on non-integral process control panel; engineering accept/ reject decision; store test data	Keep files on all receiving, in-process, & non-destructive inspection & destructive test records for each vehicle
• Noncritical (N/C)	• Failure will not cause loss of vehicle			
SECONDARY • Fatigue critical (FA/C) & economic life critical (EL/C)	CARRIES SECONDARY AIR & OTHER LOADS • Failure will not cause loss of vehicle but may cause cost critical parts replacements	90% area; engineering accept/ reject decision based on defect standard (defect panel or lead tape); store data	Preliminary, but limited, physical and mechanical testing on non-integral process control panel; engineering accept/ reject decision; store test data	Keep files on all receiving, in-process, & non-destructive inspection & destructive test records for each vehicle
• Noncritical (N/C)	• Failure will not cause loss of vehicle • No cost or fatigue critical parts			
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure replacement of parts causing minor inconvenience, not cost critical	None	None	None

4.4.1.3 Summary of allowables and building block test efforts for DOD/NASA prototype composite aircraft structure

In the above sections, composite material allowables development needed for prototype aircraft is detailed along with the related building block test effort required for such structure development. Both allowables requirements and building block structural test requirements are related to aircraft structure part criticality classifications and then each is related to the test/evaluation/analysis categories that need to be interrogated to study the risk involved. For allowables the categories are preliminary and final values and physical defect minimum requirements in each classification. For the building block structures development test effort categories, the procedure used is the progressive scale up of the size of the test parts along with going from single to multiple load paths and adding joints to the test structure as it gets bigger. And, finally, the relationship of the quality assurance requirements from those required for design allowables for flat panels to those required for major structural components to those required for full size structure are presented for the six QA needs categories for each structural classification of the parts to be built.

The Part A allowables effort will provide for acceptable risk and cost effective allowables for composite structure prototypes. The Part B building block structures test development effort will satisfy the goals of:

1. Appropriate conceptual development,
2. Proof of concept and analytical methods development,
3. Structural verification testing for analytical methods, and
4. Structural integrity testing and FEM validations.

Once these goals are achieved, the user will have acceptable risk, cost effective prototype composite aircraft structure that will have the necessary integrity and reliability needed for the specific aircraft being developed.

4.4.2 Aircraft for EMD and production

A detailed description of the allowables and building block test effort needed for acceptable risk and cost effective DOD/NASA engineering and manufacturing development (EMD) and production composite aircraft structure is presented in the following sections. Section 4.4.2.1 presents the PMC composite allowables generation for DOD/NASA EMD and production aircraft structure. In Section 4.4.2.2, the PMC composites building block structural development for DOD/NASA EMD production aircraft is detailed. And finally, a summary of allowables and building block test efforts for DOD/NASA EMD and production composite aircraft structure is given in Section 4.4.2.3.

4.4.2.1 PMC composite allowables generation for DOD/NASA EMD and production aircraft structure

Allowables generation is needed to support the building block test program depicted in Figure 4.4.2.1, Part A consists of five steps:

1. Experimentally generate ply level static strength and stiffness properties including the testing of 0^o or 1-axis tension and compression, 90^o or 2-axis tension and compression and $0^o/90^o$ or 12-axis edgewise shear specimens with stress/strain curves utilizing, to the extent possible, ASTM D 3039, D 3410, and D 3518.

2. Experimentally generate quasi-isotropic laminate level, static strength and stiffness properties including the testing of x-axis plain and open hole tension and compression specimens and tension loaded double shear bearing specimens per ASTM D 3039 for tension and compression and bearing specimens per other standards, respectively, that are currently under development in the ASTM D-30 Committee.

3. The test data generated will be reduced, statistically, to obtain allowable type values using the B-basis value (90% probability, 95% confidence) approach. For EMD prototypes use the guidelines in Section 4.4.1.1.

4. Develop input ply allowables for use in analytical methods that can be used in design/analysis. In general the lower of the ultimate or 1.5 x yield strength reduced values should be used for tension and compression. Edgewise shear strength ultimate values should be used for allowables when edgewise shear strength is not critical. The reduced (1.5 x yield) ultimate edgewise shear strength should be used when edgewise shear loads are critical.

5. Laminate design should be fiber-dominated by definition, i.e., a minimum of 10% of the plies should be in each of the 0^o, $+45^o$, -45^o, and 90^o directions. For tape and fabric laminates, always input the 0^o or 1-axis strength allowable values in both the 1- and 2-axis slots in the analytical methods for tensile and compressive loads. Shear inputs will be as described above. This approach was first presented by Grimes in Reference 4.4.1.1. All laminates should be balanced and symmetric.

A structure classification/allowables chart which defines the relationship between aircraft structure criticality and the allowables requirements for EMD and production is presented in Table 4.4.2.1(a). In Table 4.4.2.1(b) structural classification vs. physical defect maximum requirements are given so that the physical defect size parameter varies indirectly with the aircraft structure criticality. Thus, aircraft structure criticality controls the reliability of the data (allowables) and the material quality that are necessary to support it.

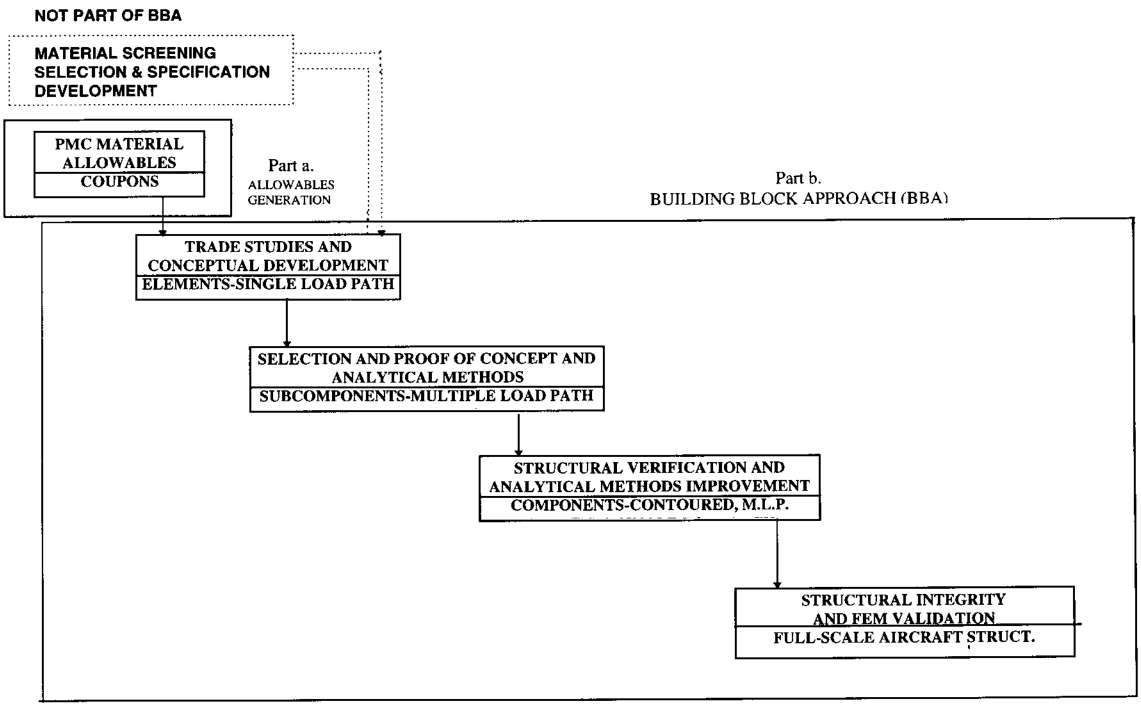

Figure 4.4.2.1 *Aircraft structure development goals using Building Block Approach (BBA)*

TABLE 4.4.2.1(a) *DOD/NASA aircraft structure classification vs. PMC allowables data requirements for EMD* and production*

PART A
(Reference Figure 4.4.2.1)

Aircraft Structure Classification		Allowable Data Requirements for EMD and Production* Design	
Classification	Description	EMD* (Tape/Fabric)	Production (Tape/Fabric)
PRIMARY • Fracture critical (F/C)	CARRIES PRIMARY AIR LOADS • Failure will cause loss of vehicle	1-lot materials testing 8-replicates per test type	Based on: 5-lots of materials testing 8-replicates per test type
• Noncritical (N/C)	• Failure will not cause loss of vehicle, cost critical replacement or repair	1-lot materials testing 6-replicates per test type	4-lots of materials testing 6-replicates per test type
SECONDARY • Fatigue critical (FA/C) and economic life critical (EL/C)	CARRIES SECONDARY AIR AND OTHER LOADS • Failure will not cause loss of vehicle, cost critical replacement or repair	1-lot materials testing 4-replicates per test type plus fatigue testing	3-lots of materials testing 5-replicates per test type plus fatigue testing
• Noncritical (N/C)	• Failure will not cause loss of vehicle • Not cost or fatigue critical	N/A	2-lots of materials testing 4-replicates per test type
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure/replacement minor inconvenience, not cost critical	Based on 1. Estimates using data on similar materials, or 2. Vendor data, or 3. Journals, magazines and books	1-lot of materials testing 3-replicates per test type

*For EMD, use procedure given for prototypes in Section 4.4.1

TABLE 4.4.2.1(b) *DOD/NASA aircraft structure classification vs. PMC physical defect minimum requirements for EMD* and production*

PARTS A AND B
(Reference Figure 4.4.2.1)

Aircraft Structure		Physical Defect Maximum Requirements for Parts: Carbon or Glass Reinforced PMC Example	
Classification	Description	Tape	Fabric
PRIMARY • Fracture critical (F/C)	CARRIES PRIMARY AIR LOADS • Failure will cause loss of vehicle	≤2% porosity over ≤5% of area. No delaminations allowed. No edge delaminations allowed (including holes).	≤3% porosity over ≤5% of area. No delaminations allowed. No edge delaminations allowed (including holes).
• Noncritical (N/C)	• Failure will not cause loss of vehicle, cost critical replacement or repair.		
SECONDARY • Fatigue critical (FA/C)	CARRIES SECONDARY AIR & OTHER LOADS • Failure will not cause loss of vehicle, cost critical replacement	≤2% porosity over ≤10% of area. No delaminations. No edge delaminations allowed (including holes).	≤3% porosity over ≤10% of area. No delaminations. No edge delaminations allowed (including holes).
• Noncritical (N/C)	• Failure will not cause loss of vehicle • Not cost or fatigue critical		
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure/replacement minor inconvenience, not cost critical	≤3% porosity over ≤10% of area. Delaminations over ≤2% of area. Repaired edge delaminations ≤4% of edge length or hole circumference are allowed.	≤4% porosity over ≤15% of area. Delaminations over ≤2% of area. Repaired edge delaminations ≤4% of edge length or hole circumference are allowed.

*For EMD, use procedure given for prototype in Section 4.4.1

4.4.2.2 PMC composite building block structural development for DOD/NASA EMD and production aircraft

Part B of the flowchart in Figure 4.4.2.1 defines the building block test effort in the general categories of:

1. Trade studies (element-single load path),
2. Selection, proof of concept, and analytical methods (sub-component-multiple load paths),
3. Structural verification and analytical methods improvement (contoured composite-multiple load path), and
4. Structural integrity and FEM validation (full-scale aircraft structure testing).

The allowables shown in Figure 4.4.2.1 Part A and in Table 4.4.2.1(a) logically flow into Part B, building block testing. Table 4.4.2.1(b) on physical defect requirements applies to both Parts A and B. The Part B building block test effort is delineated in Table 4.4.2.2(a) in accordance with the part's structural classification. The four categories above are defined in detail for each structural classification, with the higher structural classification requiring more testing and analysis. The key point here is that these are guidelines for structural development testing. The actual structural testing needed for a specific classification of structure could be more or less, depending on the vehicle's mission and whether it is manned or unmanned. Knowing the structural part classification, the aircraft's purpose and mission, risk analysis can be applied to minimize testing cost and risk. FEM and closed form composite analysis methods utilizing proper mechanical and physical properties and allowables input data will be necessary every step of the way. Failure modes and loads (stresses) as well as strain and deflection readings must be monitored and correlated with predictions to assure low risk. The use of FEM or other analysis methods alone (without testing) or with inadequate testing that does not properly interrogate failure modes, stresses (strains), and deflections for comparison with predictions can create high risk situations that should not be tolerated.

Another risk issue for composite structure is quality assurance (QA), a subject that applies to both Parts A and B. Table 4.4.2.2(b) presents the nominal QA requirements for the categories of

1. Material and process selection, screening, and materials specification qualification,
2. Receiving inspection/acceptance testing,
3. In-process inspection,
4. Non-Destructive inspection (NDI),
5. Destructive testing (DT), and
6. Traceability.

The QA requirements in each of these categories vary with the structural classification, with the higher classification requiring more quality assurance. By following the procedure outlined in this table, the amount of QA necessary to keep risk at an acceptable level can be ascertained. Again the amount of QA needed and the risk taken will be a function of the aircraft type and mission and whether it is manned or unmanned. Risk and cost are inversely proportional to each other for composite structural parts in each classification, so the determination of acceptable risk is necessary to this building block test program for EMD and production.

TABLE 4.4.2.2(a) *DOD/NASA aircraft structure classification and goals vs. PMC building block development tests for EMD* and production*, (continued on next page).

PART B (Reference Figure 4.4.2.1)

Aircraft Structure		Building Block Structural Development Test Effort	
Aircraft Structure Development Goals		Trade Studies and Conceptual Development Analysis	Selection and Proof of Concept Testing and Analytical Methods Development
Classification	Description	Element - Single Load Path	Sub-Component - Multiple Load Paths (Including Joints)
PRIMARY	CARRIES PRIMARY AIR LOADS	Concept and analytical methods development - static and fatigue test (mandatory)	Proof of concept and analytical methods - static and fatigue test (residual strength)
• Fracture critical (F/C)	• Failure will cause loss of vehicle	6-each stiffening configuration 6-each joint configuration	4-box beam/cylinder static ultimate 6-box beam/cylinder: fatigue and residual strength
• Noncritical (N/C)	• Failure will not cause loss of vehicle, cost critical replacement or repair	4-each stiffening configuration 4-each joint configuration	3-box beam/cylinder: static ultimate 1-fatigue, residual strength
SECONDARY	CARRIES SECONDARY AIR & OTHER LOADS	Concept and analytical methods development - static and fatigue test (mandatory)	Proof of concept and analytical methods - static (DLL/fatigue/residual strength test)
• Fatigue critical (FA/C) & economic life critical (EL/C)	• Failure will not cause loss of vehicle, cost critical replacement	3-each stiffening configuration 3-each joint configuration	3-box beam/cylinder: static (DLL/fatigue/residual strength test)
• Noncritical (N/C)	• Failure will not cause loss of vehicle • Not cost or fatigue critical	2-each stiffening configuration 2-each joint configuration	2-fatigue residual strength required
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure/replacement minor inconvenience, not cost critical	Concept development/static test/analytical methods check 1-each most critical configuration	Proof of concept: element testing plus analysis 1-fatigue, residual strength

*For EMD, use procedure given to prototypes in Section 4.4.1

TABLE 4.4.2.2(a) *DOD/NASA aircraft structure classification and goals vs. PMC building block development tests for EMD* and production*, concluded

PART B (Reference Figure 4.4.2.1)

Aircraft Structure		Building Block Structural Development Test Effort	
Aircraft Structure Development Goals		Structural Verification Testing for Analytical Methods	Structural Integrity Testing for FEM Validation
Classification	Description	Component With True Contours - Multiple Load Paths	Full Scale Aircraft Structure: Simulated Air Loads & Load Paths
PRIMARY	CARRIES PRIMARY AIR LOADS	Structural verification: static and durability and damage tolerance tests	Structural integrity validation - static strain survey & proof test; static test to DUL/failure or fatigue test depending on budget and schedule requirements
• Fracture critical (F/C)	• Failure will cause loss of vehicle	3-different large structural sections: static damage tolerance to DUL/failure 6-large structural sections: damage tolerance and durability plus residual strength (3 configurations)	3-different proof tests - critical flight load condition: strain/deflection survey and fatigue and residual strength to DLL, to DUL and failure if required
• Noncritical (N/C)	• Failure will not cause loss of vehicle, repair or replacement cost critical	2-large structural section: static and durability critical damage tolerance to DLL, then take to DUL/failure for residual strength test	2-proof tests - critical flight load condition: strain/deflection survey and static test to DLL, durability testing and static residual strength to DUL and failure if required
SECONDARY	CARRIES SECONDARY AIR & OTHER LOADS	Structural verification and analytical methods improvement: static and durability and damage tolerance tests (DUL/failure)	Structural integrity validation - static strain survey & proof test; static test to DUL and failure if required
• Fatigue critical (FA/C) & economic life critical (EL/C)	• Failure will not cause loss of vehicle, cost critical replacement	3-large structural sections: static damage tolerance to DUL/failure	1 proof test - critical flight load condition: strain/deflection survey and static test to DLL, to DUL if required
• Noncritical (N/C)	• Failure will not cause loss of vehicle • Not cost or fatigue critical	No testing required - proved by element tests and analysis	No testing required - proved by element test
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure/replacement, inconvenient, not cost critical	Structural verification by proof test/analysis No testing required - verification by element testing	Structural integrity validation by previous tests and analysis No testing required - validation by subcomponent testing

*For EMD, use procedure given to prototypes in Section 4.4.1

TABLE 4.4.2.2(b) *DOD/NASA aircraft structure classification vs. PMC quality assurance requirements for EMD* and production,* (continued on next page).

PARTS A and B (Reference Figure 4.4.2.1)

Aircraft Structure		Quality Assurance Requirements		
Classification	Description	M&P Selection, Screening, & Qualification	Receiving Inspection/ Acceptance Testing*	In-Process Inspection
PRIMARY • Fracture critical (F/C) • Noncritical (N/C)	CARRIES PRIMARY AIR LOADS • Failure will cause loss of vehicle • Failure will not cause loss of vehicle, repair or replacement cost critical	Physical, mechanical, & process variable evaluation & complete specification development; Record, evaluate, select & store test data	Per complete M&P specifications - minimum physical, mechanical, & process property requirements - test for acceptability; engineering accept/reject decision; store test data	Per complete process specification & drawings - inspect/record for conformance & use engineering judgment for accept/reject decision; store test data
SECONDARY • Fatigue critical (FA/C) & economic life critical (EL/C) • Noncritical (N/C)	CARRIES SECONDARY AIR & OTHER LOADS • Failure will not cause loss of vehicle, cost critical replacement • Failure will not cause loss of vehicle • Not cost or fatigue critical	Complete physical, mechanical, & process variable evaluation & complete specification development; Record, evaluate, select & store test data	Per complete M&P specification - minimum physical, mechanical & process property requirements - maximum tests for acceptability; engineering accept/reject decisions and store test data	Per complete process specifications & drawings - inspect/record for conformance & use engineering judgment for accept/reject decisions; store test data
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure/replacement minor inconvenience, not cost critical	Limited physical property tests; use vendor recommended process; store data	Vendor certification	Worker self-inspection per vendor process

*For EMD, use procedure given for prototypes in Section 4.4.1

TABLE 4.4.2.2(b) *DOD/NASA aircraft structure classification vs. PMC quality assurance requirements for EMD* and production*, (concluded).

PARTS A and B (Reference Figure 4.4.2.1)

Aircraft Structure		Quality Assurance Requirements		
Classification	Description	Non-Destructive Inspection (NDI)	Destructive Testing (DT)	Traceability
PRIMARY • Fracture critical (F/C)	CARRIES PRIMARY AIR LOADS • Failure will cause loss of vehicle	100% area; Engineering accept/reject decision based on defect standard (defect panel); store data	Physical and mechanical property testing on integral process control panel; engineering accept/reject decision; store test data	Keep files on all receiving, in-process, & non-destructive inspection and destructive test records for each vehicle
• Noncritical (N/C)	• Failure will not cause loss of vehicle, repair or replacement cost critical			
SECONDARY • Fatigue critical (FA/C) & economic life critical (EL/C)	CARRIES SECONDARY AIR & OTHER LOADS • Failure will not cause loss of vehicle, cost critical replacement	100% area; Engineering accept/reject decision based on defect standard (defect panel); store data	Physical and mechanical property testing on nonintegral process control panel; engineering accept/reject decision; store test data	Keep files on all receiving, in-process, & non-destructive inspection & destructive test records for each vehicle
• Noncritical (N/C)	• Failure will not cause loss of vehicle • Not cost or fatigue critical			
NONSTRUCTURAL • Noncritical (N/C)	NON- OR MINOR LOAD BEARING • Failure/replacement minor inconvenience, not cost critical	Visual, dimensional	None	Keep materials receiving inspection records.

*For EMD, use procedure given for prototypes in Section 4.4.1

4.4.2.3 Summary of allowables and building block test efforts for DOD/NASA EMD and production composite aircraft structure.

In the above sections, composite material allowables development needed for prototype aircraft is detailed along with the related building block test effort required for such structure development. Both allowables requirements and building block structural test requirements are related to aircraft structure part criticality classifications and then each is related to the test/evaluation/analysis categories that need to be interrogated to study the risk involved. For allowables, the categories are preliminary and final values and physical defect minimum requirements in each classification. For the building block structures development test effort categories, the procedure used is to progressively scale up the size of the test parts, along with going from single to multiple load paths and adding joints to the test structure as it gets bigger. And, finally, the relationship of the quality assurance requirements from those required for design allowables for flat panels to those required for major structural components to those required for full size structure are presented for the six QA needs categories for each structural classification of the parts to be built.

The Part A allowables effort will provide for acceptable risk and cost effective allowables for EMD and production composite structures. The Part B building block structures test development effort will satisfy the goals of:

1. Appropriate conceptual development,
2. Proof of concept and analytical methods development,
3. Structural verification testing for analytical methods, and
4. Structural integrity testing and FEM validations.

Once these goals are achieved the user will have acceptable risk, cost effective EMD and production composite aircraft structure that will have the necessary integrity and reliability needed for the specific aircraft being developed.

4.4.3 Commercial aircraft

4.4.3.1 Introduction

This section describes an (commercial) approach to determining and verifying material allowables and design values for commercial aircraft composite structures. The approach provides a systematic method of dealing with composite materials, from initial materials screening to the final certification of actual structure.

The focus of this section describes the use of the building block approach to derive and validate material allowables and design values for structures fabricated using advanced composite material laminates. How the building block approach was used on the Boeing 777 commercial aircraft is described in Section 4.4.3.8 for an example.

4.4.3.2 The building block approach

To accommodate the unique features of composites, a method for determining relevant design properties has been devised. This is the “building block approach.” This method provides a systematic way of treating composite materials to obtain design information. The life cycle of composite structure, from when a candidate material is first screened, to the final production part, is broken down into a number of different blocks. To complete a structure each block, with its essential information, needs to be built and understood. This method is illustrated in Figure 4.4.3.2, and is described in Section 4.4.3.8 for application to the Boeing 777.

This results from the extensive experience gained from certification of many different structures. Typically commercial aircraft structures certify by analysis supported by tests. It should be noted that this approach does not imply that each block is performed only after the lower one is completed, in fact some level of structural element and sub-component testing should be performed as early in the design cycle as possible to reduce risks and to validate design concepts.

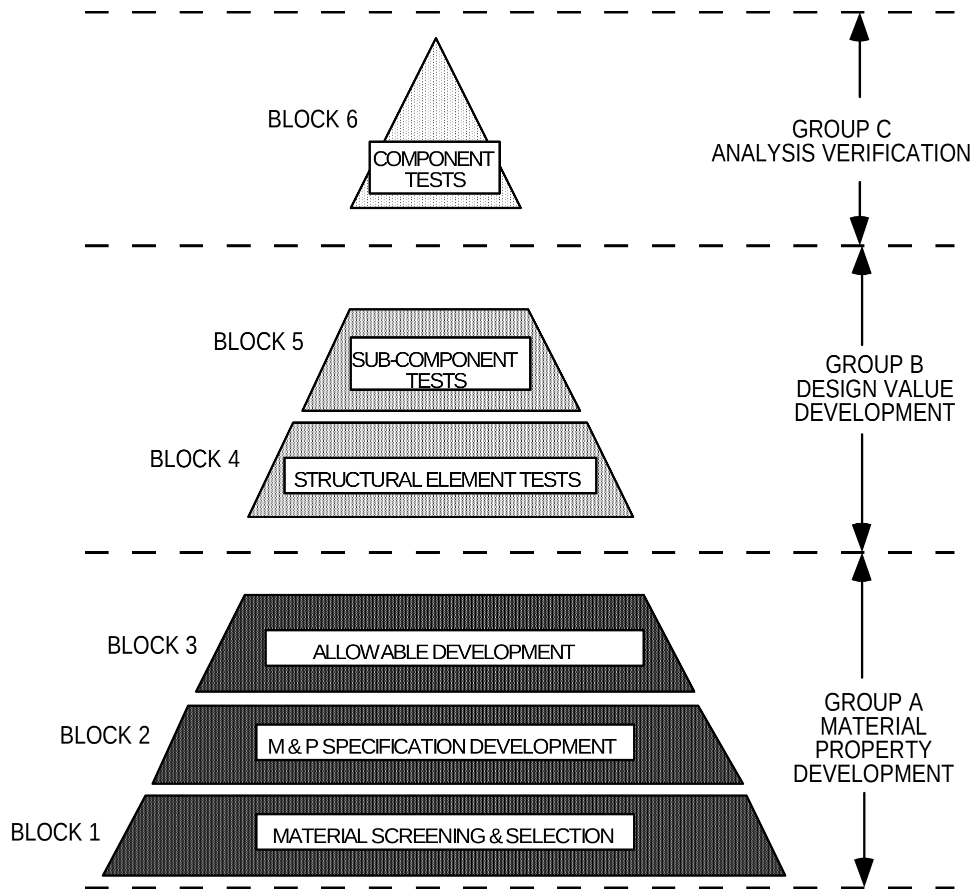

FIGURE 4.4.3.2 *Building block approach.*

4.4.3.2.1 Certification approaches

The approach taken to certify a structure impacts both the methods of analysis and allowable requirements used. There are two approaches that can be taken: certify by test or certify by analysis. While each has many features in common, emphasis is on different points of the design process. It is also possible to use a combination of these approaches to satisfy the unique needs of individual aircraft.

For a certify-by-test approach, (point design testing), the final basis for certification is testing the complete structure. The allowables and analysis methods are used for sizing, but final proof is by testing the full-scale structure. The amount of effort to develop material properties and validate analysis methods depends on the degree of risk a program chooses to assume. While this approach may drastically lower the cost of the program, it may not reveal design flaws until late in the project, or to mitigate the risk a weight penalty would result. In addition the cost of individual complex tests are much higher while being much more limited in their application. Also, the information gained over the course of the program may be of no practical use to other programs. So the next project would not benefit from their experience.

The other validation approach, certifying by analysis, assumes that the behavior of the structure can be predicted through analysis. This approach makes use of approved allowables and analysis methods.

The initial costs of this approach may be greater than the certify-by-test approach, but the results may be relevant to other programs and long-range cost may be greatly reduced. This method also enables the program to better analyze problems associated with liaison work, design changes, fleet support and airplane derivatives.

Regardless of which approach is taken, or mixture of approaches, sufficient testing of representative structure must be conducted to validate that approach. In the case of the analytical certification approach, there may be sufficient information from past history from either identical designs or research and development activities to reduce the program-specific element tests. However, this requires the use of validated configurations and analysis tools.

4.4.3.2.2 Allowables versus design values

In common practice, the terms “allowable” and “design value” are often misunderstood as being interchangeable. While both terms are related, they do not have the same meaning. The following definitions are used:

a. Allowable - A material property value (e.g., modulus, maximum stress level, maximum strain level) that is statistically derived from test data.

b. Design Value - A material property or load value that takes into consideration program requirements (e.g., fitting and scaling factors, cutoff levels) and that has been approved for use in the design and analysis of structure.

4.4.3.2.3 Lamina vs. laminate derived allowables for predicting strength

The aerospace industry has two general approaches to analyzing composite laminate strength. Both approaches use laminated plate theory for stiffness calculations using ply moduli values. Both approaches calculate the ply level strains at a point in the laminate using the applied loads on the structure. A failure criterion is applied to each ply of the laminate. The difference in the approaches is in the failure theories and the test data used in conjunction with the failure criteria.

The first approach is the lamina (or ply) failure theory approach. This method uses allowables established for the individual plies of the material using unidirectional or cross-ply laminate tests. These values are tailored for use as the inputs to a lamina failure -theory model. In most cases, correction or modification factors must be applied to either the ply design values or elsewhere in the analysis. This is to account for lamination or structural load path effects which are not reflected in the lamina specimen tests used to obtain the allowables. To obtain these factors, tests of the actual laminates and structure must be conducted.

The advantage of using this approach is that, initially, allowables are only needed at the ply level. This means that the allowables testing can be done on a small number of specimens, and often the same test data as used for material qualification can be used as part of the allowables database. Unfortunately, failure theories using lamina level test data have not been shown to correlate well over the range of potential failure modes. Therefore, unless very conservative lamina values are used, laminate-level tests are required to verify the predicted failures or to create the modification factors. Additional testing or factors may also be needed to account for the production methods used to fabricate parts.

The second approach uses allowables and design values derived from tests on representative laminates. Ply-level information is generally only collected to obtain moduli. The allowables are based on linearized laminate failure strains (calculated using nominal moduli and ply thickness). They are used in a maximum strain failure criteria evaluated on a ply-by-ply basis at a given point in the laminate. The key difference from the lamina approach is that the strain allowables are a function of the specific laminate ply percentages and stacking sequence for the ply being analyzed. This approach has the advantage of interrogating the variables that may impact the performance of actual structure. Variables such as stacking sequence and processing irregularities may be included in the testing from which the allowables are statistically derived. Additional correction factors to account for laminate effects are not required. Disadvantages include somewhat larger test specimens, the increased numbers of test specimens to cover the numerous lay-ups that are representative of the structure, and the restrictions that may have to be placed on the design. To reduce the number of variables, design criteria that limit the permitted fiber orientation and stacking sequences are established. An advantage of this approach is that laminate test specimens have been shown to be less sensitive to test variables and irregularities, thereby reducing data scatter and resulting in more accurate material properties.

Both approaches have unique requirements and impact how the building block approach is implemented. When establishing an allowable/design-values program, the engineer needs to clearly understand what analysis approach is being used for the structure, the data requirements for the approach taken and the validation requirements for the selected analysis. In either case care must be taken to account for the variability introduced by the method of manufacturing as well as the base materials used to fabricate the structure.

4.4.3.2.4 Product development

A sufficient amount of work is needed to understand the requirements and limitations of materials being considered for a specific product, and to ensure that these are understood before initiating allowable and design-value development. In most cases, these factors are examined in independent research and development (IR&D), early product development, or some other such program that examines the potential use of a structure and identifies the critical material and geometric considerations. Only after these critical considerations are known can the appropriate screening, allowables, and design-value testing be defined.

4.4.3.3 Composite road map

The development and validation of allowables and design values is not an independent activity, but part of the larger product-development process. It is only through the use of common design and analysis practices that information can be generated that is applicable to more than one specific application. Even then, special care must be taken to ensure that the unique features of a specific structure are taken into account. The engineer must be aware that the building block approach is only one part of the overall system. Figure 4.4.3.3 illustrates those processes that influence allowables development.

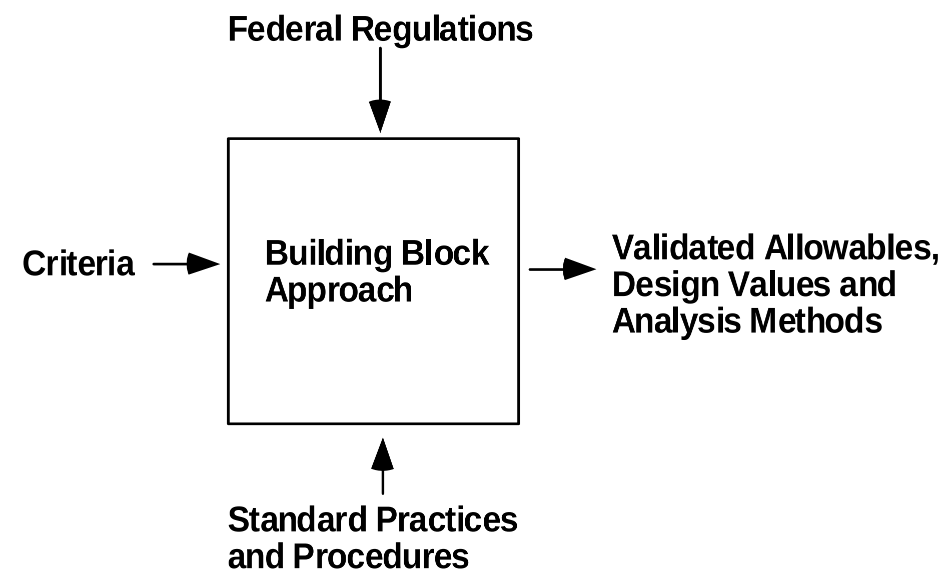

FIGURE 4.4.3.3 *Factors that influence the building block approach.*

4.4.3.3.1 Criteria

Before starting any allowables program the engineer must have an understanding of the criteria being applied. The criteria define program structural requirements, operational environment requirements, durability and damage tolerance requirements, and many other factors that must be accounted for in the design of a structure. It is through the criteria that manufacturer, customer, and regulatory agency requirements are defined for the engineer.

4.4.3.3.1.1 Generic criteria

Generic criteria are needed to have commonality between programs and to promote standard processes within groups. For this application, "generic criteria" refers to criteria that apply to more than one program. It is vital to allow information generated on one program to be applicable to the next.

While it is true that details may vary between groups, there is a set of basic issues that must be addressed by any criteria.

a. Design Philosophy - The general concept of how the structure will be analyzed and certified must be understood. This is especially important in those programs that involve teaming with other companies. There are a number of differing approaches in designing structure that require special and distinct allowables.

b. Method of Certification - The method by which the structure will be certified affects the test requirements. The method of compliance is often directed by the certifying agency and usually reflects the current rules and regulations. Method of certification may also define the regulatory agency's and/or customer's involvement in the development and implementing of test plans.

c. Design Requirements and Objectives - The criteria being applied must clearly define the operational requirements and objectives of the product. They must reflect the customer's intended use and operational environment.

4.4.3.3.1.2 Program criteria issues

While generic criteria allow common processes and procedures to be used for a family of structures, there is always a requirement to have program-specific criteria. It is through the program criteria that specific details of the structures performance requirements are passed to design engineers. The program criteria also provides a method for the incorporation of newly developed items that may not have made it into the generic criteria at the start of a program or, because of the uniqueness of the structure, cannot be put into the general criteria. Whenever possible, the program criteria should not be developed to supersede the generic criteria, but to supplement them. The more dependent on specific criteria a program becomes, the more difficult it is to incorporate lessons learned on one project into the next. For this reason, those criteria developed at the program level need to be continually evaluated for possible inclusion into the generic criteria documentation.

4.4.3.3.2 Regulations

Depending on the ultimate use of the structure, a host of regulations define how and when allowables and design values are used in design. In a majority of the cases, regulations are covered within the criteria.

Commercial airplane structure must be designed in compliance with Federal Aviation Administration (FAA) and other agencies regulations outside the USA. While these are generally covered by the criteria, often the engineer must directly use these regulations.

FAA regulations are published in a series of books titled "Federal Aviation Regulations (FAR)," with additional guidance provided in Advisory Circulars. Official memos from the FAA may further clarify regulations on specific topics. In addition to the FAA, other regulatory agencies (such as the European JAA and the Russian airworthiness agencies) may be involved. The engineer establishing allowables and design values must be aware of all of the regulations that may pertain to the structure.

4.4.3.4 Commercial building block approach

The commercial building blocks may be divided into three groups, as illustrated in Figure 4.4.3.2.

The strength estimation of complex structural details and their certification requirements found in commercial programs necessitates an integrated test plan. That plan will progress from small specimens, through the various degrees of specimen complexity, to full-scale structure. Each level in the test plan uniquely interrogates the structural response of the composite design. However, accurate interpretation of data from any level is normally dependent upon results from other levels.

Once the data for any given material are obtained, any change in material systems or processes may require a repeat of tests at different levels in the building block plan to maintain certification.

In this building block approach to composite materials, seven blocks are identified. For the purposes of this section, the seven blocks have been combined into three major groups: material property evaluation (Group A), design-value development (Group B), and analysis verification (Group C).

Each building block must be addressed regardless of the approach taken. It is the degree of risk each program is willing to assume that determines which blocks are to be used and which will be scaled back. For currently existing materials and methods, entire blocks may already be completed, while new materials need to be evaluated in every block.

4.4.3.5 Group A, material property development

This group deals with those blocks that have the main purpose of defining the general behavior of the material, illustrated in Figure 4.4.3.5. Because of the numerous tests generally involved, testing is often performed using smaller, less complex specimens. Program requirements may dictate that limited numbers of larger, more complex tests be conducted to determine the critical properties that need to be investigated during material screening. This will ensure that the correct decisions are made in terms of material selection.

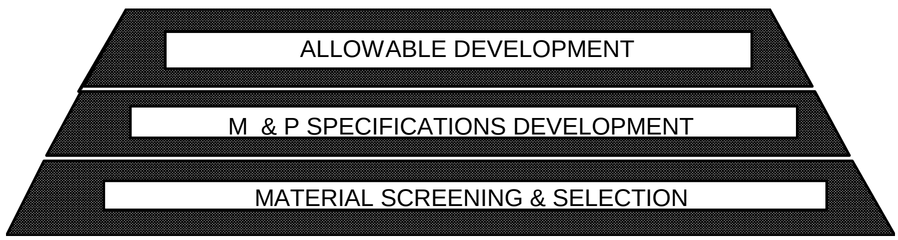

FIGURE 4.4.3.5 *Blocks in material property evaluation.*

4.4.3.5.1 Block 1 - material screening and selection

The first block's objective is to gather data on candidate materials and to make a decision on which material(s) will be selected for a given project. At this stage, the materials and the processes may not be well defined or controlled by specifications. This early testing has typically been confined to basic specimens because of the large number of candidate materials involved. Also, a program may require more complex tests if the final material selection must be based on configuration-specific tests. Since there are only limited controls (no specifications) placed on the materials at this point, it is impossible to establish firm allowables from this data alone. Estimates of basic material allowables may be provided to aid in trade studies and preliminary design. It is highly probable that the values will be adjusted as the understanding of the material system matures.

4.4.3.5.2 Block 2 - material and process specification development

The second block assumes that the preliminary material and processing specifications have been prepared for the material system that is selected. The objective of testing at this stage is to validate the specifications, thereby gaining an understanding of how the material behavior is affected by the process variables. This permits qualification of the material. It is important that the key mechanical properties needed to support design be identified by this stage so that these properties may be economically examined for a number of production batches. This will enhance understanding of the material behavior. Preliminary allowables may be derived from this level of testing because preliminary specifications are in place. However, not all material variables have been investigated, so firm allowables cannot be derived. Data obtained may be usable in the database needed to compute firm allowables, but the material and process specifications may not be modified. Specification changes after the fabrication of the test specimens may invalidate the test results and any allowables derived from them.

4.4.3.5.3 Block 3 - allowables development

In block 3 the material is fully controlled by both a material specification and a process specification. The objective is to provide “firm” material allowables suitable for design. Usually, the majority of the testing to be conducted on a new material is conducted at this stage of development. If the material specification has not been altered since the qualification tests, qualification data generated may be used as part of the allowables database. Only data from material purchased and fabricated under existing specifications are acceptable to certifying agencies for allowable development.

The main characteristics and objectives of these tests are summarized as follows:

a. Development of statistically significant data - The database developed should be sufficient to develop “A” or “B” -basis allowables. Obtaining the required dataset involves information from several raw material production runs (batches) and from parts representing several fabrication runs.

b. Determining the effects of environment - Test data should cover the complete environmental range necessary to design the structure. This includes the testing of moisture-conditioned specimens. This database will then provide environmental “compensation” factors relative to the room-temperature-ambient (RTA) condition. This facilitates interpretation of RTA tests on specimens of subcomponent-type complexity and greater.

c. Determination of notch effects - Notch sensitivity is included in the allowables by testing specimens with both filled and open holes. The influence of fastener torque must also be examined.

d. Defining changes in properties due to lamination effects - The data should be derived from specimens covering the complete range of laminate configurations used in the structure. This includes ply orientations percentages, stacking sequences, laminate thicknesses, tape/fabric hybrids, etc.

e. Understanding the effects of manufacturing induced anomalies ("effects of defects") on the structure - Evaluation of permitted defects needs to be understood at the structural element level in order to establish process specifications and to provide data for MRB actions on rejectable defects.

f. Understanding how sensitive the structure is to the fabrication process. Testing of structural elements are needed to evaluate the effects of any change in processing to the structural response.

The properties required for in-plane, tension, and compression allowables should be developed from uniaxially loaded specimens. The test matrix should include laminates encompassing the complete range of structural configurations in the design. Allowables should be generated for both unnotched and notched configurations. Notched testing may involve open and/or filled hole test coupons, depending on specific program design criteria. Use of a typical fastener and/or type used in the actual structure is recommended. While not classically considered material properties, allowables derived for geometry-dependent features (open- and filled-hole specimens) are frequently required for design.

Since allowables specimens are small coupons, it is economical to obtain enough tests to have statistical significance. Basic material properties are being obtained at this level. In fact, the engineer needs to be aware that values being obtained are configuration dependent. Values such as open-hole compression, filled-hole tension, and bearing, as well as some out-of-plane tests (short-beam shear and other interlaminar tests) are often used directly in the analysis methods used to design structure. These tests are strongly influenced by their configurations. Standard specimen configurations are designed to provide information that is directly applicable in Boeing analysis procedures.

4.4.3.6 Group B, design-value development

As illustrated in Figure 4.4.3.6, the objectives of Group B are to develop design values that reflect the actual structure. This testing may overlap those tests conducted to determine material allowables, as described in Section 4.4.3.5.3. Unlike those tests, testing for design values requires a preliminary configuration with general sizing. Design-value tests may become very specific and not applicable for use on other programs unless similar structures are being designed. The engineer must exercise caution when using design values developed for other programs.

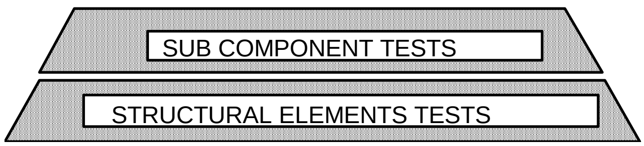

FIGURE 4.4.3.6 *Blocks in design-value development.*

4.4.3.6.1 Block 4 - structural element tests

Block 4 comprises local structural details that are repeated within the structure. The intent is to develop design values that are related more to structure than to basic material allowables developed per Section 4.4.3.5.3. For example, bearing is considered to be a structural, rather than a material, property. Typical structural elements are joints, frame sections (e.g., radius parts), and standard stiffener sections.

The main characteristics and objectives of these tests are summarized as follows:

a. Development of design values that are structural configuration related. This contrasts with the basic material allowables developed in block 3 which are generic to most configurations.

b. Understanding the effects of manufacturing induced anomalies ("effects of defects") on the structure. Evaluation of permitted defects needs to be understood at the structural element level in order to establish process specifications and to provide data for MRB action on rejected defects.

c. Understanding how sensitive the structure is to the fabrication process. Testing of structural elements are needed to evaluate the effects of any change in processing to the structural response.

Generally, these factors are very dependent upon repetitive local structural details, and are developed from tests of these details referred to as "elements" in the building block plan. The data developed, which may be generic in nature, is frequently used to support analytical techniques. These techniques are used for developing margins of safety in composite structure and they normally have a strong semi-empirical basis. The following subsections illustrate typical examples.

4.4.3.6.1.1 Bolted joints

The properties required for the strength determinations of bolted joints are:

a. Bearing - This property is a combination of a number of potential failure modes(compression bearing, shearout, cleavage, net section, fastener pull-through, etc.) which are strongly influenced by joint geometry and configuration, ply percentages, stacking sequence, fastener type and other variables. All of these effects must be accounted for in the bearing design values. Present analytical capability cannot account for fastener rotation (tilting) in bolted joints. Bearing design data must be obtained from tests on realistic joint configurations (typically stabilized, single-shear joints).

b. Bypass - The material-related allowables database includes basic open- and filled-hole strengths. These are derived by using fasteners and hole sizes typical of those in the actual structure. These can be used to represent pure bypass strength. However, it is frequently necessary to generate data for other fasteners and also to evaluate fastener pattern effects. Special attention should be paid to fastener clamp-up. Filled-hole tension details are generally tested with full clamp-up, while filled-hole compression is conservatively tested at a value less than full clamp-up.

c. Bearing-bypass - The interaction strength is a predictable property. However, the present analytical techniques rely upon the development of empirical interaction curves from tests of realistic joint configurations.

d. Fastener pull-through - For reliable verification of structural integrity, tests must be conducted on realistic structural details.

e. Fastener strength–While not a composite property in itself, the strength of the fastener will influence the behavior of the composite material being joined, and must be considered in bolted joint analysis and design value development. The strength of the fastener itself is influenced by the joint configuration and strap materials. The lower interlaminar stiffnesses and strengths typical of composite laminates, compared to metallic materials, result in a much greater occurrence of fastener failure modes in composite joints. Analytical methods using empirical fastener factors have been developed to predict fastener failure mode strengths in joints with composite straps.

4.4.3.6.1.2 Stiffener sections

Data is required to support the analysis of stiffener strengths, many of which are standard parts repeated throughout the structure. Typical failure modes requiring data are as follows:

a. Crippling properties - Most structure, with any form of compression and/or shear loading, requires the development of a crippling strength database. This database can be used to support post-buckling strength methodology.

b. Stiffener pull-off - This failure mode is relevant when a design employs any form of a cobonded or cocured stiffener. Present analytical capability cannot reliably predict this failure mode, and the development of detail test data is essential.

4.4.3.6.1.3 Beam and clip flanges

Data is required to analyze out-of-plane failures in curved beams. Properties are predictable on a linear basis from the material allowables database. Strength prediction in the out-of-plane direction requires failure data from tests on representative parts. Data is typically developed from bending tests of a curved laminate section. The resulting design values should be grouped along with interlaminar shear data under the heading of out-of-plane properties. These properties are particularly sensitive to processing, and can be used in evaluation of process sensitivity.

4.4.3.6.1.4 Sandwich structure

Test data is normally required to analyze the strength of sandwich structure. This data accounts for effects such as cocure, core and facesheet thickness', bagside waviness, and impact damage not found in laminate test articles.

4.4.3.6.2 Block 5 - subcomponent tests

In block 5, configurations are more complex than those in block 4. They are typically sections of a component. These tests permit assessment of load redistribution due to local damage. Specimen boundary and load introduction conditions are more representative of the actual structure than in the element tests. Biaxial loading can be applied. The level of specimen complexity allows incorporation of representative structural details. Typical examples of subcomponent configurations include picture-frame shear, deep-beam shear, and uniaxial tension and compression panels. The level of specimen complexity allows for the testing of multistiffened panels, panels with large cutouts, and damaged panels. Subcomponents must be of sufficient size to allow proper load redistribution around flaws and damage.

Secondary loading effects should be seen in this level of specimen complexity. The resulting load distributions and local bending effects become observable, and out-of-plane failure modes become more representative of full-scale structure.

Environmental testing may still be meaningful in these tests. Significant multiaxial loading and potentially different failure modes, when present, complicate interpretation of test results. The differing environmental sensitivity of the various failure modes contributes to this. For example, the elevated-temperature-wet (ETW) condition, while increasing sensitivity to compression-dominated failure, may reduce sensitivity to tension-dominated failure when compared to the RTA condition. The results from RTA tests should be adjusted to account for environmental sensitivity in the resulting failure mode. The characteristics and objectives can be summarized as follows:

a. Applicability of design values and analysis - Evaluation of the effect of structural complexity and scale-up upon basic allowables data and data analysis methods.

b. Effect of damage, static - Accounting for damage by development of configuration specific design values.

c. Effect of damage, fatigue - Demonstration of “no detrimental damage growth” under operational fatigue loading.

4.4.3.7 Group C, analysis verification

These tests represent the final stage in the certification process for static and fatigue loading, illustrated in Figure 4.4.3.7. Success is very sensitive to program/customer criteria. At this level, it is desirable to perform extensive verification of analysis and computer modeling. This requirement is necessary due to the static-notch sensitivity of typical composite structure. Load redistribution capability does not exist to the same extent as that found in typical metal structure. Major objectives of these tests are:

a. Verification of internal loads model and resulting stress, strain and deflection predictions.

b. Large-scale verification of design and analysis methodology.

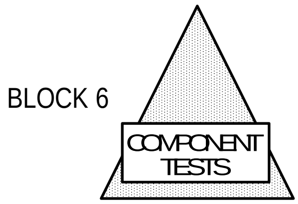

FIGURE 4.4.3.7 *Blocks involved with analysis verification.*

4.4.3.7.1 Block 6 - component test

Block 6 testing involves large and complex specimen configurations that are representative of the actual structure. In many cases these tests are performed only to design limit load to verify analytical strain and deflection predictions.

In some cases, the customer or regulatory agency may require that the test be performed to failure. In these cases, careful choice of the loading condition is essential because failure tests produce data relevant only to the particular failure mode, which may not be critical over the full environmental range. For example, tension-dominated failures are frequently not as environmentally critical as compression failures, (i.e., the tension-environmental compensation factor is normally less than the compression factor). Consequently, factoring of a tension-dominated failure load may not yield the minimum or maximum load capability of the structure over the full environmental range.

For successful verification of analytical predictions of the component's structural behavior, the component must be thoroughly instrumented with strain gages and deflection indicators. Choosing the gage types, instrumentation, and gage locations must be given careful consideration. The data collected must be correlated with the analysis methods predictions and discrepancies rationalized.

4.4.3.8 Boeing 777 aircraft composite primary structure building block approach

4.4.3.8.1 Introduction

This section outlines the building block approach for a large primary structure component for a commercial aircraft. The approach presented here is a summary of the approach used to support design and certification of the Boeing 777-200 CFRP empennage (Reference 4.4.3.8.1). The empennage has carbon fiber reinforced plastic (CFRP) main torque box structure in the horizontal and vertical stabilizers. The torque boxes are of two spar and multi-rib construction and use mechanical fasteners for major attachments. The structural design environment for the 777-200 empennage encompasses the range of temperatures from -65°F to +160°F.

Certification, in this case, was accomplished through structural analysis supported by test evidence obtained over a range of test article sizes. As described in Section 4.4.3.4 the "building block" approach involves tests at the coupon, element, subcomponent, and component levels. While much smaller in quantity, the subcomponent and component test results comprise an important portion of the test evidence required to validate analytical methods and demonstrate the required levels of static strength and damage tolerance.

Certification requires the demonstration of required levels of static strength, durability and damage tolerance as well as the ability to predict stiffness properties. Demonstration of compliance for composite structure includes sustaining design ultimate loads with damage at the threshold of visual detectability (barely visible impact damage, BVID) and sustaining design limit loads with clearly visible damage. In addition, it must be demonstrated that levels of damage smaller than those that reduce the residual strength to Design Limit Load capability will not experience detrimental growth under operational loading conditions.

The regulatory requirements applicable to commercial transport aircraft are defined in FAR Part 25 and JAR Part 25. In addition to the regulations, the FAA and JAA have identified acceptable means of compliance for certification of composite structure: FAA Advisory Circular AC 20-107 and JAA ACJ 25.603, “Composite Aircraft Structure”. The advisory circulars include acceptable means of compliance in the following areas: 1) effects of environment (including design allowables and impact damage); 2) static strength (including repeated loads, test environment, process control, material variability and impact damage); 3) fatigue and damage tolerance evaluation; 4) other items - such as flutter, flammability, lightning protection, maintenance and repair.

The typical composite structure certification approach is primarily analytical, supported by test evidence at the coupon, element, subcomponent and component level, and full-scale limit load test at ambient environment. The environmental effects on the composite structure are characterized at the coupon, element and subcomponent levels and are accounted for in the structural analysis. Supporting evidence includes testing through a “building block” approach where material characterization, allowables and analysis methods development, design concept verification, and final proof of structure are obtained. The approach is illustrated in Figure 4.4.3.8.1

Experience with similar structure was important in developing the 777 certification program. The 7J7 horizontal stabilizer and the 777 pre-production horizontal stabilizer programs validated analytical methods, design allowables, fabrication and assembly processes applied to the 777 empennage structure. Significant additional knowledge and experience was accumulated in characterizing the behavior of composite aircraft structure. This experience database has been augmented by the 737 composite stabilizer fleet experience and numerous other production applications in control surfaces, fixed secondary structure, fairings and doors.

4.4.3.8.2 Coupons and elements

Laminate level allowable design strain values covering each failure mode and environmental condition are obtained from coupon and element level tests using a range of lay-ups covering the design space. These are corrected for material variability following MIL-HDBK-17, Volume 1, Section 8 statistical analysis procedures. Detail design values are verified by representative subcomponent tests accounting for the effects of environment.

Coupon level tests are conducted in unnotched, open-hole and filled-hole configurations for in-plane laminate allowables. Statistical allowables curves are derived using regression analyses and room temperature test data. Factors to account for environmental effects are determined using smaller quantities of data. Additional coupon level tests are used to determine interlaminar properties, and to assess durability, manufacturing anomalies, bonded repair and environmental effects. Element level tests, such as bolted joints, radius details and crippling specimens, are used to derive specific design values for the range of tested configurations. These values, along with the statistical allowables, are used in analytical predictions of structural capability.

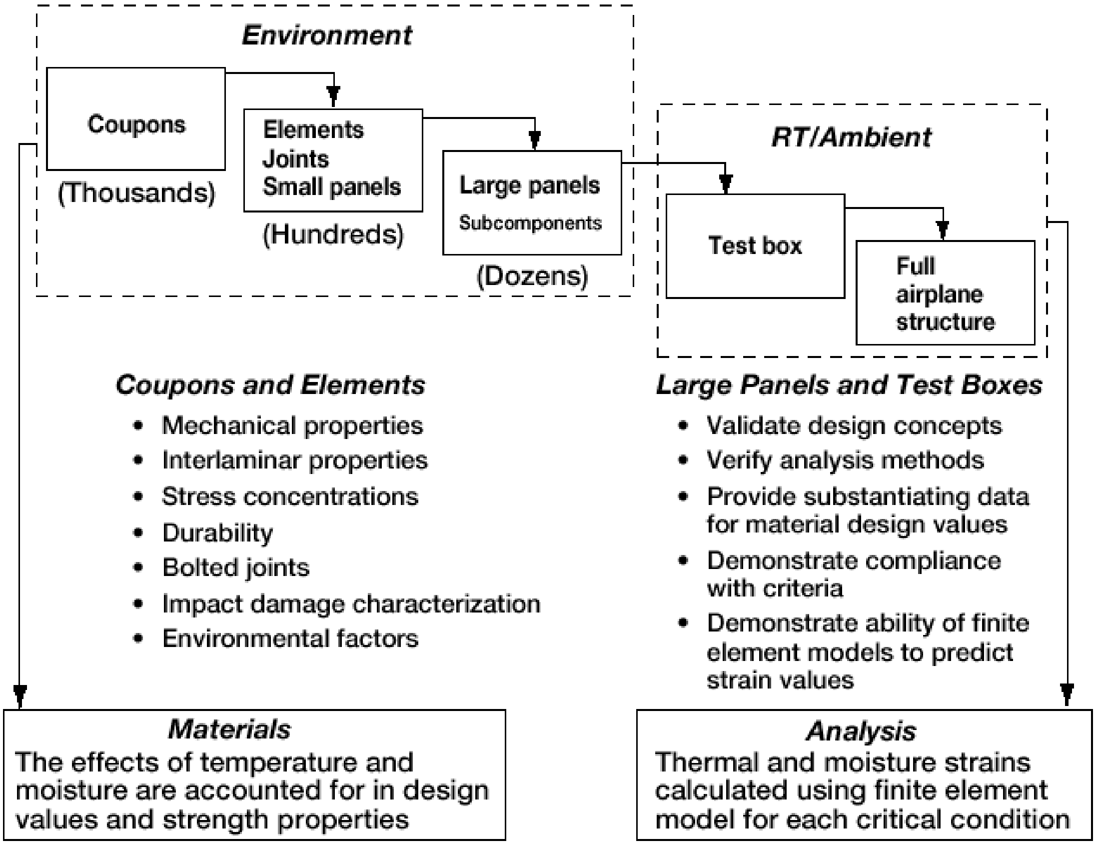

FIGURE 4.4.3.8.1 *Building block approach for commercial aircraft primary structure.*

An extensive coupon and element level test program was conducted in support of new 777 composite structure applications. These tests were conducted to establish material stiffness properties, statistical allowables and strength design values, and to validate analytical methods. Laminate level statistical allowables were established for unnotched and notched conditions following Mil-HDBK-17 recommended procedures. Up to 16 separate batches of material were included in the statistical allowables. These batches included prepreg material from two carbon fiber lines and three prepreg facilities. Approximately 25 different laminate lay-ups were included in the allowables database, with 0° fiber percentages ranging from 10% to 70%, and +/-45° fiber percentages ranging from 20% to 80%.

Testing covered laminate, joint and structural configurations typical of the 777 empennage, temperatures from -65°F to 160°F, moisture conditioned laminates, and the effects of manufacturing variations and defects allowed within the process specifications. A limited amount of impact damage testing was performed at the element level. Test article configurations ranged from simple rectangular coupons to bolted joint, angle-section, I-section and shear panel element tests.

4.4.3.8.3 Subcomponents

Subcomponent tests are conducted to establish point design values and to validate methods of analysis for such design details as a skin panel, spar, rib, horizontal stabilizer centerline splice joint or vertical stabilizer root joint structure. These design values account for the effects of environment, the presence of barely visible impact damage, and for large damages. Design values accounting for the effects of impact damage are primarily derived from subcomponent testing. This is due to the fact that the critical impact damage locations are typically not at simple acreage locations, but at a stress concentration (such as at the edge of an access hole) or over a substructure element (such as on the skin over the centerline of a stiffener). The subcomponent test results comprise a significant portion of the test evidence required to validate analytical methods and demonstrate the required levels of static strength and damage tolerance for the 777 empennage.

TABLE 4.4.3.8.3 *Summary of subcomponent tests for 777 empennage.*

Test Type	Number of Tests
Bolted Joints (Major Splices)	110
Rib Details	90
Spar Chord Crippling	50
Skin/Stringer Compression Panels	26
Skin/Stringer Tension Panels	4
Skin/Stringer Shear/Compression	6
Skin/Stringer Repair Panels	6
Skin Splice Panels	2
Stringer Runouts	4
Spar Shear Beams	6
Total	**305**

A number of the subcomponent test articles were moisture conditioned prior to test. Moisture conditioning was conducted in an environmental chamber at 140°F and 85% relative humidity. Test articles were left in the chamber until at least 90% of the equilibrium moisture content was reached.

The following critical design values and methods of analysis were validated by the subcomponent test results:

a. Compression ultimate strength design value curve for stiffened skin panels.

b. Shear-compression ultimate strength interaction curve for stiffened skin panels.

c. Compression and tension damage tolerance analysis for stiffened skin panels.

d. Strength of bolted and bonded repair designs for stiffened skin panels.

e. Bolted joint analysis and design values for the skin panel-to-trailing edge rib joints.

f. Static compression and tension strength, and tension fatigue performance of the horizontal stabilizer centerline splice joint.

g. Analytical methods for spar strain distributions, web and chord stability, and peak strains at cutouts.

h. Analytical methods for rib shear tie and chord strength and stiffness.

i. Peak strain design values for rib shear tie cutouts.

Several test types were used to demonstrate no-growth of small damages under operational repeated loading. These tests complemented the results from the full-scale component fatigue testing, and involved:

a. Axially loaded flat panels
b. Shear loaded flat panels with cutouts
c. Stiffened panel with a bonded repair
d. Spar shear beams with web cutouts
e. Centerline splice joint stiffened panel

4.4.3.8.4 Components

There are two primary damage tolerance requirements described in FAR and JAR 25.571 and the advisory circulars: damage growth characterization, and residual strength capability. As in the case of static strength, damage tolerance certification is based on analysis supported by tests at the element and subcomponent levels. Considering the applied strains, materials and design concepts, a no-growth approach for damage tolerance was selected for the 777 empennage, similar to that used for previous composite structure. This approach is based on demonstrating that any damage that is visually undetectable will not grow under operational loads. Structures with undetectable damage must be capable of carrying ultimate load for the operational life of the airplane.

The no-growth behavior of CFRP structure was demonstrated in numerous subcomponent tests and two full-scale cyclic load tests: the 7J7 horizontal stabilizer and the pre-production 777 horizontal stabilizer. In each case, visible damage was inflicted on the test article that underwent spectrum type repeated loading. Damage sites were inspected for growth during the test sequence. In addition, the full-scale tests demonstrated the following characteristics required for damage tolerance compliance:

a. Manufacturing anomalies allowed per the process specifications will not grow for the equivalent of more than two design service lives.

b. Visible damage due to foreign-object impact will not grow for the duration of two major inspection intervals (considered to be two “C” checks, 4000 flights per “C” check for the 777).

c. The structure can sustain specified residual strength loads with damage that can reasonably be expected in service.

d. The structure can sustain specified static loads (“continued safe flight loads”) after incurring in-flight discrete-source damage.

4.4.3.8.5 777 pre-production horizontal stabilizer test

The 777 CFRP pre-production horizontal stabilizer test program was initiated to provide early test evidence supporting the 777 empennage structural configuration. The test article was a partial span box, nearly identical to the production component. The minimum gage outboard sections were eliminated for cost considerations and replaced with load application fixtures. The test article included typical, specification-allowed process anomalies, as well as low-velocity impact damage up to and beyond the visual threshold. The purpose of the test program was to:

a. Demonstrate the ‘no detrimental damage growth’ design philosophy.

b. Verify the strength, durability, and damage tolerance capability of the structure.

c. Substantiate the methods of analysis and material properties used to design and analyze a CFRP stabilizer.

d. Evaluate the combined load effects of shear, bending, and torsion that empennage structure would experience during flight.

e. Verify the capability for predicting strain distributions.

f. Substantiate mechanical repairs.

e. Provide cost verification data on the fabrication of this type of structure.

The pre-production horizontal stabilizer test program consisted of 12 test sequences, as shown in Table 4.4.3.8.5.

TABLE 4.4.3.8.5 *Pre-production test box load and damage sequence.*

Test Sequence	Damage Types and Test Loadings
1.	Perform all small (BVID) damages
2.	Design limit load static strain survey.
3.	One lifetime fatigue spectrum, 50000 flights, including 1.15 LEF. (Load Enhancement Factor)
4.	Design limit load static strain survey.
5.	One lifetime fatigue spectrum, 50000 flights, including 1.15 LEF.
6.	Design limit load static strain survey.
7.	Design ultimate (select cases) load static strain survey.
8.	Two 'C' check fatigue spectrum (8000 flights) with small and visible damages, including 1.15 LEF.
9.	"Fail-safe" test; 100% design limit load static strain survey with small and visible damage.
10.	"Continued safe flight" loads test; 70% design limit load static strain survey with small, visible, and element damages.
11.	Visible and element damages repaired. Design ultimate load static strain survey.
12.	Destruction test. Strain survey up to destruction.

One of the test objectives was to validate the "no-growth" design philosophy for damage. To do this, impact damages were inflicted on the test box at the barely-visible level. Fatigue testing was conducted for load cycles representative of two design service lifetimes. Periodic ultrasonic inspection revealed an absence of detrimental damage growth. This test included a 15% L.E.F (load enhancement factor) to account for possible fatigue scatter associated with the flat S-N curves typical of composite materials.

Limit load strain surveys and initial ultimate load testing results demonstrated the predictive capability of the FEA internal loads model.

To demonstrate residual strength capability, the test box was further damaged with visible impacts. Visible damages are those that are easily detected by scheduled maintenance inspections. Fatigue testing representative of two inspection intervals again verified the no-growth approach. Limit load testing verified the structure was capable of carrying the required loads (FAR 25.571b) with these damages existing in the structure. The test box was then inflicted with major damage in the form of saw cuts to the front and rear spar chords and a completely severed stringer/skin segment. Capability to sustain continued safe-flight load (approximately 70% of limit load for stabilizer structure) was demonstrated (FAR 25.571e). Again, the deliberately inflicted damages were ultrasonically inspected and showed no detrimental growth. Residual strength testing substantiated the analytical predictions and empirical results based on subcomponent test characterization.

Upon completion of the damage tolerance testing, the cut element damages and the major through-penetration impact damages were repaired using bolted, titanium sheet metal repairs. The configurations chosen were representative of the mechanical repairs planned for the 777-200 Structural Repair Manual. All repairs were designed to restore the structure to design ultimate load capability. Repairs were performed with external access only simulating in-service repair conditions. The test article was subjected to design ultimate loads (DUL) with the repairs in place.

The test article was loaded to destruction using a symmetric down bending load case. Final failure occurred above the required load level. The skin panel failure was predicted using the analytical methods and design values derived from five-stringer compressive panel subcomponent tests.

4.4.3.8.6 Fin root attachment test

Two large subcomponent tests were conducted to evaluate the primary joint of the 777 vertical stabilizer root attachment to the fuselage. The objectives of the tests were to:

a. Verify the capability of the vertical stabilizer CFRP skin panel and titanium fittings to transmit design ultimate tensile and compressive loads.

b. Verify the durability of the joint and determine the fatigue sensitive details.

c. Validate the analytical methods used to design the structure.

The two test articles consisted of a four bay section of CFRP skin panel with two titanium root fittings. The first article was subjected to static testing in a series of limit and ultimate load conditions in tension and compression, culminating in a destruction test under tensile loads.

The objective of the fatigue test was to find potential fatigue critical areas, and investigate crack growth behavior. The second test article was tested with cyclic loads at a constant amplitude followed by a tensile residual strength test. The fatigue loading was conducted at four times the maximum 777-200 vertical stabilizer fatigue loads. The fatigue test was followed by residual strength tests in compression to limit load and in tension to failure.

4.4.3.8.7 777 horizontal stabilizer tests

The 777 horizontal stabilizer and elevators were tested to demonstrate limit load capability and verify accuracy of analytically calculated strains and deflections. The tests were conducted separately from the airplane since the attachment to the body is determinate. The test specimen was a structurally complete production article; omitted were non-structural components and systems not essential to the structural performance or induced loading of the stabilizer. Three critical static load conditions were included in the test: up, down and unsymmetric bending. The loading sequence was similar to the pre-production box. Limit load strain survey results were used to demonstrate the predictive capability of the FEA model.

Additional testing was performed which was not required for certification. This included fatigue, ultimate load and destruct testing. The horizontal stabilizer was subjected to 120,000 flights of spectrum fatigue loading, without any load enhancement factors, to satisfy the program objectives. This test was primarily intended to verify the fatigue characteristics of the metallic portion of the stabilizer. The composite structure was verified by the pre-production test box described earlier. Ultimate load and destruct testing was meant to supplement the data that was acquired as part of the certification program and to verify future growth capability. Three load cases were run representative of up, down and unsymmetric bending. The critical down bending load case was used for the destruct run. The test box was subjected to barely visible impact damage and loaded to failure.

4.4.3.8.8 777 vertical stabilizer test

The 777 vertical stabilizer including the rudder was tested as part of the airplane full-scale. Again, the purpose was to demonstrate limit load capability and verify accuracy of analytically calculated strains and deflections. Testing was conducted indoors at ambient conditions. Three critical conditions tested included maximum bending (engine-out), maximum torsion (hinge moment), and maximum shear (lateral gust).

A completely separate test using another production airframe was conducted to verify the fatigue behavior of the 777. As a part of this test, the vertical stabilizer and rudder were subjected to 120,000 flights (considered three design service objectives) of spectrum fatigue loading. No load enhancement factors were applied, as the primary purpose of the test was to validate the fatigue performance of the metallic parts of the structure.

4.4.3.8.9 Future programs

A building block approach used on a future program will take into account lessons learned on the Boeing 777. A pre-production test box will not be used on the next program unless significant changes in materials and configuration warrant such a test article. The “no damage growth” philosophy will be satisfied at the subcomponent level and include a L.E.F. Full scale testing will not use a L.E.F as the metallic fittings and joints are the critical articles to be concerned with. This assumes that future designs will still be a hybrid of composites and metallic structure. Testing a structural box to failure may or may not be required depending on the level of change when compared to past testing. If a program has future derivatives planned, testing to failure may be done to understand future airframe growth potential.

4.4.4 Business and private aircraft

4.4.4.1 High performance

This section is reserved for future use.

4.4.4.1.1 Introduction

This section is reserved for future use.

4.4.4.1.1.1 Background

The general aviation market ranges from 4 seater personal or trainer airplanes costing less than $200,000 to intercontinental jets selling for close to $40 million. Airplanes weighing over 12,500 lb take off weight or with more than 10 occupants must be certificated under FAR 25 regulations, in other words, to the same rules as the wide body airliners. The smaller commuter airliners may be still certificated under FAR 23 commuter category for take off weight less than 19,000 lb and less than 19 passengers. Although most general aviation airplanes will not see heavy hours per year usage there are commuter airliners in service which have seen over 50,000 flights. Another sub-set of the GA market is trainers, general transportation, and special mission aircraft for military customers, these include surveillance and air ambulance operations. Often these are certificated under FAA rules in order to give the customer a non-developmental airplane. Military trainers typically experience usage of about 1,000 hours per year.

4.4.4.1.1.2 Building Block Rationale

Element and sub component testing has been historically used in metallic airplanes to identify fatigue and crack growth characteristics of critical joints and details, especially since the introduction of damage tolerance requirements in FAR 25 in the late seventies. Also in the late seventies, carbon fiber reinforced epoxy (CFRE) parts were first introduced into commercial airplane service. These parts tend to be anisotropic, statically notch sensitive (as opposed to the fatigue notch sensitivity of aluminum alloys), heavily process dependent, and tooling intensive. These characteristics add to the program risk. Full scale test articles will not be available until late in the development cycle, by which time the program risk of test revealed inadequacy or unacceptable materials or process is huge.

Risk reduction is the major justification for a building block approach. Cost reduction is also a factor: Material tests allow alternate materials to be specified; element tests can identify allowable intrinsic manufacturing defects; MRB and acceptable rework activity can also be substantiated during element tests; finally, the scope of full scale static and fatigue testing can be reduced with a program of analysis supported by smaller tests.

4.4.4.1.2 Typical building block program

4.4.4.1.2.1 Material lamina tests

These tests are conducted to qualify a new material and/or supplier, establish receiving inspection criteria, and to provide raw data from which lamina allowables may be defined. These tests are typically conducted at the material supplier with witnessing from and approval by the using company.

Typical Matrix—Material Lamina Tests

PROPERTY	**NUMBER OF BATCHES (6 TESTS EA BATCH)**		
	CTD	**RTD**	**ETW**
TENSION 0 **Strength, modulus, and Poisson's**	**1**	**3**	**3**
COMPRESSION 0 **Strength and modulus**	**1**	**3**	**3**
TENSION 90 **Strength and modulus**	**1**	**3**	**3**
COMPRESSION 90 **Strength and modulus**	**1**	**3**	**3**
IN-PLANE SHEAR **Strength and modulus**	**1**	**3**	**3**

4.4.4.1.2.2 Material laminate tests

These tests are conducted to compare the performance of new material to the baseline materials and to provide design guidelines for properties not readily calculated from the laminar properties. These tests are also typically conducted at the material supplier with witnessing from and approval of the using company.

Typical Matrix—Material Laminate Tests

PROPERTY	NUMBER OF BATCHES (6 TESTS EA BATCH)		
	CTD	RTD	ETW
Bearing strength	1	1	1
Compression after impact	1	1	1
Open hole tension strength	1	1	1
Open hole compression strength	1	1	1
Fluid Exposure			
Fuel		1	
Deice fluid		1	
Hydraulic fluid		1	
Cleaning solvent		1	

4.4.4.1.2.3 Element tests - critical laminates

The most simple of these tests are conducted to demonstrate that a classical laminated plate analysis will predict the strength and stiffness of critical laminates with input of lamina properties from the material test program.

Tests are also conducted to provide certification data for failure modes not readily predicted by currently accepted analysis methods. For example: strength after barely detectable impact damage, called threshold of detectability (TOD) impact damage in FAA advisory material; flaw growth from TOD impact damage; strength after detectable damage; flaw growth rates from detectable damage; lightning strike resistance; flame resistance.

In fabrication of specimens for the above tests, it will benefit a manufacturer to consider a range of defects intrinsic to the manufacturing process, but which may not significantly degrade the structural properties. Therefore, laminates may be deliberately fabricated with porosity, voids, and minor delaminations from which shop inspection and NDI criteria may be validated.

There may also be customer economic/maintenance issues which require tests of typical but not necessarily critical elements. These could include doorstep and floorboard damage resistance, runway debris potential damage, hail storm damage, baggage impact resistance, and step or no step criteria for external surfaces.

Typical Element Test Matrix—Critical Laminates

PROPERTY	NUMBER OF TESTS		
	CTD	RTD	ETW
Tension strength			
Virgin	3	3	3
Impact damage	3	3	3
Detectable	3	3	3
Compression strength			
Virgin	3	3	3
Impact damage	3	3	3
Detectable damage	3	3	3
Shear strength			
Virgin	3	3	3
Impact damage	3	3	3
Detectable damage	3	3	3
Tension flaw growth			
From impact damage		3	
From detectable damage		3	
Compression flaw growth			
From impact damage		3	
From detectable damage		3	
Shear flaw growth			
From impact damage		3	
From detectable damage		3	

4.4.4.1.2.4 Element tests - critical joints and details

Throughout a composite there may be joints and splices which must be shown to be capable of carrying ultimate loads under applicable environmental conditions and the required residual strength loads after damage or partial failure. Such critical details may also be subject to variability due to the manufacturing processes. For example: bolt torque loads, bond pressure, bond line max and min thickness, shop ambient conditions, cure cycle variations, misalignment during assembly, and so on. These joints and details are also likely to be exposed to in-service loads and damage cases; these could include: cyclic loading due to gust, maneuver, and landings, impact damage, direct lightning strike or internal current transfer due a strike elsewhere.

Critical details other than joints and splices might include such items as: reinforcing frames around doors, windows, and windshield openings, ply build-ups and drop offs, and reinforcements and attachments for systems and equipment.

The type of loading applied to validate joints and critical details will depend on the internal load applied in the loaded structure; typically derived from finite element analysis. The example in the typical matrix below assumes a bolted and bonded joint subjected to tension and bending in the full scale structure, and where the bolts alone must carry a required residual strength load.

Typical Test Matrix - Joints and Critical Details

PROPERTY	NUMBER OF TESTS		
	CTD	RTD	ETW
Tension strength			
Virgin	3	3	3
Max bond line	3	3	3
Bond voids	3	3	3
Lightning damage		1	
Bending strength			
Virgin	3	3	3
Max Bond line	3	3	3
Bond voids	3	3	3
Lightning damage		1	
Bolts alone strength			
Virgin	3	3	3
Max gap	3	3	3
Min e/d	3	3	3
Miss-aligned	3	3	3
Tension flaw growth			
Max bond line		3	
Bond voids		3	
Bending flaw growth			
Max bond line		3	
Bond voids		3	

4.4.4.1.2.5 Sub-component tests

Sub-component tests are tests of critical portions of a component, a component being a wing, fuselage, or empennage. The sub-components are themselves full scale and typically three dimensional, but a section of the component and not the whole component. Often small compromises will be made in order to fabricate the test articles early in the development program. Examples of the type of compromises applied are: wing box sections without airfoil contour or taper, fuselage sections made cylindrical and without taper, and window frames or access panel frames fabricated and tested as flat panels, neglecting exterior curvature.

Sub-component tests are conducted when new materials, new manufacturing methods, or new structural configurations are introduced; examples may include: RTM resin and process, co-cured parts, filament winding or automated fiber placement, and metal reinforcements or fittings.

Typical Sub Component Tests

Sub Component	Test type	Loading	Environment
Wing or stabilizer Box	Static	Bending/torsion	RTD and ETW
	D&DT	2 lifetimes	RTD
	Res Strength	Bending /torsion	RTD
Wing or stabilizer Box	Static	Bending/torsion	RTD
Pressure Bulkhd Installation	Static	Operating and ult Pressure	RTD
	D&DT	2 Lifetimes	RTD
	Res strength	Oper and ult pressure	RTD

4.4.4.1.2.6 Full scale tests - static

One of the benefits of a building block approach is that the extent of full scale testing can be reduced based on the test results from lower levels of testing and validation of analytical methods by comparison to those results. Based on this methodology, a limited number full scale test load cases will be tested, and tested under ambient temperature/moisture only. The other temperature/moisture conditions can be cleared by analysis or by direct comparisons of strain data to element test results. Similarly, other load cases can be cleared by analysis.

They may be interest from the customer or the certificating agency in a full scale test to failure. This would be conducted after all other uses for the test article had been exhausted and such a test would provide confirmation of the critical structure, failure mode, and margin of safety.

4.4.4.1.2.7 Full scale tests - durability and damage tolerance tests

Full scale testing of composite structure to demonstrate tolerance of in-service repeated loads both in the as-manufactured condition and after inflicted damage is the industry norm in aero structures. Usually a load enhancement factor of 1.15 is applied to enable two test lifetimes to represent one service lifetime with a B-basis relationship based on variability in flaw growth.

4.4.4.2 Lightweight and kit

This section reserved for future use.

4.4.5 Rotorcraft

As with the previous application examples, the BBA for rotorcraft is divided into Design Allowables, Design Development, and Full Scale Substantiation testing. Unlike the previous examples, both military and civilian substantiation methods are discussed interchangeably in this section. This combined treatment is due to the fact that, unlike fixed-wing aircraft, military and civilian rotorcraft are similar in size, cost, mission-profile, etc. (for utility, not attack helicopters).

Customer or regulatory substantiation requirements pertain only to assurance of structural integrity, not economic/programmatic risk. Nonetheless, since reducing programmatic risk is a major motivation for much of the building block test/analysis process, these types of tests are also addressed. Finally, relevant general references are listed at the end of this section (References 4.4.5(a) through (i)).

By far the most significant difference in design and substantiation of rotary- versus fixed-wing aircraft is the existence of a complex system of dynamic components in rotorcraft, which typically have more in common with gas turbine engine systems (blades, shafts, gearboxes, high cycle fatigue loads, etc.) than fixed-wing airframe structures. Common rotor system composite materials include glass/epoxy as well as carbon/epoxy, since flexibility and high inertia are preferred design attributes of certain rotor system components, such as blades and yokes. The high stiffness and low weight of carbon/epoxy is appropriate for other components, such as cuffs, grips, and certain large blade spars. Hybrid carbon-glass structures are also common. Note also that there are few, if any, secondary or nonstructural components (e.g., fairings or access covers) in the rotor system (and very few multiple load paths). The drive system is designed and analyzed separately from the main and tail rotors (typically by a different group of engineers), and consists of transmission, gear boxes, and drive shafts. Unlike the rotor and airframe, the drive system has few critical composite material applications, which are restricted mainly to carbon/epoxy shafts, although research has been done on continuous-fiber gearbox and transmission cases, and short-fiber bearing cages and races. An overview of structural criticality issues, or informal classifications, is given in Table 4.4.5.

TABLE 4.4.5 *Rotorcraft (composite) structural criticality.*

Type of Structure	Type of Component		
	Airframe	Rotor System	Drive System
non-redundant, primary	fully-monocoque tailboom, pylon support	single-lug joints, blades, cuffs, yokes, grips	drive shafts
multiple load path, primary	frames, longerons, ribs, spars, skins	multiple-lug joints, certain yokes and grips	none
flight-critical, secondary[1,2]	certain external doors and fairings	none	none
non-flight-critical, secondary (e.g., “nonstructural” in previous tables)[1]	all other doors, fairings, etc.	none	none

Notes:

1. FAR 29.613 does not distinguish between primary and secondary structures, only single vs. multiple load paths.
2. Secondary structure is flight-critical when its failure causes system (rather than structural) failures, e.g., a door departing the airframe in flight critically damages the rotors or control system.

Unlike the dynamic systems, the rotorcraft airframe structure does share much in common with fixed-wing airframe structures, e.g., carbon/epoxy semi-monocoque shells, and is treated as such. In fact, rotorcraft companies often have separate design and stress analysis groups for airframe, rotor, and drive systems, all served by common aerodynamics, structural dynamics, external and internal loads, and fatigue groups. Thus, each of the following subsections is divided into separate airframe, rotor, and drive system discussions.

For airframe, rotor, and drive systems, the maximum physical defect size requirements for primary, secondary, and nonstructural classifications are similar to those noted in previous sections for DoD and transport category civilian fixed wing aircraft (see Tables 4.4.2.1(a) and 4.4.2.1(b)). The main difference being that since defect sizes should "be consistent with the inspection techniques employed during manufacture and service" (Reference 4.4.5(a), para. 7.a.(2)), the limited NDI capability of the typical civil rotorcraft operator may result in larger allowable defect sizes (and may vary from one civil program to another). Thus, although discussion of these requirements will be minimized in this section, the manufacturing-level QA standards for rotorcraft, from coupons through full scale test articles, are of the same level as for large/complex fixed wing aircraft noted in Tables 4.4.2.xx and 4.4.3.xx, even though allowable defect sizes may be larger.

Within each subsection, static, fatigue, and damage tolerance substantiation requirements are addressed separately, if relevant. While these requirements are discussed at all levels of airframe substantiation, damage tolerance requirements for the rotor and drive systems are addressed exclusively at the full scale component testing level of the building block process, since that is the only level of the building block process at which they typically take place.

4.4.5.1 Design allowables testing

In general, design allowables testing is the most basic step in the building block process. Data from this level provide analytical input for strength, stiffness, and environmental/processing effect knockdown factors. Generally using small uniaxially loaded coupons, a great deal of statistical assurance is gained, but little or no analysis verification or structural substantiation is done. In this regard, rotorcraft do not differ significantly from the large/complex fixed-wing aircraft discussed in three of the building block examples considered previously.

4.4.5.1.1 Airframe

There are no significant differences between composite airframe design allowables testing for military EMD/production and FAR Part 25 fixed wing aircraft, and the subject military and civilian rotorcraft. In all cases, the airframes are separated into primary, secondary, and nonstructural components (or in terms of FAR 29.613, "single load path" or "multiple load path" instead of "primary" and "secondary"), each with differing levels of statistical assurance required for mechanical strength and differing levels of acceptable material quality. Suggested design allowables data guidelines for rotorcraft airframes may thus be found in Tables 2.3.1.1, 2.3.2.3, and 2.3.5.2.2 of Volume 1 and Tables 4.4.2.1(a) and 4.4.2.1(b) of this chapter. These guidelines should encompass all necessary data for point design analysis of laminates (strength and stiffness) and simple joints (e.g., bearing/by-pass for mechanical fastening), accounting for generic stress concentration (open holes), statistical (basis values), and environmental effects (temperature, humidity, and fluid soak), on all applicable material types and forms.

For airframes, fatigue life requirements are generally met through the use of conservative static design allowables, as in fixed-wing aircraft. However, when certain components (particularly the tailboom and roof beams/pylon supports) are deemed fatigue-critical, durability requirements are met via design development and full scale substantiation testing as described in later sections.

For airframes, damage resistance/tolerance requirements are met via development of B-basis design allowables using open hole (OHT and OHC) laminate-level, and sub-component-level static strength-after-impact testing (generally in compression, i.e., compression after impact (CAI)). A detailed description of damage resistance/tolerance requirements and approaches is given in Volume 3, Chapter 7. Further validation of damage resistance/tolerance is performed at the full scale test article level, as discussed below and in Volume 3, Chapter 7.

4.4.5.1.2 Rotor system

Design allowables testing for the rotor system is less extensive than for the airframe, since the components are generally substantiated via full scale fatigue testing, rather than by a combination of testing and analysis, as is the airframe. Stress analysis of rotor components is used for static sizing and also plays a critical role in programmatic risk mitigation (e.g., engineering and management confidence that there will be no surprises in full-scale testing) prior to full scale component fatigue testing. Thus B-basis ply strengths (developed per the Volume 1, Section 2.3.2.3 guidelines) are necessary (but not the extensive notched strength allowables used on airframes).

S-N curve shapes for environmental and stress ratio effects are developed in the design allowables phase of testing via a statistically significant number of coupon fatigue tests, using specimen geometries such as short beam strength (SBS) or unnotched tension, to later be applied to component-level mean S N data. A preliminary check of fatigue endurance limit is also sometimes made using this coupon-level data. However, unless a component is well below its material endurance limit, more detailed life predictions must be made using component-level fatigue testing. Unlike metals, composite component fatigue life below the endurance limit is not typically predicted using coupon-level S-N curves, since delaminations and local geometric effects not found in coupons dominate composite structural fatigue failures.

Unlike fatigue-critical metallic structures, the lack of a validated damage-tolerance-based analytical fatigue life prediction methodology for composites precludes the use of coupon-level fracture toughness or strain energy release rate allowables (equivalent to metallic da/dN vs. ΔK testing) to predict life on a damage tolerance basis.

Suggested design allowables requirements for rotor system components, in addition to those of Table 2.3.2.3(b) in Volume 1, are shown in Table 4.4.5.1.2.

Table 4.4.5.1.2 *Example of additional rotor system design allowables testing guidelines beyond Volume 1, Table 2.3.2.3(b).*

Test Type	Static				Fatigue			
	CTD	RTA	ETW	Purpose	CTD	RTA	ETW	Purpose
Unnotched tension[1,2]	(2)	(2)	(2)		--	12	9	env. & statistical K
OHT[1]	6	6	--	point dsn allow.	9	12	--	env. & statistical K
OHC	--	6	6	point dsn allow.	--	--	--	
SBS[2,3]	(2)	(2)	(2)		--	12	9	env. & statistical K
core shear	--	12	9	generic allow.	--	--	--	
core crush	--	12	9	generic allow.	--	--	--	

Notes:
These tests are typically repeated for each significant variation in material form, process, and/or lay-up.
1. Either R = 0.1 or R = -1 for fatigue testing (depending on intended component).
2. Static data included in Table 2.3.2.3(b).
3. R = 0.4 for fatigue testing.

4.4.5.1.3 Drive system

Design allowables testing for the drive system is less extensive than either the airframe or the rotor system, since (a) the components are completely substantiated via full scale fatigue testing, rather than by a combination of testing and analysis, as in the airframe; and (b) the geometry and loading, at least for drive shafts, is more straightforward than either rotor system or airframe components. Requirements for B-basis ply strengths, and coupon-derived environmental and stress ratio knockdown factors are similar to those for the rotor system. Suggested design allowables requirements for drive system components, in addition to those of Table 2.3.2.3(b) in Volume 1, are shown in Table 4.4.5.1.3.

TABLE 4.4.5.1.3 *Example of additional drive system design allowables testing guidelines beyond Volume 1, Table 2.3.2.3(b).*

Test Type	Static				Fatigue			
	CTD	RTA	ETW	Purpose	CTD	RTA	ETW	Purpose
±45 Tension[1,2]	(2)	(2)	(2)		9	12	9	env. & statistical K
SBS[2,3]	(2)	(2)	(2)		--	12	9	env. & statistical K
bolt bearing	--	12	9	generic allow.	--	12	9	env. & statistical K

Notes:
1. R = 0.1 for fatigue testing.
2. Static data included in Table 2.3.2.3(b).
3. R = 0.4 for fatigue testing.

4.4.5.2 Design development testing

Design development testing may be separated into three general categories:

- Element - single load path,
- Subcomponent - multiple load path but subscale or partial component, and
- Component - multiple load path/full scale component (but not for structural substantiation purposes).

The purposes for these tests vary, and include specialized strength allowables (e.g., damage tolerance), design trade studies, analysis development and validation, and cost/schedule-based risk mitigation. Rotorcraft-specific details of these categories and purposes are discussed in the three following sub-sections.

4.4.5.2.1 Airframe

Similar to fixed-wing aircraft, rotorcraft airframe development testing mainly consists of critical joint and free-edge (e.g., tabouts, access holes, etc.) risk mitigation and analysis validation. In rotorcraft airframes, these tests are more likely to be performed in fatigue as well as statically, in order to validate fatigue life predictions and to reduce risk prior to (or in lieu of) full scale airframe fatigue substantiation testing. Unlike fixed-wing aircraft, lightly loaded rotorcraft airframe shells are more likely to be of sandwich panel design (even for primary structure) since they are often bending stiffness rather than strength critical. Facesheets can be as thin as one ply of fabric. Thus, panel buckling tests are also often performed at the element and subcomponent levels.

Fatigue testing is limited to the aforementioned joint and/or access hole fatigue issues. Damage tolerance testing is often done at the design development stage, and takes the form of specialized element-level allowables generation typically using impact-damaged structural elements (e.g., 3-stringer panels, curved honeycomb panels, etc.). Table 4.4.5.2.1 presents possible design development testing requirements for rotorcraft airframes.

TABLE 4.4.5.2.1 *Example of airframe design development testing guidelines.*

Test Type	Static			Fatigue[3]		
	RTA	ETW	Purpose	RTA	ETW	Purpose
stiffener pull-off	12	5	special allowable[1]	3	--	design risk reduc.
stiffened CAI panel	12	5	special allowable[1]	--	--	
sandwich CAI panel	12	5	special allowable[1]	--	--	
bolted splice joint	6	3	trade study, analysis validation	3	--	design risk reduc.
shear panel w/cut-out	3	--	design risk reduc., analysis validation	3	--	design risk reduc.
stiffened shear panel	3	--	analysis validation	--	--	
sandwich shear panel	3	--	analysis validation	--	--	
stiffened compr. panel	3	--	analysis validation	--	--	
sandwich compr. panel	3	--	analysis validation	--	--	
complex subcomponent	5	3	design risk reduc.	3	--	design risk reduc.
tailboom component	3[2]	--	trade study	1	--	design risk reduc.

Notes:
1. Specimen quantities are highly variable for special allowables, reflecting case-specific trade-offs between testing cost and severity of statistical reduction.
2. Typically loaded to DUL*LEF rather than failure. Test article subsequently available for fatigue and/or damage tolerance testing. Impact damage sometimes included on early static article.
3. Typically constant amplitude unless a simple combination of load cases is available early in design process.

4.4.5.2.2 Rotor system

Rotor system design development testing mainly takes the form of single load path lug element static and fatigue testing to mitigate risk, generic subcomponent testing to screen rotor hub materials under multiaxial fatigue conditions, and design-specific subcomponent testing to mitigate design risk. Table 4.4.5.2.2 presents possible design development testing requirements for rotor systems.

4.4.5.2.3 Drive system

Drive system design development testing mainly takes the form of design-specific end-fitting element static and fatigue testing to mitigate risk. Table 4.4.5.2.3 presents possible design development testing requirements for drive systems.

TABLE 4.4.5.2.2 *Example of rotor system design development testing guidelines.*

Test Type	Static			Fatigue[1]		
	RTA	ETW	Purpose	RTA	ETW	Purpose
[0/45] laminate flexure	12	5	special allowable	12	12	allowable S-N curve
[0/45] laminate torsion	12	5	special allowable	12	12	allowable S-N curve
generic tension-bending flexbeam element	--	--		12	--	matl screening, effects of defects
M/R blade lug element	3	--	design risk reduc.	6	--	design risk reduc.
generic tension-torsion flexure element	3	--	design risk reduc.	6	--	design risk reduc.
M/R cuff subcomponent	3	--	design risk reduc., analysis validation	6	--	design risk reduc.
M/R grip component	3	--	design risk reduc., analysis validation	6	--	design risk reduc.
M/R flexure or yoke component	3	--	design risk reduc., analysis validation	6	--	design risk reduc.

Notes:
1. Typically constant amplitude unless a simple combination of load cases is available early in design process.

TABLE 4.4.5.2.3 *Example of drive system design development testing guidelines.*

Test Type	Static			Fatigue[1]		
	RTA	ETW	Purpose	RTA	ETW	Purpose
[0/45] laminate torsion	12	5	special allowable	12	12	allowable S-N curve
generic multiple-bolt joint element	12	5	special allowable	12	12	allowable S-N curve
design-specific joint element	12	5	special allowable	12	12	allowable S-N curve
molded blower blisk spin test	--	--		3	--	design risk reduc.
driveshaft component	3	--	trade study	3	--	design risk reduc.

Notes:
1. Typically constant amplitude unless a simple combination of load cases is available early in design process.

4.4.5.3 Full scale substantiation testing

Unlike the design development tests, full scale substantiation testing is performed on fully conforming (i.e., fabricated and inspected per production-level specifications) full scale components or systems, witnessed by the procuring or regulating agency, in order to meet specific procurement/regulatory requirements.

4.4.5.3.1 Airframe

Static test articles of the complete airframe structure are always required of new designs unless significant commonality exists with prior production aircraft. A limited number of load cases (due to complexity and cost issues) are usually demonstrated under room temperature ambient conditions up to design ultimate load (DUL), which also includes factors for environmental effects and strength scatter developed form lower-level testing. Full scale airframe fatigue test articles (unlike static articles) are not always performed, but are becoming more prevalent as major components, such as cabins or tailbooms are switched from metal to composite for the first time. Table 4.4.5.3.1 presents possible full scale substantiation testing requirements for airframes.

TABLE 4.4.5.3.1 *Example of airframe full scale substantiation testing guidelines*

Test Type	Static			Fatigue		
	RTA	ETW	Purpose	RTA	ETW	Purpose
tiltrotor wing STA	1[1]	--	cert./qual.	--	--	
tiltrotor fuselage STA	1[1]	--	cert./qual.	--	--	
tiltrotor empennage STA/FTA	1[1]	--	cert./qual.	1[2]	--	cert./qual.
tiltrotor wing/fuselage FTA	--	--		1[2]	--	cert./qual.
tailboom component	1[1]	--	cert./qual.	1[2]	--	cert./qual.

Notes:
1. Loaded to DUL*LEF's, in some cases damaged (customer-dependent), then tested to failure.
2. Spectrum fatigue loaded for 2 lifetimes, damaged, spectrum fatigue loaded for 1 lifetime, then (sometimes) statically tested to failure. See Chapter 5 for more details.

Full-scale airframe fatigue test articles provide the ultimate substantiation of structural life when used, otherwise full-scale component-level testing suffices. Damage tolerance requirements are met via analysis (using CAI and OH allowables) and induced damage full-scale substantiation tests. Component and airframe system static test articles are typically damaged in several critical locations, via imbedded and/or impact-induced delaminations, and must survive up to DUL, including environmental and scatter factors (see Volume 3, Chapter 5 for further details). Certain regulatory requirements also include substantiation of damage tolerance for two inspection intervals or two fatigue lifetimes. Thus fatigue test articles are also tested in a damaged condition. If imbedded damage is not used, impact events are often induced after having already endured two component-lifetimes of undamaged testing, and the resulting spectrum-loading life, together with an appropriate scatter factor, defines the required inspection interval.

4.4.5.3.2 Rotor system

Full scale fatigue substantiation testing is performed on all new design rotor system components, either individually or as a system. Typically, the inboard and outboard ends of a main rotor blade are tested separately. Other composite parts, such as yokes/flexbeams, cuffs and grips are tested as complete components. Since rotor components are more amenable to environmental conditioning, it is often possible to test these components in a wet (e.g., 80% - 85% RH equilibrium) condition rather than applying load factors to account for environment in an approximate sense. Typically, four to six components are tested at a variety of constant amplitude oscillatory load levels in order to generate a component-level S-N curve. A safe life/flaw tolerant method of life prediction is used under a variety of load spectra. Miner's rule is used to relate constant amplitude S-N data to spectral loading. Table 4.4.5.3.2 presents possible full scale substantiation testing requirements for rotor systems.

TABLE 4.4.5.3.2 *Example of rotor system full scale substantiation testing guidelines.*

Test Type	Static			Fatigue		
	RTA	ETW	Purpose	RTA	RTW	Purpose
M/R blade attachment & cuff component	1	1	cert./qual.	4 - 6[1] 2[2]	1[1] 1[2]	cert./qual. dam. tolerance
M/R grip component	1	1	cert./qual.	4 - 6[1] 2[2]	1[1] 1[2]	cert./qual. dam. tolerance
T/R blade attachment & cuff component	1	1	cert./qual.	4 - 6[1] 2[2]	1[1] 1[2]	cert./qual. dam. tolerance
M/R flexure or yoke component	1	1	cert./qual.	4 - 6[1] 2[2]	1[1] 1[2]	cert./qual. dam. tolerance
T/R flexure or yoke component	1	1	cert./qual.	4 - 6[1] 2[2]	1[1] 1[2]	cert./qual. dam. tolerance

Notes:
1. Constant amplitude (undamaged) certification testing.
2. Spectrum fatigue loaded for 2 lifetimes or inspection intervals, with imbedded manufacturing flaws (only); impact damage induced; then spectrum fatigue loaded for 1 lifetime or inspection interval. Combinations of constant amplitude and spectrum approaches are often used.

The full scale constant amplitude tests are preformed to determine adequacy of the as-manufactured structure and to identify fatigue critical areas for implanting manufacturing flaws and inducing impact damage in subsequent damage tolerance substantiation full scale fatigue test articles. These flawed/damaged full scale components are tested under representative spectral loads in order to establish fatigue life and/or set inspection intervals. The sizes of initial damage/flaws are determined by analyzing their risk and detectability. Also, the recommended fatigue life and/or inspection intervals are reduced from the test results by factors based on the damage/flaw risk, its detectability, and criticality of failure modes induced by the damage/flaws. Further details of rotor system damage tolerance requirements are given in Volume 3, Chapter 7.

4.4.5.3.3 Drive system

Full scale fatigue substantiation testing is performed on all new design dynamic system components, either individually or as a system. Typically, composite drive shafts are tested separately, while gearboxes are tested as complete mechanical systems. Since components such as drive shafts are more amenable to environmental conditioning, it is often possible to test these components in a wet (e.g., 80% - 85% RH equilibrium) condition rather than applying load factors to account for environment in an approximate sense. Typically, four to six components are tested at a variety of constant amplitude oscillatory load levels in order to generate a component-level S-N curve. A safe life/flaw tolerant method of life prediction is used under a variety of load spectra. Miner's rule is used to relate constant amplitude S-N data to spectral loading. Table 4.4.5.3.3 presents possible full scale substantiation testing requirements for drive systems.

TABLE 4.4.5.3.3 *Example of drive system full scale substantiation testing guidelines.*

Test Type	Static			Fatigue		
	RTA	ETW	Purpose	RTA	RTW	Purpose
driveshaft component	1	--	cert./qual.	4 - 6[1] 2[2]	1[1] 1[2]	cert./qual. dam. tolerance
blower assembly	--	--		4 - 6[1]	--	cert./qual.

Notes:
1. Constant amplitude (undamaged) certification testing.
2. Spectrum fatigue loaded for 2 lifetimes or inspection intervals, with imbedded manufacturing flaws (only); impact damage induced; then spectrum fatigue loaded for 1 lifetime or inspection interval. Combinations of constant amplitude and spectrum approaches are often used.

The full scale constant amplitude tests are preformed to determine adequacy of the as-manufactured structure and to identify fatigue critical areas for implanting manufacturing flaws and inducing impact damage in subsequent damage tolerance substantiation full scale fatigue test articles. These flawed/damaged full scale component flaw-size, damage tolerance and testing requirements are essentially the same as those described in Section 4.4.5.3.2 above for the rotor system.

4.4.6 Spacecraft

This section is reserved for future use.

4.5 SPECIAL CONSIDERATION AND VARIANCES FOR SPECIFIC PROCESSES AND MATERIAL FORMS

4.5.1 Room Temperature

This section is reserved for future use.

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