17 Structural Certification and Testing

This section focuses on the process of certification of structure and the testing that is required for demonstrating compliance to the requirements.

Contents

17.1 References, Nomenclature and Terminology

17.1.1 References

Reference	Title
17-1	Flansburg, B. D., "External Static Loads Analysis Manual," PM4063, Lockheed Martin Aeronautics, Ft. Worth, TX (2015)
17-2	Norwood, D.S. and Selvarathinam, A., "Composite Structural Analysis Manual," PM4056, Lockheed Martin Aeronautics, Ft. Worth, TX (2014)

17-3	anon, "Department of Defense Standard Practice Aircraft Structural Integrity Program," MIL-STD-1530C, United States Air Force, Dayton, OH (2005)
17-4	anon, "Department of Defense Joint Services Specification Guide: Aircraft Structures," JSSG-2006, Wright Patterson Air Force Base, OH (1998)
17-5	anon, "Airworthiness Certification Criteria," MIL-HDBK-516C, Department of Defense Handbook, Wright Patterson AFB, Dayton, OH (2014)
17-6	anon, Metallic Materials Properties Development and Standardization (MMPDS), Battelle Memorial Institute for the Federal Aviation Administration, William J. Hughes Technical Center, Battelle, Columbus, OH (current version)
17-7	anon, "Fastener Test Methods," NASM1312, National Aerospace Standards Committee, Aerospace Industries of America, Inc., Arlington, VA
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17-16	Dally, J.W. and Riley, W.F., Experimental Stress Analysis, 4th Edition, College Home Enterprises, TN (2005)
17-17	anon., Composite Materials Handbook CMH-17, Revision G, Materials Sciences Corporation, Secretariat, Philadelphia, PA (2012)

17.1.2 Nomenclature

Symbol	Description	Units
A	area	in^2
ASIP	Aircraft Structural Integrity Program	
ASTM	American Society of Testing Materials	
AVFEM	Air Vehicle Finite Element Model	
CDR	Critical Design Review	
COTS	Commercial Off The Shelf (Equipment)	
CTH	Cyclic Test Hours	hrs

Symbol	Description	Units
DLL	Design Limit Load	
E	Young's Modulus	psi
EFH	Equivalent Flight Hours	hrs
ETH	Equivalent Test Hours	hrs
f	Stress	psi
FCA	Functional Configuration Audit	
FGFEM	Fine Grid Finite Element Model	
GVT	Ground Vibration Test	
IFEM/STTGUI	Integrated Finite Element Tool Suite/Structural Test Tool Graphical User Interface	
K_{SG}	Strain Gage Factor	
L	Length	in
LVDT	Linear Variable Displacement Transducer	
MMPDS	Metallic Materials Property Development and Standardization	
N	Running load	lb/in
M	Moment	in-lb
microstrain	10^{-6} inch/inch	
P	Load	lbs
PCA	Physical Configuration Audit	
PDR	Preliminary Design Review	
PRR	Production Readiness Review	
R	Resistance	ohm, Ω
SDC	Structural Design Criteria	
SDT	Structural Development Test	
SDR	System Design Review	
SFH	Spectrum Flight Hours	hrs
SLAP	Service Life Assessment Program	
SOF	Safety of Flight	
SOT	Safety of Test	
SRR	System Requirements Review	
STM	Structural Test Memo	
t	Thickness	in
TAR	Test Anomaly Report	
TSRR	Test Safety and Readiness Review	
TRR	Test Readiness Review	
V	Voltage	volts
γ	shear strain	inch/inch or microstrain
ε	axial strain	inch/inch or microstrain
ρ	resistivity	
ν	Poisson's ratio	

17.1.3 Test Terminology

Term	Definition
Counterbalance loads	A distributed load condition that counteracts, as closely as possible, the weight and center of gravity location of all of the hydraulically counterbalanced test loading hardware (cradles, pads, whiffletrees, fittings, etc.)
Dump	Immediately release all hydraulic pressure forcing the test to an unloaded condition. Initiated by a control loop error.
Dump tuning	The process in which a prescribed load condition is applied to the test article and intentionally dumped while a high speed data buffer records all parameters throughout the event. The data is then used to adjust individual hydraulic manifold valve settings. Flow control valve adjustments will be made, as necessary, until the test set-up is optimized for smooth unloading.
Hold	Hold the test at the current load level
Interlock	Immediately release all hydraulic pressure forcing the test to an unloaded condition. Initiated by a system communication or (system) hardware failure
Null Pacing	Static or Dynamic – slow down the rate of load application until lagging instrumentation channels come into compliance
Stop	Ramp the test to the unloaded state in a predetermined, controlled amount of time
Tare loads	A distributed load condition that counteracts, as closely as possible, the weight and center of gravity location of the test article
Zero-g	The stress free state of the wing with all tare and counterbalance loads applied
Zero-g offsets	All strain gage and deflection measurements when the test article is at zero-g. Offsets are used to zero the gages before the test article is loaded.

17.2 Introduction

In order for a company to be given approval to manufacture and sell an aircraft a governmental certifying agency must review the design, analysis and testing to ensure the aircraft meets the design requirements. In the United States, the certifying agencies are the U.S. Air Force, U.S. Navy or U.S. Army for U.S. military aircraft or the Federal Aviation Administration for civilian aircraft. Other countries may have their own certifying agencies as well. While the certification process involves every aspect of the airplane, this section examines the certification of the airframe structure and provides an introductory overview of the process with a focus primarily on airframe static strength.

17.2.1 Aircraft Structural Integrity and Flight Certification

Aircraft structure is designed to the requirements detailed in the program specific Structural Design Criteria (SDC) document which is derived from the Weapon System Specification. During the proposal and early design phases of a program, the mission and capability of the aircraft is defined and is used in the development of the SDC, which is based on government issued specifications tailored to the specific aircraft program. Section 2 of Reference 17-1, PM4063 discusses in detail the government specifications related to aircraft design and the tailoring process.

17.2.1.1 Steps to Certification and Governing Specifications

Although other specifications may be in use on legacy aircraft, the current primary governing specification for aircraft structure is JSSG-2006[1], Reference 17-4, and any new aircraft would use this as a starting point for structural requirements. Section 4 of Reference 17-4 provides requirements for verification and validation of the basic criteria which are integral to satisfying the certification requirements. The discussions in PM4057 Section 17 will use the JSSG-2006 as a basis for the discussion of the various aspects of certification and testing.

In addition to the JSSG-2006, MIL-STD-1530C, Reference 17-3 and NADC-87089-60, Reference 17-13, provide information on the structuring of an aircraft program, including time phased planning, analysis and testing tasks to ensure aircraft structural integrity goals are met for the Air Force and Navy, respectively.

Once an aircraft model is designed, Lockheed Martin must demonstrate to the government certifying agency the aircraft's compliance to the design criteria. The demonstration artifacts that must be presented include the design drawings, analysis and correlated test results. At the end of this process, if the certifying agency is satisfied, the aircraft is certified safe to fly and can then be sold and fielded. MIL-HDBK-516C, Reference 17-5, Section 5 provides the framework and checklist for the certification process.

17.2.1.2 Structural Design Criteria

The SDC for each aircraft program is unique to that program. If more than one variant of the aircraft is fielded, there may be more than one SDC for that program. Reference 17-1, Section 2.8 provides a listing of each active Lockheed Martin program, the governing SDC and the specification basis for that model. The Structural Design Criteria document is based on the active military or civilian specification in place at the time the contract is initially set. For derivatives or modifications of existing aircraft platforms, the SDC is likely the original program SDC, with or without modifications. Careful consideration should be given to the ramifications if the SDC is to be upgraded to the most current specification. While there are many areas of the design which will be unaffected by the criteria in the new specification, there may be some areas where there will be significant redesign, cost and schedule associated with the changes.

The SDC should be considered as a contract between the engineers designing the airframe and the customer and the language of the SDC will define if a particular requirement is binding or a "nice to have." Reference 17-1, Section 2.2 discusses specification language and how it should be interpreted; however, the short version is that if the word "shall" is used, it is a binding requirement that the airframe must meet. Words like "should," "will," and "must" represents something that is desirable. The design team should view this document as being firm requirements and not open to frivolous changes. However, as the program matures, specific changes to the SDC may be negotiated with the customer if it is determined that meeting a specific item is physically not possible, results in a significant weight or performance penalty, adds capability or provides an improvement. The customer and certifying agency must agree to any requested deviations.

[1] JSSG-2006 was released in 1998. The 2006 is a document number and is unrelated to year of release or revision.

Any deviation from the parent specification shall be jointly agreed to in writing by the contractor and customer and documented in the SDC. The deviation needs to be unambiguous and clearly stated. The leaders involved on the customer and contractor teams will change throughout the life of an aircraft program. Any verbal agreements can be forgotten or ignored as these leaders change. Such undocumented agreements greatly increase the potential for significant adverse impacts to the program's cost and schedule.

Not only does the SDC provide a set of requirements that the airframe must be designed for and tested to, it also becomes the roadmap and checklist for demonstration of the airframe’s capability during the certifying phase of the program.

17.2.1.3 Strain-Based Certification

With the advent of complex detailed finite element models which are used to determine internal load distributions within the structure and the use of statistically based material properties, the typical path to certification for airframe structure is through analysis supported by test, sometimes called strain-based certification. In this approach, a series of design critical ultimate loads are applied to a full-scale airframe and strain gage data representing internal loads and aircraft deformations are measured. Although buckling may be permissible by design at some locations, strength failures resulting from the application of ultimate load during test are not expected. Reasons why failures are typically not expected are that the design critical margins of safety include environmental conditioning and statistically based material properties while full-scale testing is typically conducted under ambient conditions.

To minimize the risk associated with full-scale testing and as a part of the overall data required to support strain-based certification, much testing is done prior to the full-scale airframe tests. These range in complexity from simple coupon testing to obtain statistically based, environmentally conditioned material properties, to element tests representing individual details, to subcomponent tests which may represent a critical joint or a single sub-assembly of the airframe. This data is then used in the design analysis of the airframe prior to the full-scale static testing.

After full-scale testing the measured data is correlated with predictions made from the finite element model-based analysis and any modification to the test model is propagated to the air vehicle model. These relatively coarse models are generally used only for the development of internal loads distributions and not for final stress analysis. Finally, the structural analysis is updated with the new air vehicle model results and/or analysis modifications to form the certification analysis of the aircraft.

This test-model-analysis-test correlation approach provides insight into how to best analyze/model key aspects of the structure and verifies and validates that the analysis does predict the structural behavior and test article strains and internal loads. Further discussion of the steps to analysis validation is provided in Section 17.12.

For component and full-scale testing a finite element model is integral with the process and the models should be representative of the test article including the manner in which the loads are applied and any test restraints. For the component level and full-scale static tests, the maximum load levels might be ultimate load with the goal of obtaining strain gage data, representing the internal loads, for a number of critical design conditions through-out the design envelope. As a part of the strain-based certification approach, the structure is not taken beyond ultimate load to failure. The measured data representing test internal loads is then used to compare with model internal loads for correlation. If there is a significant unexplained difference between the test and model results, an adjustment of the finite element model may be required. The revised finite element model, along with the flight measured loads resulting from flight test is then used to generate the detail part structural certification analysis. From this, the final strength envelope which is published as a part of the Strength Summary and Operating Restrictions Report (SSOR) can be determined. The SSOR report, along with the structural certification analysis, provides the final verification artifacts for certification. See Section 17.2.1.4 for more discussion on Certification Analysis.

Strain-based certification is done for a number of reasons:

- Every part in the airframe cannot be tested to ultimate for its critical design condition so demonstrating the correspondence between the air vehicle FEM variant used for strain predictions and the measured strains demonstrates that the air vehicle FEM is representative of the structure and the internal loads distributions and subsequent stress analysis are reasonable, thus providing validation of the analysis.
- Validation of control point selection
- There are many parts on the airframe that have multiple zero or near-zero margins of safety for a variety of load conditions, so testing to failure for one part and one condition doesn't validate the overall design for the total loads envelope nor does a cyclic failure of one part validate (or invalidate) the overall design life of the airframe.
- Often the full-scale static test vehicle is used for other purposes after test and is not taken to failure. See Section 17.3.4 for discussion.

While strain-based certification is used within all current and recent programs, the decision to waive the requirement for taking the full-scale static test article to failure usually evolves during the course of the program and must have certifying agency, customer and contractor concurrence documented in writing. With lesser articles, such as component tests, it is recommended that the article be taken to failure for either the most critical condition or the condition in which there is the most uncertainty in loads (such as a component loaded by dynamic response loads). The rationale behind this is that if there is a proven failure load then the criticality of unexpected overshoots or load increases can easily be evaluated.

17.2.1.4 Certification Analysis Requirements

During the design phase of an aircraft program, a design analysis is performed. This provides assurances that the as-designed aircraft has positive margins of safety and full life for the predicted set of aircraft loads throughout the flight envelope. The design analysis is typically not a formal report but should be archived. Depending on customer, it may or may not be available for their use, although at some point they may review this analysis. Reference 17-3, MIL-STD-1530C requires that the design analysis be revised after all full-scale ground and flight testing has been completed and the results have been interpreted, evaluated and correlated. The design analyses correlated to ground and flight testing is the certification analysis, is used to establish the certification basis of the aircraft and is generally a deliverable contractual item. See PM4057 Section 2.10 for a discussion of stress report content and format.

The certification analyses provide the engineering source data for any operational limits, restrictions, maintenance actions or inspections. The analyses reports are an important part of the documentation artifacts required for airworthiness certification as discussed in Reference 17-5 and also form the basis for inputs to the Strength Summary and Operating Restrictions (SSOR) report, which provides the final operating envelopes for the fielded aircraft and the Force Structure Maintenance Plan (FSMP), which provides the required inspections for the fielded aircraft.

Depending on the customer and contractual requirements the contents of the certification analysis reports may vary. As a minimum it should provide analysis and margins of safety for all Class I and Class IIA structure (reference PM4057 Section 2.2.1.1) and life predictions for all fracture critical structure and durability critical structure.

17.2.2 Aircraft Structural Integrity Test Requirements Overview

Reference 17-4 the Joint Service Specification Guide, JSSG-2006, Reference 17-3 Mil-Std-1530C, Aircraft Structural Integrity Program and Reference 17-13, the Navy Aircraft Structural Integrity Program require testing as a part of the verification process and as an integral part of the certification process. This testing includes static strength, dynamic, flight testing, durability and damage tolerance, vibration, acoustics and aeroelasticity requirements as described in the sections below. In addition, Appendix A of Reference 17-4 provides insight and lessons learned from other aircraft platforms. In the sections following, a description of the JSSG-2006 requirements for all testing is provided. Details on the testing required for composite materials can be found in Section 18, Reference 17-2, PM4056.

17.2.2.1 Static Strength Testing

Reference 17-4, Paragraph 4.10.5 *Static Strength*, states:
"Laboratory load tests of instrumented airframe and major parts thereof, shall verify that the airframe structure static strength requirements of (JSSG-2006)3.10.5 are met. This instrumentation is required to validate and update the structural strength analyses. The applied test loads, including ultimate loads, shall reflect those loads resulting from operational and maintenance loading conditions."

The requirement then continues with specifics on the types of static testing which may be required. This is summarized in Table 17.2.2-1.

Table 17.2.2-1 Static Strength Testing Required per Reference 17-4 JSSG-2006.

Test Type	Purpose	Rationale
Development Tests	Establish design concepts, provide design information, establish design allowables, and provide early design validation.	These tests are critical in reducing and managing the design risk such that the program goes into the full-scale static test with a reasonable chance of success.
Design Development Tests	Coupon/Element- Run with sufficient sample size to determine statistically compensated allowables	These tests are necessary to establish design concepts and to provide design information and early design validation where data does not exist or is incomplete.
	Structural Configuration (Component/ Subcomponent) Development Tests - Run with a smaller sample size than coupon tests.	Results are used to validate the analytical procedures and establish design allowables.
	Large Component Development Tests –The actual number and types of tests will depend upon considerations involving structural risk, schedule, and cost, typically no more than one or two of each configuration.	These tests are to allow early verification of the static strength capability and producibility of final or near-final structural designs of critical areas.

Test Type	Purpose	Rationale
Design Development Tests for Composites. See PM4056 Section 18.	Design Development Testing for Composites uses a building block approach. This is essential for composite structural concepts, because of the mechanical properties variability exhibited by composite materials, the inherent sensitivity of composite structure to out-of-plane loads, their multiplicity of potential failures modes, and the significant environmental effects on failure mode and allowable. Special attention to development testing is required if the composite parts ultimate strength is to be certified with a room temperature/lab air static full-scale test.	Sufficient development testing must be done with an appropriately sized component to validate the failure mode and failure strain levels for the critical design cases with critical temperature and end of life moisture.
Static Tests – Complete Airframes	Static tests, which include tests to design ultimate load, shall be performed on the complete, full-scale airframe to verify its ultimate strength capability	To establish static strength envelope and verify the overall strength/stiffness of the airframe
Failing Load Test	After static ultimate testing, the failing load test shall be conducted to fail the airframe by increasing the test loads of the most severe test loading condition	Determine the failure strength of the aircraft. This may be waived with customer concurrence.
Functional Proof Test Prior to First Flight	Prior to the first flight of the first flight article, proof tests shall be conducted to demonstrate the functioning of flight-critical structural systems, mechanisms, and components whose correct operation is necessary for safe flight. Structurally, typically conducted for control surface: Control Surface Proof of Operation (CPoO); cockpit or cabin pressure	Safety Requirement.
Strength Proof Tests	Strength proof tests shall be successfully performed on every airframe or parts thereof to be operated before ultimate load static tests are successfully performed or if static tests are not performed.	Safety Requirement: Demonstrate the capability of the airframe to withstand maximum mechanical loads expected to be encountered in flight without failure or detrimental deformation.
Pressurization Proof Tests	Pressurization proof tests shall be successfully performed on every airframe prior to pressurized flight.	Safety Requirement: Demonstrate the capability of the airframe to withstand maximum pressure loads expected to be encountered in flight without failure or detrimental deformation.

17.2.2.2 Dynamic Strength Testing and Drop Tests

Reference 17-4, Paragraph 4.10.6 *Dynamic Strength*, states:
"Prior to release for flight verification testing, component or total airframe laboratory testing shall be conducted to demonstrate energy absorption compliance and to validate design loads analysis. For land-based aircraft with maximum limit sink rates less than or equal to 10 feet per second (fps), system functions may be demonstrated by component landing gear jig drops which demonstrate both design conditions and the required reserve energy conditions. For shipboard aircraft, drop tests of the complete airframe shall be conducted."

This series of testing is describing full-scale component or full-scale testing of the landing gear system. In addition, prior to first flight a series of taxi tests will be conducted to verify proper functioning of the gear system.

17.2.2.3 Interim Strength and Final Strength Flight Release: Structural Flight Test

Reference 17-4, Paragraph 4.10.7 (b) *Initial and Interim Strength Flight Release* states:
"*Prior to flight beyond the initial strength flight release, the accuracy of the loads predictive methods shall be validated by using an instrumented and calibrated flight test air vehicle to measure actual loads and load distributions during flight within the initial strength flight release envelope. Also, prior to flight beyond the initial strength flight release, the strength proof test requirements of (JSSG-2006) 4.10.5.4 shall be successfully met if the ultimate static strength tests have not been performed. Extrapolations of the measured data beyond the initial flight limits shall be used to establish the expected conservatism of the predictive methods for flight up to limit loads. This procedure of loads measurement and data extrapolation shall be used to validate the conservatism of the strength analysis and strength proof tests for each incremental increase in the strength flight release envelope up to limit loads or the strength envelope cleared through the strength proof testing of (JSSG-2006) 4.10.5.4, whichever is less."*

This is the basis for the requirement to perform instrumented flight testing and flight test correlation to strength predictions as a means of verification of the externally applied loads and the strength of the airframe. The last statement also requires an incremental expansion of the flight envelope based on previous lower load level flights. The initial safety-of-flight strength clearance is supported by the static test, the Ground Vibrations Test, and a mass properties and structural durability analysis. Typically the durability testing is not complete and may not have started prior to initial flights. Subsystems will require some degree of durability testing, typically on the order of 10% of life.

Reference 17-4, Paragraph 4.10.8 invokes a similar testing/correlation procedure for the final strength flight release.

17.2.2.4 Durability Tests

Reference 17-4, Paragraph 4.11.1.2 invokes the requirement for testing to ensure the airframe structure meets the requirement that the airframe remain free of cracking, delaminations, disbonds, deformations, and defects of paragraph 3.11.1 for two lifetimes. The testing, called out in Reference 17-4, Paragraph 4.11.1.2.1, includes many of the same development, design development and composite design development tests required per Table 17.2.2-1, except that the loads applied are cyclical instead of a static load. The goal is to determine spectrum effects validating critical component durability and validate the durability analysis tools and methodology.

JSSG-2006 Paragraph 4.11.1.2.2 also requires a full airframe durability article to show that the airframe meets the life specified in Paragraph 3.2.14. The requirements are to show a minimum of two lifetimes of durability testing using a spectrum derived from and consistent with the flight loads and flight spectrum. Any truncation, elimination or substitution of load cycles must be coordinated with and approved by the certifying agency. A third lifetime may be performed to support damage tolerance requirements, repair/modification changes, usage changes and life extension potential.

17.2.2.5 Damage Tolerance Tests

Reference 17-4, Paragraph 4.12.2 (b) requires
"*Tests, development (___) and full-scale (___) damage tolerance tests are required to demonstrate that the airframe structure meets the requirements of (JSSG-2006) 3.12. The material properties derived from development tests shall be consistent and congruent with those properties of the same material, in the same component, used by the other structures disciplines. See (JSSG-2006) 3.2.19.1.*"

This paragraph requires testing of damage tolerance coupons to determine the material properties for damage tolerance analysis. This is also discussed in Section 17.4. It also references full-scale testing which may be done with a full-scale component or as a part of the full-scale durability article as discussed in Section 17.2.2.4; however, for metallic materials the emphasis is typically on the validation of the analysis methodology through the use of coupon level data supplemented by full-scale component tests.

17.2.2.6 Vibration and Aeroacoustics Tests

Reference 17-4, Paragraph 4.5.1.2 requires testing to characterize the aircraft aeroacoustic environment and the resulting structural durability life. This includes:

- Aeroacoustic tests which utilize the uncertainty factors on sound pressure level and duration as specified in the acoustic requirements section
- Aeroacoustic tests of structural components to verify the aeroacoustic durability analysis
- Full-scale aeroacoustic tests required to verify the durability
- Ground and flight aeroacoustic measurements
- Jet blast deflector acoustic and thermal measurements.

Reference 17-4, Paragraph 4.6.2 requires vibration development testing for structures which cannot adequately be analyzed, ground vibration tests of a complete airframe to characterize the natural frequencies, mode shapes, and damping of vibration of airframe components and ground and flight vibration measurements to verify the actual vibration levels and demonstrate there are no excessive vibrations.

17.2.2.7 Aeroelasticity Tests

Reference 17-4, Paragraph 4.7 requires that analyses and tests are required to verify that the aircraft can operate in the flight environment associated with operational use required by the required aeroelastic stability requirements. Tests are described in Table 17.2.2-2.

Table 17.2.2-2 Required Aeroelasticity Testing per JSSG-2006 (Reference 17-4)

Test Type	Specific Testing
Wind Tunnel Model	Low Speed Flutter Model Tests
	High Speed Flutter Model Tests
	Unsteady Pressure Measurements

Test Type	Specific Testing
Laboratory Tests	Component Ground Vibration Tests
	Mass Measurements of Control Surfaces and Tabs
	Control Surface, Tab, And Actuator Rigidity, Free Play and Wear Tests
	Component Stiffness Tests
	Balance Weight Attachment Verification Tests
	Damper Qualification Tests
	Thermoelastic Tests
Air Vehicle Ground Tests	Ground Vibration Modal Tests
	Aeroservoelastic Air Vehicle Ground Test and Flight Control augmentation System
Air Vehicle Flight Tests	Initial Flight Speed Limits
	Flight Flutter Tests
	Flight Aeroservoelastic Stability Tests

17.2.3 Design Development Testing and Test Complexity Levels

Where there is insufficient data, testing of various complexity is performed to establish material properties, design concepts, and early design validation. Below is the description of these tests, taken from Reference 17-4.

This approach is sometimes referred to as building block testing with the implication that each subsequent test builds on the data obtained from earlier, simpler testing to create a comprehensive picture of the structural robustness. Sometimes “building block testing” is used to only refer to the testing to certify composite materials; however, this manual and Reference 17-2 use it in a more general sense to encompass all metallic and composite testing required for structural certification.

Goals of the building block testing prescribed for demonstration of structural integrity include:

- Materials Characterization and allowables development
- Design analysis validation and calibration at the element, subcomponent, component and full-scale test levels
- Design verification at the element, subcomponent, component and full-scale test levels.

Throughout the testing process, strength and life properties, analysis constants and/or empirical adjustments are developed and are dependent not only on the criteria and customer requirements but also on the types of failure criteria and life methods built into Lockheed Martin Aeronautics strength and life analysis methods. This is a part of the validation process discussed in Section 17.12. Because of differences in analysis methodologies/philosophies, different aircraft manufacturers approach this differently and the resulting constants or adjustments are not universal.

Development testing for composites, covered in detail in Reference 17-2, Section 18, is essential for composite structural concepts because “*of the mechanical properties variability exhibited by composite materials, the inherent sensitivity of composite structure to out-of-plane loads, their multiplicity of potential failures modes, and the significant environmental effects on failure mode and allowable. Special attention to development testing is required if the composite parts ultimate strength is to be certified with a room temperature/lab air static test. Sufficient development testing must be done with an appropriately* *sized component to validate the failure mode and failure strain levels for the critical design cases with critical temperature and end of life moisture*."[2]

Note that quoted paragraph from the JSSG-2006 discusses the need for *"sufficient development testing must be done with an appropriate sized component."* highlights an issue and concern when conducting development testing for composite materials. This issue is often referred to "scale-up effects". When a coupon or element test is performed the specimen is small and the loading is usually simple, perhaps uniaxial. As the test part becomes more complicated in geometry or loading and more closely resembles the actual design, other complex failure modes can often be uncovered or it can be discovered that temperature effects come into play in a manner not represented in coupon level testing. This makes it very important to structure the composites test program to include tests of different scale and complexity to verify the structural behavior of the final structure.

With the exploration of new metallic material manufacturing methods and joining techniques, such as laser deposition, electron beam direct manufacturing, powder sintering and friction stir welding, *etc.* similar types of development testing as is done for composite parts may become necessary for metallic parts built from these new approaches. All of the current metallic analysis methods are based on correlation to wrought product testing. The use of traditional metallic analysis methods with statistically based material properties from coupon test specimens, as might be done for a new plate material, may not be sufficient to ensure structural integrity. Element, sub-component and component tests may also be required for the critical failure modes.

Table 17.2.3-1 provides a quick summary of the definition of the different test levels and associated objectives. The sections below describe in more detail each of these. Reference 17-2 will discuss the composite tests in more detail.

Table 17.2.3-1 Design Development Test Level Definitions and Objectives

Test Level	Description	Objectives
Coupon	Material characterization tests that include physical, material or design allowable properties. Test method is typically based on an ASTM standard or LM test specification.	Material screening, material qualification, or design allowables.
Element	Structural tests of a generic individual structural element, structural bolted or bonded joint assembly, or representative section of a stiffened structure and typically have a single component of loading.	Manufacturing development, design allowables, analysis calibration, repair validation, risk reduction, or certification.
Sub-Component	Structural tests of an airframe structural sub-assembly. More geometrically complex than a structural element, yet not identifiable as a stand-alone component. Subcomponents are typically structurally representative and often have multiple load components.	Manufacturing development, analysis calibration, risk reduction, or certification.

[2] Reference 17-4, Section 4.10.5.1.1(d)

Test Level	Description	Objectives
Component	Standalone testing of a full-scale airframe component.	Manufacturing development, analysis calibration, risk reduction, or certification.
Full-Scale	Static or durability ground testing of a full-scale airframe test article.	Analysis calibration or certification.

17.2.3.1 Coupon/Element

Coupon and element tests are typically simple tests with a single load component. Coupon tests are typically run using standardized specimens defined in ASTM specifications or in company specifications. References 17-9 for fiber reinforced composite materials and 17-8 for metallic materials provide a summary of coupon testing preferred at Lockheed Martin Aeronautics. An element test is a generic, but non-standard test specimen which has been designed for a specific purpose typically to test a single structural element a bolted or bonded joint assembly or a representative section of stiffened structure. For coupon and element tests there are sufficient specimens tested to allow for calculation of a statistically based design value. Both coupons and elements typically have a single load component.

Tests of this type are performed for both metallic materials and composite materials and typically run to obtain:

- Material selection information
- Material properties for selected program materials
- Environmental effects such as temperature, moisture, chemical resistance, corrosion resistance
- Fasteners systems, joint and fastener allowables
- Bond strengths
- Processing evaluation to examine all corners of the allowable processing window
- Effects of defects determination
- Impact resistance
- Minimum skin gage to preclude leakage or moisture intrusion
- Crack growth response
- Durability behavior
- Spectrum truncation

See Reference 17-2, Section 18 for further discussion of coupon testing for composite materials.

17.2.3.2 Structural Configuration Sub-Component Tests

Because these are larger more complicated specimens and loading than the coupon or element tests, these are typically run in smaller numbers than the coupon/element tests. The results are used to validate analytical procedures and establish point design allowables for a structural detail. Sub-components are full-scale design details which are more geometrically complex than an element but not identifiable as a standalone component. These are typically loaded with multiple components of load. Actual material properties and dimensions should be used when determining empirical correction factors and the lower range of test results used for design allowables compatible with the usual statistical methods. Tests of this type are performed for both metallic, composite and hybrid assemblies and are typically run for:

- Specific configurations of splices and joints

- Buckling and crippling allowables
- Panels (4 stringer, 5 stringer, unstiffened)
- Panels with cutouts, framing or other details
- Tension, shear or lug fittings
- Critical structural areas which are difficult to analyze due to complexity and for which test validation is desirable
- Manufacturing method evaluation including acceptable variations such as maximum gaps, gap pull-up and differing shim materials and thicknesses
- Composite failure modes and strain levels
- Bonded core and core termination details
- Environmental effects on composite failure modes and strain levels

These tests may be run for static strength or durability life. Loading can be accomplished using actuators, pressure pads or a combination and the article may be loaded by a single load component or by a combination of several. Any durability testing could be performed using a uniform load spectrum, a blocked spectrum of differing load levels, or a random spectrum based on the aircraft loading. Static strength tests should be taken to failure and life tests should have a residual strength test after all cyclic testing is complete. For composite or hybrid designs, this level of testing will often be done using worst-case environmental conditioning. See Reference 17-2 Section 18 for more discussion on composite tests of this type.

17.2.3.3 Component Development Tests

These tests, larger and more complicated than the specimens described in section 17.2.3.2 are performed to allow for early verification of static strength or life of a final or near-final design. These are typically complete standalone assemblies such as a fuel tank, wing carry through box, wing pivot fittings or a full-scale component such as a control surface, vertical tail, empennage, *etc*. This type of test can also serve to verify producibility concepts or new manufacturing processes or materials and verify risk associated with them. This test may be repeated for the final design for certification.

The actual number and types of tests will depend on the perceived structural, cost and schedule risks; however one static and one durability or one combined static-durability of each specimen type is not uncommon. Tests of this type are performed for both metallic, composite and hybrid assemblies for which there are significant unknowns:

- Critical splices or joints
- Large Fittings
- Stability critical structure to verify end or edge fixities
- Post buckled structural assemblies
- Out of plane loading in composites
- Environmental effects on large scale composite assemblies
- Fuel tank hybrid structure
- Wing-only tests

Often the horizontal and vertical tails, rudder or the entire empennage is tested at the component level for static strength and durability life. The full-scale full airframe test articles can then be simplified to have dummy tails for load introduction. This has advantages for the components as well since it may allow them to be tested in an environmental chamber or it may allow for the buffet cycles to be implemented using a shaker table. A final advantage is that, at the full-scale component level, the article can be taken to failure for an ultimate or residual load test. If these parts are tested on-aircraft this typically cannot happen.

Ground vibration testing of key critical components is also performed prior to assembly into the aircraft. These are non-destructive tests that can be performed on components of flying articles. Measurements can include natural frequencies, mode shapes and structural damping of an individual component. Components which may fall into this category are control surfaces, pylons, flaps, horizontal stabilizers, control surface actuators, and racks for supporting external stores.

17.2.3.4 Full-scale Complete Airframe Ground Tests

Typically, for all new aircraft programs there are a minimum of two full-scale full airframe test articles one for static strength and one for durability/damage tolerance testing.

For derivative aircraft, one or both of these tests may be waived with the approval of the certifying authority and customer; however, this requires that the airframe and its loadings are essentially the same as that of a previous airframe which was verified by full-scale static and durability tests. Thus any significant changes in load paths, manufacturing techniques or materials would have to be examined very closely in the determination of whether or not it is appropriate to request a waiver for one or both tests. If the full-scale tests are waived, it is likely that major component tests would be required to verify any significant changes to the structure or load paths particularly for stability critical (static) or durability critical (life) structures.

For aircraft modifications such as the addition of radomes or other local changes, the new components may be designed to an increased safety factor or reserve margin of safety which presupposes that traditional, well characterized materials and manufacturing techniques are used and load paths and analysis method are well understood, *i.e.*, classical approaches are used. The reserve margin of safety typically specified by the JSSG-2006, Reference 17-4 is 0.25 or a safety factor of 1.875[3]. This approach would need to be approved by the customer and certifying agency prior to implementation.

It is NOT recommended that the reserve margin approach be considered with a full airframe derivative, as the discussion in Reference 17-4, Appendix A4.10.5.2 indicates *"however this level of safety is not considered acceptable for a fleet of aircraft, but may be acceptable for a small number of flight test vehicles."*

17.2.3.4.1 Full-scale Static Test

A single instrumented full-scale static test is performed for the majority, if not all, new aircraft programs to support the verification of ultimate strength capability. This is done through testing of a limited number of flight-representative full-airplane test conditions to ultimate load resulting in a strain-based verification of Air Vehicle FEM internal loads followed by a certification analysis to substantiate the ultimate strength envelope. The certification artifacts are then the test-correlated FEM, the updated certification strength analysis and the SSOR report.

The static test article is one of the early airframes built on the assembly line and should be representative of the operational vehicles in both design and quality. It should be a complete airframe with doors, panels

[3] Reference 17-4 JSSG-2006, Paragraphs A3.10.5.2 and A3.10.9

and fairings. In-flight opening doors may be subjected to local door-unique test conditions. Control surfaces and edges can be present or they can be removed and replaced with load introduction fittings. Holes for systems (electrical, hydraulic, fuel) should be present with fasteners. Any substantive systems support or racks should be present. Any repairs or dispositions done during manufacture should be careful to not over-strengthen the repaired area such that the load distributions are not representative or any inherent weaknesses in the airframe are negated. Section 18 discusses material review board actions and the test articles.

The airframe is loaded with multiple load actuators and pressure pads which apply loads to represent flight cases and strain gages are monitored for the structural response. The strain gage data is later used for correlation of the air vehicle finite element model which has been modified to include the load introduction fittings/pads. See Section 17.9 for more details on test monitoring and procedures.

The objectives of the full-scale static test include:

- Demonstrate ultimate load on the air vehicle for a limited number of critical conditions which allows for the expansion of the flight test envelope to limit load[4]
- Application of design ultimate external loads on the test article to demonstrate static strength stability-critical load conditions
- Demonstration of component global stability for design loads, *e.g.*, vertical tail or wing box
- The collection of necessary data to verify internal load predictions of the air vehicle finite element model as part of the post-test correlation effort
- Conduct expanded capability load testing, beyond original design loads, as necessary, to demonstrate increased structural capability beyond the original design envelope for increases in gross weight, maneuver capability, etc.
- To provide a method for refining loads measurements without additional calibration or instrumentation of the flight test vehicle for loads bridges common to the flight test aircraft.

The results of the post-test strain gage-FEM model correlation are used to perform the certification analysis which substantiates the ultimate structural strength of the airframe.

17.2.3.4.2 Full-scale Durability Test

Durability tests conducted by applying a flight-by-flight load sequence to a structurally complete full-scale airframe are the most effective means of evaluating the effect of the loading environment on an airplane structure. The use of a complete airframe ensures the correct relative stiffness and flexibility between adjacent structural components and results in loading distributions which are most representative of the aircraft. Thus, a second instrumented full-scale test article is used for durability testing.

The durability test article is built under the same ground rules as the static test article. It is also loaded using multiple actuators and pressure pads. It is one of the early airframes built on the assembly line and should be representative of the operational vehicles in both design and quality. It should be a complete airframe with panels and fairings. In-flight opening doors are typically omitted and replaced with load fittings or they can be used to introduce their loads into the durability article. Control surfaces and edges can be present or they can be removed and replaced with load introduction fittings. It should include

[4] Reference 17-4, JSSG-2006, Paragraph A3.10.7 discusses interim flight clearances. Typically the flight test aircraft can be flown to 80% of the maximum static ground test load prior to the completion of the full scale static ultimate tests.

systems brackets, all systems attachments (fuel, electrical, hydraulic, *etc.*), holes, *etc.* in the airframe structure. Typically the systems and system components are omitted but the attaching holes are drilled and attaching hardware installed. Any substantive systems support or racks should be present. Any repairs or dispositions done during manufacture should be careful to not over-strengthen the repaired area such that the load distributions are not representative or any inherent weaknesses in the airframe are negated or to make an area fatigue critical where the as-designed structure was not fatigue critical. Section 18 discusses material review board actions and the test articles.

The loading arrangement for the durability article may or may not be the same as for the static article. The test loads applied are in the form of a spectrum of loads representing blocks of 500 or 1000 hours of flight, which are repeated to achieve the required number of lifetimes of testing, typically two. After the second successful lifetime, cracks or damage may be introduced and the article cycled for a third lifetime.

When all cyclic testing is completed, a residual strength test to failure may be performed. Many programs opt not to fail the durability article since it can cloud the teardown findings and Reference 17-4, A4.11.1.2.2.(f) allows for a number of options after the two lifetimes of testing:

- Continued durability combined with damage tolerance testing
- Continued durability testing for the purpose of life extension and/or modification verifications
- Residual strength testing to failure
- Damage tolerance testing, fail-safe testing, and battle damage tolerance testing
- Usage spectrum sensitivity testing

The final decision on test-to-failure should be made in conjunction with the requirements from the customer. More discussion on the test article configuration, test spectrum, and test procedures can be found in Reference 17-10, SLM 14 and in PM4057 Section 17.9 Test Monitoring and Procedures.

Another key aspect of the durability test is that regularly scheduled inspections of critical areas is performed and any cracks found are closely monitored and repaired, if necessary, before they become catastrophic. At the completion of testing it is expected that a teardown of the test article be performed to include areas which have initiated cracking or delaminations. Analyses of test anomalies are correlated with test results and must show that they meet the aircraft durability requirements.

17.2.3.4.3 Ground Vibrations Test

Complete air vehicle ground vibrations tests (GVT) is performed by the Dynamics and Flutter engineers on the first aircraft prior to first flight and repeated on the flutter flight test vehicle prior to its first flight. It is sometimes repeated on the last aircraft produced under the development contract (SDD or EMD). These tests are required for all new aircraft or if changes which may affect the structural dynamic characteristics have been made for a modification or derivative program. The goal of the GVT is to measure the structural modes of vibration for use in verification of the dynamics models. The structure is excited using a vibratory force and the response is measured. Data collected should include natural frequencies, mode shapes and damping of vibration of airframe components. The excitation can be sinusoidal or random. Each has advantages as described in Reference 17-4:

- *"Sinusoidal has the advantage of permitting on-line examination of the modes, easy linearity evaluation of each mode, and minimum reliance upon complex data reduction computing programs"*

- *"Random testing has the advantage of reducing test time in that the complete set of measurements need not be repeated for each mode and reliance is placed upon the data reduction method in obtaining orthogonal modes rather than on the skill of the vibration test engineer"*

However, random testing may not provide adequate data for nonlinear systems. Test configurations should look at all variables including different fuel states, variable geometries, different store load-out combinations and the air vehicle configuration should be representative of a complete ready-to fly article, including all items of appreciable mass, systems, control surfaces, doors, *etc.*

Correlation with the dynamic finite element model to the ground vibration test results is performed during and after test.

The GVT is also used to measure landing gear mode shapes, frequencies, and modal damping for the modes of the landing gear with the wheels free from the ground. The GVT results can be used to resolve and prevent transient gear vibration problems.

17.2.3.5 Flight Test

A number of instrumented flight test vehicles are also required. Some are required for structural verification but others are used for verification of mission systems, low observables, etc. The flight test articles used specifically for analysis verification are instrumented and serve specific purposes including

- Loads flight testing which is used to validate the external loads, maneuver simulations and aircraft response, and to demonstrate the ability to fly the critical design conditions
- Buzz, buffet, aero-acoustics, and dynamics testing
- Aeroelastic flight testing to verify aeroelastic stability (flutter), airspeed margin, damping requirements, aeroservoelastic stability and free-play requirements
- Flying Qualities

Loads flight testing can be accomplished for a number of different types of aircraft and for different reasons and prior to testing the goals need to be clearly identified. Table 17.2.3-2 describes some different flight test types and provides examples.

Table 17.2.3-2 Types of Structural Loads Flight Tests

Type of Flight Test	Examples
Experimental	Polecat (P-175), F16-XL, CATBIRD
Technology Demonstrator	Advanced Composite Cargo Aircraft (ACCA), Multi-Axis Thrust Vectoring (MATV)
Prototype Testing	YF-22, X-35
Full-scale Development	F-35, F-22
Follow-on Flight Testing: • Store Certification • Control System Testing, • Structural Improvements, • Control Law Changes	 Penguin MK3 on F-16 F-16 Block 40 Digital Flight Control Computer F-16 Leading Edge Flap Schedule Changes

Flight test aircraft are fully completed aircraft, early builds on the assembly line, and should be representative of the production design. They may be instrumented during the build phase for any instrumentation in areas inaccessible after build.

The instrumentation on the loads flight test vehicles are for the purpose of determining overall internal loads response to specific flight conditions and are typically placed on multiple wing butt line or fuselage station cuts. These are used for correlation to the external loads analysis. As such, the placement of these strain gages is determined by the external loads engineers. These same strain gages will also be repeated on the static test article, the durability test article and possibly be a part of the Load and Environmental Survey (L/ESS) aircraft instrumentation package. Prior to first flight the flight test article will be placed into a load fixture with a set of actuators similar to, but often fewer than, the static test article for loads calibration testing. A small number of flight conditions, sometimes referred to as strain survey conditions, will be simulated by the jacks to 60-80% of design limit load to determine the strain gage response. From these known loads and measured responses, transfer equations are determined to allow the flight test engineers to read in-flight instrumentation and know what loads are being applied to the airplane in-flight. See Section 17.10 for a further discussion of loads calibration.

17.3 Test Planning

Because testing is an integral part of the overall certification process, high level test planning starts very early in the program, during the development of the SDC, since one of the considerations in the tailoring of the requirements is the verification and validation process for each requirement. As the program progresses, the test planning becomes more detailed. Reference 17-3, the Aircraft Structural Integrity Program (ASIP) and Reference 17-13, the Navy Aircraft Structural Integrity Program (NASIP) provide an overall guide for how an aircraft structural integrity program should be structured for the Air Force and Navy, respectively, in terms of planning, analysis and testing in a time phased set of tasks.

Test planning occurs in a number of phases. Initially the test planning may include an estimation of the number and complexity of the tests. As the airframe is designed, candidate element, subcomponent and component tests will be put forth by the design teams. These might be obvious choices such as horizontal or vertical tails to be tested at the component level or it could be a new feature or design, such as a composite seal groove or chevron, or a new hybrid joint design or a component test of a part made from a new material or process. Information necessary for this step includes:

- Short description of the test with a sketch showing possible restraints and load introduction approaches
- Clearly stated test purpose and goal
- Type of test (static, durability, damage tolerance, acoustic durability, stiffness, etc.)
- How many replicates
- Environment
- Initial cost estimate
- Rationale for the test (why is it needed)
- Risk rating and proposed path to certification if the test is not performed.

This will be reviewed by a committee of senior engineering management personnel such as the Chief Structures Engineer and managers of the various structural disciplines. From this a down selected, prioritized list of structural development tests (SDT) will result. For each of the proposed tests remaining on the SDT list a test plan will be developed.

A crucial participant in any test planning activity is the test laboratories. The test engineers are familiar with what has been done before, how specimens can be loaded, any associated safety aspects and how long a particular type of test might take. They also will be responsible for test fixtures, instrumentation, load trains, whiffle tree design and anything related to the actual execution of the test including day-to-day operations. They should be involved early in the process and consulted often.

The importance of a good test plan is often overlooked and some programs assign that task to inexperienced engineers because it is viewed only as a milestone to be accomplished. A comprehensive, well thought-out test plan done by an experienced engineer can reduce program risk and save both time and money. One of the key aspects of this task is to manage the expectations of the analysts, participating subject matter experts (SME's) and customer as to the purpose and success criteria for the test or series of tests. Testing is the realm where the design and analysis meet reality and an integral part of the planning process is to help clarify some of the more nebulous requirements such as what constitutes failure, *i.e.*, first pop, first ply, or something else or "what is detrimental deformation" in actual hardware, *etc*. This is done through discourse and the written, approved plan.

The foundation of the test plan is a clear, concise description of the approach, constraints, loading and schedule. It is incumbent on the test planning engineers to address any unrealistic expectations, at the earliest possible time, about how the test goals can be achieved in terms of any or all of these items. The test plans are written in multiple passes with each one providing more definition and detail. As soon as issues arise they should be addressed and resolved appropriately.

17.3.1 Aircraft Structural Integrity and Program Phases

Figure 17.3.1-1, from Reference 17-3, outlines the tenets of the aircraft structural integrity plan as defined by the Air Force certifying agency. Each major new aircraft development program is required to develop an Aircraft Structural Integrity Plan (ASIP). Similar plans are developed for mechanical subsystems (MESIP) such as avionics and propulsion systems.

- Task I is generally the design information phase where basic design information is defined and documented in the various plans, material selection is made and joining techniques defined. It is at this point that test planning begins in earnest.
- Task II is the design analysis and development testing phase, with the coupon, element, subcomponent and some component tests carried out.
- Tasks III is the testing phases where full-scale ground and flight testing is accomplished.
- Task IV is where test correlation, certification analysis and force structural maintenance plan is completed. Planning and development for the Loads/Environmental Spectra survey and Integrated Aircraft Tracking are also finalized
- Task V is the deployment phase.

At the bottom of Figure 17.3.1-1 is the time phasing of each of the ASIP tasks with key program milestones. A similar approach is taken in Reference 17-13 for the U.S. Navy certifying agency.

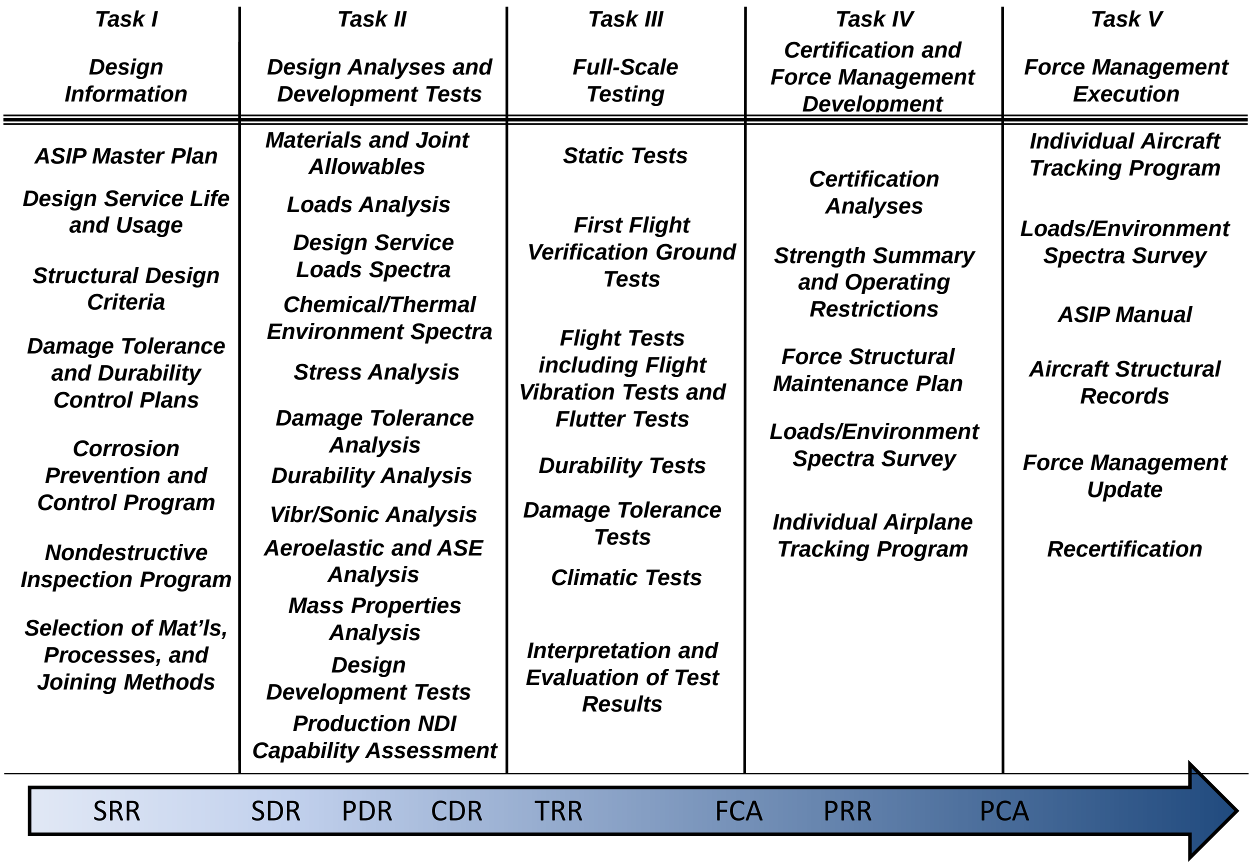


Figure 17.3.1-1 The Five Tasks of the Aircraft Structural Integrity Program (Reference 17-3)

Table 17.3.1-1 lists program milestones which are shown in Figure 17.3.1-1.

Table 17.3.1-1 Typical Program Milestones

Acronym	Program Milestone
SRR	System Requirements Review
SDR	System Design Review (also called: System Functional Review)
PDR	Preliminary Design Review
CDR	Critical Design Review
TRR	Test Readiness Review
FCA	Functional Configuration Audit
PRR	Production Readiness Review
PCA	Physical Configuration Audit

Requirements taken from Reference 17-3 or 17-13 will be tailored and modified for a specific program; however, in general these documents offer a good starting point for discussion. As discussed in the introduction to Section 17-3, during the initial stages of the program, while specifics of the design configuration are not known, there will be assumptions made as to how many, if any, new materials will be developed for the airframe and that will define the number of material coupon test programs that will need to be conducted. In addition, based on past programs, a number of element, subcomponent and component tests will be assumed. Finally the number of ground test articles will be set. As the program progresses, the numbers will be refined. Table 17.3.1-2 illustrates the relative number of test specimens by type on a typical program.

Table 17.3.1-2 Typical Numbers of Specimens by Test Type – New Aircraft

Test Type	No of Specimens
Coupon	6000-10000
Element	4000-6000
Subcomponent	40-60
Component	20-30
Full-scale Ground Test	2-3
Flight Test	2-3

17.3.2 Test Classification by Objective

Part of the planning for test involves assessing the technology risks to ensure that all of the technical, regulatory and customer requirements have been addressed at the earliest part of the program cycle as is prudent in order to reduce overall program cost and risk. The approach forms an integral part of the airframe certification plan. To that end, different tests may have different objectives.

Here is a list of possible objectives for coupon through subcomponent tests:

- Manufacturing and Tooling Development
- Material Characterization‑fundamental material properties and physical characteristics
- Determination of Material Properties or Allowables‑statistically compensated elastic constants for strength analyses or average crack initiation and crack growth values for durability and damage tolerance analysis
- Determination of Point Design Allowables‑statistically compensated strength allowables for a specific design detail
- Analysis Calibration and Correlation‑empirical input data for analysis tools
- Analysis Correlation and Verification‑test results for model correlation and verification of analysis methodology
- Property Modification and Effect Factors‑account for environmental, manufacturing, or design specific effects
- Spectrum truncation studies
- Risk Reduction‑uncover unknowns and establish confidence early at lower cost
- Qualification‑confirmation of an attribute or property
- Certification‑tests not otherwise possible on full-scale airframe

Component and full-scale static tests are typically performed for model correlation and analysis validation and if taken to failure, strength demonstration. Component and full-scale durability tests are also performed for model correlation and analysis validation as well as demonstration of predicted life. In addition, if they are taken to failure, they would also be used for demonstration of residual strength.

Loads flight testing may be conducted with a number of different objectives including:

- Build-up Flights – starting with flight parameters that result in lower load levels, explore and expand the flight envelope while obtaining flight measured loads at each increment

- Flight Loads Survey to 80% of DLL – confirms critical design load conditions and provides measured loads for extrapolation to 100% prior to design loads demonstration
- Flight Envelope Expansion – Expanding the loads envelope from low-g, low speed to higher-g, higher-speed with the goal to incrementally build up to the design loads verification and design loads maneuver envelopes.
- Design Loads Verification to 100% DLL – obtain data for different types of maneuvers in the loads envelope and verify that the loads predictions match the test loads.
- Design Loads Maneuver Demonstration to 100%DLL – demonstrates structural capability to perform 100% maneuvers for critical design conditions without exceeding limit structural strength
- Comparison with previous programs - typically for a follow-on or derivative program to demonstrate how the external loads for the modified aircraft compare to the baseline aircraft loads strength envelope

Flutter flight tests are conducted to verify the flutter speed envelope and flutter speed margin within the entire flight envelope.

17.3.3 Hybrid Metallic-Composite Testing

Testing of hybrid metallic-composite structure has ushered in a new level of complexity in full-scale testing considerations. Composites are typically critical for elevated temperature/fully moisture saturated (wet) strength conditions (180-220-270 degree F, wet) which do not have the same extreme effect on most aircraft metals. From a full-scale static strength perspective, the test articles are too big to properly temperature-humidity condition them so that the composite structure can be adequately tested. So the effects of humidity and temperature are obtained from simpler tests and the material properties are appropriately adjusted. These effects are verified on increasingly more complex tests which are temperature-humidity conditioned. However, the full-scale tests are run only at room temperature to obtain strain gage data for correlation with the finite element model and analysis methodology. All parts are then reanalyzed with the correlated Air Vehicle level internal loads FE models and fine grid models, as appropriate for the final certification analysis and Strength Summary and Operating Restrictions Report using statistically based temperature / humidity-compensated material properties and the result is final verification through “strain based certification” discussed in Section 17.2.1.3.

Composite materials typically selected for aircraft structure at Lockheed Martin are not prone to degradation or damage accumulation due to durability cycling for the planned airframe life. Thus, the full-scale durability test is run primarily to demonstrate that metallic airframe structure meets the design service life requirement and is free of detrimental deformations, cracking, or damage resulting in maintenance costs or functional impairment. However, some programs have elected to introduce damage produced by low velocity impact into composite fracture critical structure on the full-scale durability article to support verification of damage tolerance requirements.

Durability and damage tolerance testing of the composites is done using the element impact damage specimens which are cycled using representative spectra or at a coupon level to address basic material concerns about microcracking, fiber breakage, thermal degradation, *etc.* In addition, an elevated temperature/ wet component level spectrum durability test for a critical component may supplement the element and coupon tests.

With the desire to extend the life of airframes to longer increments, consideration should be given to cycling the parts beyond the specific program life criteria to obtain up front insight into life extension ramifications for the selected composite material.

PM4056 Section 15 addresses durability and damage tolerance design and testing for composite parts and PM4056 Section 18 addresses the structural certification and testing of composites.

17.3.4 Reuse of Full-scale Component and Full-scale Test Articles

Because of the cost of full-scale component and full-scale test articles, these are typically multi-purpose test articles. Sometimes these decisions are made early in the aircraft program, but more frequently they are suggested later in the program as cost savings or for schedule recovery. How the test articles can be reused is a function of the testing parameters, the manufacturing build schedule, the availability of the article and the need date for the test results. Careful consideration must also be given to whether some effect of the first test can ultimately invalidate the results of the second test.

For one legacy aircraft program, after completion of the full-scale static test, the test article was repurposed as the live fire demonstration vehicle. For another aircraft program, the full airplane drop test vehicle was later used as the static test article. These decisions are not without risk. If the article fails in the first test in the sequence, then the second test will either have a repaired article or will be delayed to build an additional article; however the savings can be significant. Additionally, in spite of best effort inspections, there may be undiscovered hidden damage that places the follow-on test at risk.

Another possibility discussed on a number of programs is to have a single static-durability test article which is tested for static conditions to some level below or up to a maximum of limit load, perform durability testing for two lifetimes, followed by the ultimate tests. Finally, test the article for residual strength to failure. Some pitfalls associated with this approach:

- With metallic structure, care must be taken to not load the article to too high of a load during static testing such that there is retardation of any cracks present from manufacture that will substantively affect the predicted life from the durability test.
- If the article is failed catastrophically in durability, then there is no article (or a repaired article) for ultimate load.
- A loads instrumented flight test vehicle is limited to 80% of the maximum achieved static test load, thus the flight test schedule is severely hampered awaiting the completion of durability testing and the ultimate static cases. Flight test articles and fleet inventory without instrumentation may be restricted even further.

Thus, while this approach may be practical for a full-scale component such as an individual control surface it is typically not practical or achievable for a full-scale airframe.

Any decision to reuse test articles must be carefully discussed with all risks considered and with written concurrence from the customer and certifying agency obtained before proceeding with the plan.

Post-test storage of any full-scale or full-scale component test article is recommended for at least the duration of the engineering/manufacturing development phase of the program and perhaps beyond. The physical article is typically a large monetary investment and may be repurposed at a future date. Sometimes, floor space permitting, the full-scale static article is kept in the test frame. Durability articles, after post-test teardown, are usually stored in crates and are kept for future engineering reference.

Component articles may be crated or wrapped and stored. All of these articles should be stored indoors and sometimes the contract requires they be kept in environmentally controlled areas.

17.3.5 Implementation of Repairs Due to Premature Failure or Cracking

Many full-scale ground test articles will suffer from a failure prior to achieving all test objectives. This could be due to local actuator overload or due to the load distribution of the test article not exactly matching the flight condition, or it could be due to an overlooked detail, misunderstood load path, or an incorrect analysis assumption. Irrespective of the cause, a repair will need to be made to the test article and, depending on the cause, a repair may also have to be made to already-delivered aircraft, aircraft in the process of being built, or to the aircraft which have not been started. The repairs may or may not be identically the same.

Goals for repair of the test structure are to minimize any significant changes in load path stiffness and use good design practices to taper material, have generous radii in an effort to minimize changes to the load distribution within the test article and to preclude additional failures. If one or more repairs are performed which significantly alter the load paths resulting in large changes to internal load distribution or if the test article varies significantly from the basic airframe design, the customer may require an additional test article. As a minimum, significant repairs need to be fully documented for posterity, including clearly identifying the point in testing in which they were implemented and any associated analysis.

Repairs for existing or in-work airplanes will likely be similar to the test article, using added parts which are fastened or bonded but may use different materials or require changes due to access, disassembly requirements, corrosion resistance, *etc*.

Repairs for later, not yet started airplanes will likely be more integrated, typically machined into metal parts or added plies for composite parts or with modified detail features.

PM4057 Section 18, Structural Repair and PM4056 Section 19 Effects of Defects and Repair Concepts (Laminated Composites) discuss different types of repairs and may be helpful in determining the best approaches.

17.3.5.1 Fastener Torque

Loss of preload and loose fasteners can be a common problem on test articles. This can occur on frequently accessed doors, fairings, or permanently installed structural panels. It is recommended that prior to start of test, ground rules for re-torque be determined for different parts of the aircraft.

Sometimes the fastener loosening up is due to a manufacturing escape and the fastener was not torqued properly at the time of manufacture. If it is a door or panel accessed in the test lab, it could be a result of failure to re-torque. If the loose fastener was torqued per specification or per drawing, loosening could be a result of the loading and an insufficient torque requirement. Signs of loosening and working of the fastener are black dust or powder around the head of the fastener or visible rotation of the head or nut. Additionally, for countersunk fasteners there may be deformation or damage visible at the edge of the hole.

In the event of fastener loosening, it may be desirable to monitor the fastener and the joint for some period of testing prior to re-torque, while also monitoring the same fasteners on the opposite side of the airplane. This is typically the case for highly loaded joints to better understand their behavior. But, be aware that substructure cracking can occur when there are loose fasteners in a joint. Considerations in this decision include possibility of fretting of joint surfaces, elongation of the hole, starting a crack in the hole or fastener failure. An alternative approach is to re-torque the fastener(s) to the specification torque, torque stripe and monitor. Then determining if the fastener starts to rotate again is easy.

17.3.5.2 Bushing Migration or Back-out

A very common problem on a number of durability test articles has been bushing migration or back-out of bushings in rudders, control surfaces, flaps, doors, wing lugs, *etc*. The reasons given in the investigation of these incidents are typically that there is an unintended side force which is pushing the bushing out, the interference forces are too small, or there is missing retention hardware.

For highly loaded bushings, such as those that would be found in a wing joint, rudder actuator, leading edge flaps, positive retention hardware is recommended and the retention should not rely solely on the interference fit of the bushing in the lug or clevis. Figure 17.3.5-1 shows and example of positive mechanical retention.

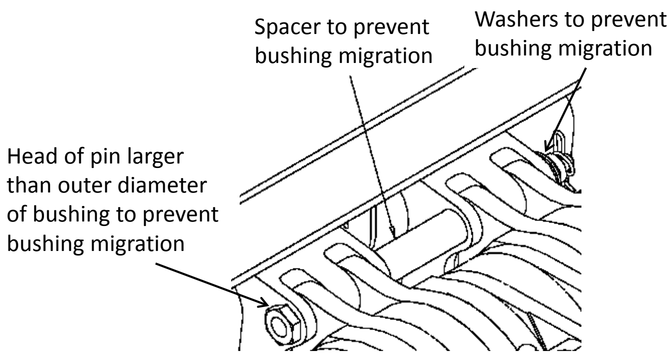


Figure 17.3.5-1 Example of Positive Mechanical Retention of Bushings in Lugs

Calculation of the push out for an interference fit bushing can be found in PM4057 Section 5.2.5.

If missing hardware is the cause of or a contributing factor in the migration the first step would be to re-assemble the joint using the correct hardware and monitor as the test continues. If that is not the issue or if installation of the appropriate hardware does not resolve the problem, one of three repairs is typically used for the bushing migration scenario on the test article:

- The bushings are monitored and the migration documented at regular intervals through the end of test.
- The bushings are removed and reinstalled (or replaced and reinstalled) using Loctite™ 635, in addition to the interference fit. Experience has shown that in most cases this resolves the tendency to migrate or significantly slows the migration. However, in at least one case it was reported to speed up the migration. In any event, regular inspections should monitor the bushings before and after repair.
- The third option is to add mechanical retention; however, this should be done with caution so that there is not a new load path created which causes bending in and premature failure of the structure.

Depending on the root cause, the fleet of aircraft may be fixed in a different manner.

17.3.6 Legacy Program Experience and Lessons Learned

The guidance and recommendations that have been presented throughout this section have the best practices from past programs included. There are some additional items which are included here because they relate to specific type of test or are applicable to a specific component.

17.3.6.1 Coupon/Element or Small Subcomponent Lessons Learned

It is recommended that at the start of a new coupon or element test that a single specimen be tested and the data reviewed by engineering prior to releasing all coupons for test. This is important to ensure that the data collected is as expected and that the procedure will yield usable results. Adjustments to the test procedure/instrumentation/set up may need to be made before testing the remaining specimens.

Each specimen should be photographed pre- and post-test for later report documentation and for posterity if someone is reviewing the report in years to come.

When possible use the standard coupon specimens discussed in Section 17.5 for testing. These have been perfected over a number of years to address issues in testing and provide standardized results.

When testing to compare to a baseline set of experiments, such as effects of defects testing, examining manufacturing changes for fastener installations, or changes which might affect durability life, always run a small sample of “baseline” specimens for the nominal condition or the original manufacturing process for comparison. This allows for a comparison of the current test set-up, approach and baseline specimen with past data. If they are comparable, then any differences are attributable to the change in process or the defect.

Any specialty fixtures that are created for testing should be saved for future reuse. A special engineering test crib should be set aside for these. The test lab will likely not retain/protect the fixture for the length of the program, even if requested to do so.

Compute stresses from coupon tests using the nominal thickness.

Analysis of the specimen, *i.e.*, predictions or sizing for a non-standard specimen, should be performed prior to testing. For durability coupons this should include specimen life calculations and using possible cyclic rates, the test duration. If the load levels are too low, specimens may run for a very long time before failure.

Particularly with coupon testing, plan for a few reserve specimens in case of a non-representative failure or a test result that requires further investigation.

For any test with fasteners, have spare fasteners available in case of breakage, failure or other unforeseen situations.

Use extensometers to determine failure of joint (bolted or bonded) coupon and element cyclic tests rather than parts broken into two pieces. Before cycling begins, load to the maximum test load level and determine the joint deflection. Set the cyclic test limits to 15-20% greater than that deflection value. The test will stop when the joint deflection under cyclic loading reaches that amount. Use this as the number of cycles to failure.

17.3.6.2 Equivalency Testing Lessons Learned

Equivalency testing occurs to show that after a change to the manufacturing process the product produced is the equivalent of the product produced prior to the change. It is most commonly used in reference to the manufacture of composite material; however, it can also occur for moving fastener lines, manufacture of metallic materials, *etc*. The objective is to perform sufficient testing to show that the previously generated, statistically based material properties or joint allowables are still valid after the change.

If possible, run a small sample of "baseline" specimens, i.e. prior to the change, for comparison. This allows for a comparison of the current test set-up, approach and baseline specimen with past data. If they are comparable, then any differences are attributable to the change in process.

Since the changes have the potential impact of changing the statistically based properties and allowables, customer participation in the process is important. Prior to start of test seek customer concurrence on the proposed test plan.

The scope of the required testing is a function of the nature and magnitude of the change. If the material manufacturing line is moved or there is a small change in the constituent ingredients then the number of tests required is minimal. If there is a process change or a large change to the constituents or if a new source for the material is being proposed then the testing will be more substantial.

The definition of equivalency should be determined prior to the start of test. It is recommended that the following are used:

- Material is fully equivalent only if all properties tested are the same or better than the original.
- If one or two of the properties come in lower than the original, then engineering judgment is used to determine the path forward. Options include adjusting the statistically based allowable for future design and declaring the material partially equivalent or declaring them equivalent if the property in question is not important in the design, the difference is small, *etc*.

Only test properties for which a good baseline database exists and test methods are suitably reproducible.

- For composites interlaminar tension, bearing and filled hole compression testing are often problematic due to test reproducibility challenges.
- When testing elevated temperature wet, it can be challenging to reproduce the baseline moisture conditioning.
- When testing elevated temperature wet water boil specimens will not yield the same result as chamber conditioned specimens
- Reference 17-17 Volume 1, Chapter 8 has additional information on equivalency testing of composite materials
- Reference 17-6 Chapter 9 has specific requirements and procedures for equivalency testing or adding additional sources for fastener joint testing and metallic materials.

17.3.6.3 Full-scale Test Lessons Learned

The full-scale article can provide a rich assortment of information that cannot be obtained from any other type of test precisely because it is a full-scale aircraft. Some of these include:

- A big part of the analysis effort for doors and panels on aircraft is in determining how effective they are when installed with the large bolt-to-hole clearances required for maintenance and how much motion occurs. By instrumenting a full-scale test article with LVDT displacement gages, the motion can be studied and by adding strain gages to the doors the amount of load carried as a function of displacement can be determined.

- The full-scale aircraft is the only place to study blade seal wear. The blade seals and boots should be included on the durability article to study the wear characteristics of this system.
- Validation of internal loads in structure with high load path redundancy.

Not all full-scale tests are conducted on full airframes. Full-scale testing can be conducted on airframe components such as vertical or horizontal tails, flaps, wing boxes, fuel tanks, or individual components, such as actuators, arresting hooks, and up-lock mechanisms, *etc*. For some of these full-scale component tests, testing to failure showing a demonstrated capability can be very important, particularly for those items which are subject to dynamic loads or which may be more prone to overload conditions. Dynamic response loads tend to be less precise because the load magnitude for dynamic response conditions is dependent on the structural response which can turn out to be different than model simulations predict. Failure testing provides a known capability if there is a situation in which these parts are overloaded.

When testing components which have shock absorbers, dampers, accumulators, *etc*. as part of their functional mechanism, having a limited quantity of spares for these items can save cost and schedule time.

Analysis of the individual components is very important prior to determination of the gage locations since complex stress fields with too few gages can result in confusion, significant speculation and rationalization. Focus on putting sufficient gages in clusters to provide correlation and validation of the model in a few key locations. Avoid stress concentration areas and areas with localized bending (unless back-to-back gages are used).

The need to pressurize the structure can occur in either the static or fatigue articles; however, pressure testing in the laboratory can rapidly become a safety issue. If the volume is large, such as a transport fuselage, then the test lab will likely require the area to be filled with foam to reduce the volume of compressed air in the event of a rupture. Alternative approaches used in the past include testing the aircraft in a water tank or wrapping the structure in a steel mesh to contain it in the event of failure.

If a fuel tank is being pressurized, the preferred approach is to use water which has a wetting agent with a phosphorescence agent so that any leaks will behave similarly to the fuel and can be easily spotted. Note that the total pressure for fuel can never be accurately simulated. In-flight fuel pressures are a result of a uniform ullage pressure and a varying local pressure due to fuel inertia and the fuel tank accelerations. If air is used, then the test pressure will be uniform from top to bottom in the tank. If water is used, then there will be some variation in pressure due to the static head of the water but unless the fuel tank is deep this variation is small. Typically the minimum of the maximum limit design pressures is used for test.

Find tests of similar components on other programs and review the reports. They can provide a wealth of information on how the item was tested, issues, and solutions.

17.4 Statistically Based Metallic Material Properties

Material properties for use in the design of airframe structure are typically required by the SDC and the parent specification to be statistically based to ensure that the as-design parts do not fail. Per Reference 17-4, JSSG-2006, Section 3.2.19.1 Materials:

"The materials used in the airframe shall be commensurate with the operational and support requirements for the airframe. Whenever materials are proposed for which only a limited amount of data is available, the acquisition activity shall be provided with sufficient background data so that a determination of the suitability of the material can be made. The allowable structural properties shall include all applicable statistical variability and environmental effects, such as exposure to climatic conditions of moisture and temperature; exposure to corrosive and corrosion causing environments; airborne or spilled chemical warfare agents; and maintenance induced environments commensurate with the usage of the airframe. Specific material requirements are:
a. Average values of crack growth data (da/dN) shall be used in the crack growth analysis if the variation of crack growth data is a typical distribution. Reference (JSSG-2006) 3.10.4.4 for a non-typical distribution.
b. Minimum values of fracture toughness shall be used for residual strength analysis.
c. "A" basis design allowables shall be used in the design of all critical parts (see definitions (JSSG-2006) 6.1.23 through 6.1.23.4). "A" basis design allowables shall also be used in the design of structure not tested to ultimate load in full-scale airframe static testing. "B" basis design allowables may be used for all other structure which include:_____________.
d. "S" basis design allowables are acceptable for design when "A" or "B" basis allowables are not available, provided they are specified in a governing industry/government document that contains quality assurance provisions at the heat, lot, and batch level in the as-received material condition. Appropriate test coupons shall accompany the material in the as received condition and shall be subject to testing for verification of minimum design properties after final processing."

For static strength material properties for metallic materials, the approach typically taken is to develop material properties per the requirements of Reference 17-5, MMPDS. Chapter 9 of Reference 17-5 specifically describes the required testing, heat and lot requirements, numbers of specimens and preferred statistical methods for the development of basic material properties shown Table 17.3.6-1.

Table 17.3.6-1 Reference 17-5 Material Properties, Testing and Statistical Methods

Material Property
Tensile Properties (Ultimate and Yield)
Compressive Yield
Shear Ultimate
Moduli: Modulus of Elasticity, Shear Modulus
Elongation, total strain at failure, reduction of area
Stress-strain Curves
Tangent Modulus Curves
Creep
Fatigue (S-N Data)
Fatigue-Crack Propagation
Fracture Toughness

Often the development of basic metallic material properties is shared between the material manufacturer and the aircraft manufacturer and both are encouraged to submit the data for publication in MMPDS, Reference 17-6. In order to be accepted for publication, the material and process specifications for the particular material must be a commercial or government specification. But even if a material is covered only by a specific company's specification, while the material properties cannot be published in MMPDS, it is strongly recommended that they still be tested in accordance with and statistically reduced using the procedures defined by Reference 17-6, MMPDS Section 9.

MMPDS Chapter 9 also defines the testing required for joint allowables. When certain types of fasteners, *e.g.,* shear protruding head, countersunk and blind fasteners and solid and blind rivets, are tested in shear in thin sheet, they fail below the shear strength of the fastener. The failure strengths must be determined by tests of the specific sheet and fastener combination.

The benefit of adhering to the approach described in Reference 17-6 is that it is recognized as an acceptable means of compliance by both the military and commercial certifying agencies as well as by all major aircraft design and manufacturing companies. Participants from these organizations support the working groups, task groups and committees whose responsibility it is to study, maintain, and propose new guidelines when needed.

17.5 Metallic Structural Test Methods

This section discusses the fundamental coupon testing that is done in the development of material static strength properties, fastener and joint allowables and durability and damage tolerance properties.

17.5.1 Metallic Coupon Testing

The standard structural test methods for coupon level testing are generally defined in industry specifications. The ones typically preferred at Lockheed Martin Aeronautics have been summarized in Reference 17-8 along with any LM Aeronautics-unique test practices. A similar document for composite testing is found in Reference 17-9 and extensive discussion of composite coupon testing can be found in Reference 17-2, PM4056 Section 18.

A summary of the metallic material coupon testing from Reference 17-8 is shown in Table 17.5.1-1.

Table 17.5.1-1 Test Specifications for Determination of Metallic Material Properties

Test Standard	Title of Test Standard	Material Property
ASTM B 769	Test Method for Shear Testing of Aluminum Alloys	Shear: Pin
ASTM E 6	Standard Terminology Relating to Methods of Mechanical Testing	--
ASTM E 8	Test Method for Tension Testing of Metallic Materials	Elongation Tension
ASTM E 9	Compression Testing of Metallic Materials	Compression
ASTM E 21	Recommended Practice for Elevated Temperature Tension Tests of Metallic Materials	Tension – Elevated Temperature
ASTM E 111	Test Methods for Young's Modulus, Tangent Modulus and Chord Modulus	Elastic Modulus: Tension and Compression; Tangent Modulus: Compression
ASTM E 132	Test Method for Poisson's Ratio at Room Temperature	Poisson's Ratio
ASTM E 139	Recommended Practice for Conducting Creep, Creep-Rupture, and Stress-Rupture tests of Metallic Materials	Creep and Rupture
ASTM E 143	Test Method for Shear Modulus at Room Temperature	Elastic Modulus: Shear

Test Standard	Title of Test Standard	Material Property
ASTM E 209	Standard Practice for Compression Tests of Metallic Materials at Elevated Temperatures with Conventional or Rapid Heating Rates and Strain Rates	Compression – Elevated Temperature
ASTM E 238	Method for Pin-Type Bearing Test of Metallic Materials	Bearing
ASTM E 328	Standard Test Methods for Stress Relaxation for Materials and Structures	
ASTM E 831	Test Method for Linear Thermal Expansion of Solid Materials by Thermo-mechanical Analysis	Coefficient of Thermal Expansion
ASTM G 34	Test Method for Exfoliation Corrosion Susceptibility in 2XXX and 7XXX Series Aluminum Alloys (EXCO Test)	Exfoliation Corrosion
ASTM G 44	Standard Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% Sodium Chloride Solution	Salt Immersion Test
ASTM G 47	Standard Test Method for Determining Susceptibility to Stress-Corrosion Cracking of 2XXX and 7XXX Aluminum Alloy Products	Stress-Corrosion Cracking

17.5.2 Fastener Strength and Metallic Joint Testing

Fastener and joint testing for metallic joints typical use NASM-1312, Fastener Test Methods, Reference 17-6. Table 17.5.2-1 summarizes the test methods available in this specification. While many of these tests are used for quality control in fastener system specifications, some are additionally used to determine the fastener and metallic joint allowables. This is noted in the comment column of Table 17.5.2-1.

Composite joint strength testing is described in Reference 17-1, PM4056 Section 18.

Table 17.5.2-1 Fastener and Joint Testing Specifications

Test Method Specification Number	Test Method	Test Description	Comment/Discussion
NASM1312-1	1	Salt Spray	
NASM1312-2	2	Interaction	Determine the appropriate fastener shear and tension interaction equation
NASM1312-3	3	Humidity	
NASM1312-4	4	Lap Joint Shear	Determines the shear joint allowables. The preferred specimen is the two fastener configuration of NASM 1312-4 Figure 2.
NASM1312-5	5	Stress Durability	
NASM1312-6	6	Hardness	
NASM1312-7	7	Vibration	
NASM1312-8	8	Tensile Strength	Determines fastener tension allowable strength in steel plate. Typically use to

Test Method Specification Number	Test Method	Test Description	Comment/Discussion
			set the strength of the fastener, although joint strength may be below this value.
NASM1312-9	9	Stress Corrosion	
NASM1312-10	10	Stress Rupture	
NASM1312-11	11	Tension Fatigue	
NASM1312-12	12	Thickness of Metal Coatings	
NASM1312-13	13	Double Shear	Determines the double shear strength of a fastener.
NASM1312-14	14	Stress Durability (Internally Threaded Fasteners)	
NASM1312-15	15	Torque-Tension	Although not used for fastener allowables, this test can be used to determine the nut factors and torque-preload relationship for particular fastener-nut combinations.
NASM1312-16	16	Clamping Force for Installation Formed Fasteners	
NASM1312-17	17	Stress Relaxation	
NASM1312-18	18	Elevated Temperature Tensile Strength	
NASM1312-19	19	Fastener Sealing	
NASM1312-20	20	Single Shear	The preferred method for testing shear strength of fasteners is Method 13, Double Shear
NASM1312-21	21	Shear Joint Fatigue, Constant Amplitude	Determines response of lap shear joint to cyclic loading. By cycling different specimens at different load levels a stress-cycle curve can be generated. Also sheet material is specified as 2024-TX sheet; however, other materials may be used.
NASM1312-22	22	Receptacle Push-out Panel Fasteners	
NASM1312-23	23	Tensile Strength of Panel Fasteners	Determine tension strength for quick-release panel fasteners
NASM1312-24	24	Receptacle Torque-out, Panel Fasteners	
NASM1312-25	25	Driving Recess Torque (Quality Conformance Test)	

Test Method Specification Number	Test Method	Test Description	Comment/Discussion
NASM1312-26	26	Structural Panel Fastener Lap Joint Shear	Determine joint allowables for quick release panel fasteners
NASM1312-27	27	Panel Fastener Sheet Pull-up	
NASM1312-28	28	Elevated Temperature Double Shear	
NASM1312-29	29	Shank Expanding	
NASM1312-30	30	Sheet Pull-up of Blind Fasteners	
NASM1312-31	31	Torque	

Note that for Test Method 21, Constant Amplitude Shear Joint Fatigue testing, failure is defined “when the test machine will no longer maintain the load due to failure of the specimen.” but that is an unrealistic approach for durability joints in aircraft structure since the loss of stiffness and large motion will result in loads transferred to adjacent fasteners before this cyclic duration can be achieved. Thus it is recommended that extensometers be used for these tests. Before cycling begins, load to the maximum test load level and determine the joint deflection. Set the cyclic test limits to 15-20% greater than that deflection value. This means the test will stop when the joint deflection under cyclic loading reaches that amount. This is the number of cycles for specimen joint failure.

17.5.3 Metallic Material Durability and Damage Tolerance Testing

Material properties for durability and damage tolerance characteristics are defined by constant amplitude testing of un-notched and notched specimens at various values of mean and alternating stress. Reference 17-8 lists the ASTM standard test methods in use at Lockheed Martin with additional information on how the tests are conducted and required data acquisition. Table 17.5.3-1 summarizes the ASTM methods. In addition, Reference 17-10, SLM 15 provides some additional guidance on durability testing, data reduction and some non-standard Lockheed Martin coupons that have been used on legacy programs.

Table 17.5.3-1 Durability and Damage Tolerance Material Property Test Methods

Test Standard	Standard Title	Objective
LMA-D004	Metallic Test Coupon Procedures Section 14 K_{ISCC} Procedure	Stress Corrosion Cracking (K_{ISCC})
ASTM E 399	Test Methods for Plain-Strain Fracture Toughness of Metallic Materials	Fracture Toughness: Plane Strain (K_{IC})
ASTM E 466	Recommended Practice for Constant Amplitude Axial Fatigue Tests of Metallic Materials	Fatigue: Load Control
ASTM E 561	Recommended Practice for R Curve Determination	Fracture Toughness: Plane Stress
ASTM E 606	Recommended Practice for Constant Amplitude Low Cycle Fatigue Testing	a. Cyclic Stress-Stain Hysteresis Curves b. Strain Life Fatigue: Crack Initiation Properties

Test Standard	Standard Title	Objective
ASTM E 647	Standard Test Methods for Measurement of Fatigue Crack Growth Rates	a. da/aN versus ΔK Curves for Crack Growth b. Analysis Correlation and Calibration of Crack Growth Predictions[5]
ASTM E 739	Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) Fatigue Data	--
ASTM E 1823	Standard Terminology Relating to Fatigue and Fracture Testing	--

As discussed in Section 17.7, for the full-scale durability test article, it is desirable to run enough spectrum cycles to adequately test the air frame but to remove low-load cycles which do no damage. Prior to committing the full-scale airframe, coupon level tests are run to verify the truncation levels. Typically ASTM E 647 type Middle Crack Tension Specimens M(T) from Reference 17-8 Test 19 are used for this effort. Typically a baseline full spectrum is run in addition to one or more proposed truncated spectra.

These same ASTM E 647 M(T) coupons can also be used to determine marker cycle magnitudes. Marker cycles are additional cycles, usually in blocks of 5-10, inserted into the spectrum at regular intervals which are large enough to leave visible indications in the crack growth pattern of the coupon, but small enough such that they do not materially affect the life. Several different marker cycle magnitudes may be tested to determine the appropriate full-scale test levels.

One note, marker cycles have had mixed success on various full-scale fatigue and Service Life Assessment Program (SLAP) tests within Lockheed. The markings and clarity of markers are dependent on the location and local spectrum. Marker cycles can be found fairly consistently and easily in tension-dominated locations where the stress cycles are populated with more high tension than compression cycles. It can be very difficult or impossible to find marker cycles at the compression dominant locations where the stress cycles are populated with high compression cycles as well as tension cycles. With large compression cycles and shear loading there can be significant rubbing action on the fracture surface caused by compression or shear which can mask or obliterate the marker cycle indications.

17.6 Test Instrumentation Basics

There are a myriad of instrumentation types that can be used for testing and what is selected for a specific test is dependent on the test objectives and data requirements. This section has a discussion of some of the instrumentation typically used in structural testing and an overview of how it works.

It is important, prior to test, to perform predictions. This serves a number of purposes including setting expectations on the behavior and strain levels or deflections of the test specimen or test article which provides a means to verify that the behavior is as expected. If the test is not going as predicted, *e.g.* strains are significantly different than predicted or deflections are too large/too small, stop the test and investigate. It is important to understand variances early in the test so that there is time to make adjustments rather than experience premature failure or an invalid test. Predictions also allow the analyst to ensure the test article will not be overloaded or if nonlinear behavior is expected.

[5] For analysis verification of spectrum control points

This section discusses strain gage types, how to predict strain gage readings and how to take strain gage readings and determine part strains. More information on strain gage fundamentals can be found in Reference 17-16. The strain gage predictions can also be made in an automated fashion using the IFEM/STTGUI tool. This is a Lockheed Martin developed software tool used to predict strain gages and deflections based on finite element model results. Refer to section 17.15.1 for additional information.

17.6.1 Strain Gages

Strain gages are commonly used to measure the strain in a part under load. Strain gages are constructed from small wires or wire-like etched metal foil on a non-conductive backing material. A single axial metal foil strain gage is shown in Figure 17.6.1-1.

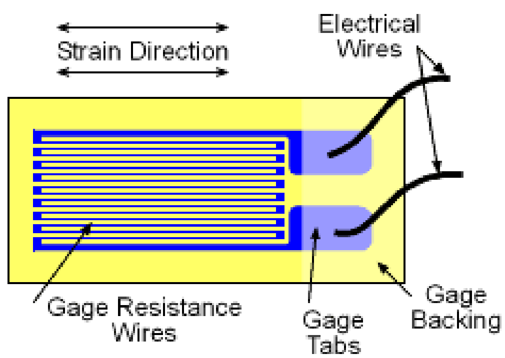


Figure 17.6.1-1 Metal Foil Axial Strain Gage

The electrical resistance of the wire or foil changes with strain. An expression for the resistance, R of the wire is given as

$$R = \frac{\rho L}{A}$$

where
ρ is the resistivity of the material
L is the length of the wire (in)
A is the cross-sectional area of the wire (in^2)

As the strain increases the wire length increases, the wire cross-sectional area decreases and, for most materials, the wire's resistivity also increases all of which result in an increase in the resistance of the wire.

At room temperature this is a linear relationship which can be expressed, using the proportionality constant, K_{SG}, as

$$K_{SG}\varepsilon_a = \frac{\delta R}{R}$$

where
K_{SG} is the strain gage factor
ε_a is the unidirectional (axial) strain (in/in)
R is the electrical resistance of the wire (Ω)
δR is the change in electrical resistance of the wire (Ω)

K_{SG} is the strain gage factor which is a constant for a given strain gage and is typically provided by the strain gage vendor. It represents the gage's sensitivity to strain. Implementation of the strain gage factor by the test equipment is usually handled by the test lab technicians; however, if the strain gage readings during test don't make sense, one of the things that should be verified is that the strain gage factors were correctly selected and programmed and that the polarity on the gage is correct.

Strain gages are glued or bonded onto the structure and wired up to the test equipment. How this process is carried out is important to the performance of the strain gage. If the gage will be subjected to a humid or wet environment, including being inside a fuel tank, the strain gage is sealed to keep out the moisture.

Simplistically, once mounted and the strain gage factors stored in memory in the test equipment, the part can be loaded and the resulting reported strains represent the actual strain in the part.

In the elastic range, the stress in the part due to an axial gage can be calculated from

$$f = E\varepsilon_a \qquad \text{Axial Strains}$$

where
f is the stress (psi)
ε_a is the unidirectional (axial) strain (in/in)
E is the Young's modulus (psi)

The above explanation is a simplified overview of how unidirectional stresses are obtained using an axial strain gage. There are a number of complications in the process flow which must be dealt with. The strain readings in metal beams are typically 10^{-3} to 10^{-6} in/in. The resistance of commercially available strain gages is either 120Ω, 350Ω or 1000 Ω and the strain gage factors are around 2.0. Thus the resistance, δR, at a given increment of load is much less than an Ohm which is less than most ohmmeters can resolve. As a result the signal is often amplified to increase the response.

It is desirable, during test, that the strain being measured is only a result of the mechanical loading that is occurring in the test article; however both the gage and the structure will respond to temperature variations in the lab or during flight. So temperature compensation is necessary and can be accomplished in a number of ways:

- Through the use of "temperature compensated" strain gages that have been manufactured to minimize the sensitivity by processing the gage material to compensate for thermal expansion in the part. These are made for specific part materials and work well for a small range of temperature variations.

- By mounting a dummy gage on the part adjacent to the actual gage, typically transverse to the measurement direction. These gages are then wired into a Wheatstone half-bridge configuration. See the discussion in Section 17.6.1.1 on how this compensates for thermal strain.
- By mounting two active gages on the part, in different directions, the sensitivity of the reading is increased but the thermal effect is zeroed out.
- By mounting 4 active gages, 2 in tension and 2 in compression, the sensitivity is further increased and the thermal effect is zeroed out. However this requires more measurement channels. On a small component test, this may not be an issue; however, a full-scale static test with its myriad of instrumentation may be channel limited.

17.6.1.1 Wheatstone Load Bridge

A Wheatstone bridge is an arrangement of strain gages which serves to both efficiently measure the small changes in resistance encountered in test and to compensate for temperature sensitivity. The generic Wheatstone bridge is shown in Figure 17.6.1-2. It has four resistance arms with an external excitation voltage, V_{in}, applied to the bridge.

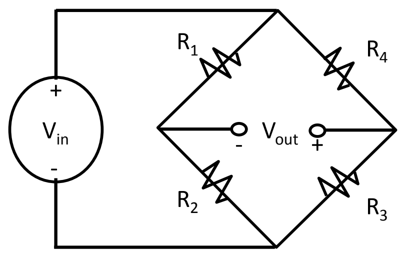


Figure 17.6.1-2 Generic Wheatstone Bridge

The output voltage in the circuit is given by

$$V_{out} = \left(\frac{R_1R_3 - R_2R_4}{(R_1 + R_2)(R_3 + R_4)}\right)V_{in}$$

where
V_{out} is the output (measured) voltage (v)
R_1, R_2, R_3, and R_4 are the resistors (Ω)
V_{in} is the excitation voltage (v)

If $R_1R_3=R_2R_4$ the bridge is in balance and the output voltage is zero, *i.e.*,V_{out} = 0. Thus, if one of the resistors, R_4, is replaced with a strain gage, R_G, any change to the strain gage resistance, $R_G+\Delta R$, results in a non-zero output voltage. Replacing a single resistor with a strain gage creates a quarter-bridge circuit. This arrangement is still sensitive to temperature but does increase the sensitivity of the circuit to the strain.

The sensitivity to temperature can be eliminated by replacing two of the resistors with gages, but with one of the gages oriented transverse to the applied strain. It is called a dummy gage and while it responds to the temperature variation, in a predominantly uniaxial stress field it has an inherently small response to the mechanical strain. Because both gages respond the same to the temperature variation, the voltage output doesn't change with temperature. This is called a half-bridge circuit.

Of more use is a variation of the half-bridge circuit where two of the resistors are replaced by active gages as shown in Figure 17.6.1-3, with one in tension and the other in compression. This provides the temperature compensation but also increases the sensitivity of the response.

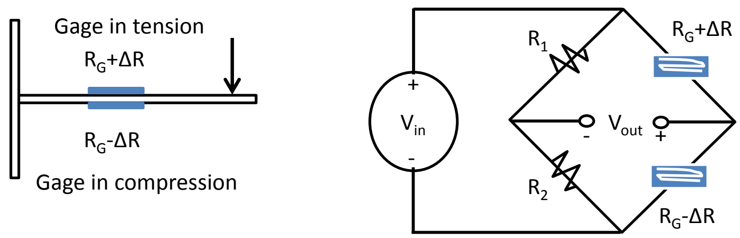


Figure 17.6.1-3 Half-Bridge Circuit with Two Active Gages

The most sensitive circuit is the full-bridge circuit where all of the resistors are replaced by gages, two opposing in tension and two opposing in compression as shown in Figure 17.6.1-4. This is the arrangement commonly used on flight test aircraft for the loads gages.[6]

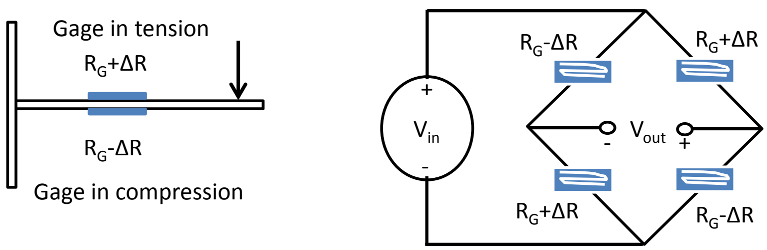


Figure 17.6.1-4 Full-Bridge Circuit with Four Active Gages

The response of this type of arrangement is very sensitive to strain and has the best thermal compensation. The response is given by

$$\frac{V_{out}}{V_{in}} = -K_{SG}\,\varepsilon \qquad \textbf{Equation 17.6.1-1}$$

where
K_{SG} is the strain gage factor discussed in Section 17.6.1
ε is the strain measured (in/in)

Equation 17.6.1-1 presumes the initial state of the bridge is balanced, *i.e.* the output voltage is zero when there is no applied strain; however, in practice this is not the case. There are resistance tolerances and strain resulting from installation of the strain gage so the strain gages must be balanced to adjust the bridge resistance to zero by using a nulling circuit or, alternatively, the initial unstrained readings can also be zeroed out in software. This step is typically carried out by the test lab technicians prior to the start of test; however, it is good to verify with them that this process has occurred.

17.6.1.2 Axial Gages

Axial strain gages measure uniaxial strains, irrespective of the strain state present. They are typically oriented in the predominant load direction, for example, there might be axial strain gages, oriented in an

[6] Flight test loads bridges report mv/V and must be calibrated to known load values on aircraft prior to testing to be useful during test. See Section 17.10 for more discussion.

inboard-outboard direction on wing spar caps to get the spanwise axial strain. If there were one located on the wing upper surface and wing lower surface at the same butt line, then the overall beam bending moment at that location could be determined.

The predictions for an axial gage starts with the stress-strain relationship and can use either a free body axial or running load or a NASTRAN beam, bar or rod axial load, P or a NASTRAN shell element running load, N. This can be expressed as

$$\varepsilon_{axial} = \frac{f}{E} = \frac{P}{AE} = \frac{N}{tE}$$ **Equation 17.6.1-2**

where
f is stress (psi)
E is the Young's elastic modulus (psi)
P is the rod, bar or beam axial load (lbs)
A is the cross-sectional area (in^2)
N is the plate or shell running load (lb/in) in the appropriate direction
t is the plate or shell thickness (in)

If the axial gage is on a surface with localized bending, such as a pressurized skin, then the strain prediction will additionally include a strain increment due to the bending based on the calculation of the extreme fiber stress divided by the Young's modulus

$$\varepsilon_{bending} = \frac{f}{E} = \frac{6M}{t^2 E}$$ **Equation 17.6.1-3**

where
f is extreme fiber bending stress (psi)
E is the Young's elastic modulus (psi)
M is the plate or shell running moment (in-lb/in) in the appropriate direction
t is the plate or shell thickness (in)

And the strain prediction would be the summation of all strain components

$$\varepsilon = \varepsilon_{axial} + \varepsilon_{bending}$$ **Equation 17.6.1-4**

The most common use for axial gages is on structure where the loading is predominantly uniaxial such as spar caps, rib caps and longerons. These types of parts are typically modeled as bar or beam elements in air vehicle level models. Axial gages can also be used on skins where the loading is strongly unidirectional or when one particular load direction is of interest.

Care must be taken to ensure the gage is located parallel to the load direction because even a small amount of off-axis strain contribution can affect the strain readings and correlation.

If there is bending present, from any source, then to fully understand and correctly interpret the state of stress or strain, back-to-back gages are necessary. If the bending is predominantly in one direction, a rosette may be backed up with an axial gage in the appropriate direction. When the strains are obtained from the test article, then the average of the back-to-back strains, *i.e.*, the symmetric portion, is used for the in-plane contribution and half the difference, *i.e.*, the anti-symmetric portion is used for the ± bending contributions.

17.6.1.3 Three Element Rosette Gages

The three element rosette gage, shown in Figure 17.6.1-5, consists of 3 axial gages located at different angles from one another. The one on the left is a 45 degree rosette gage, also called a rectangular rosette and the axial strain gages are in the 0°, 45° and 90° position. The gage on the right is a 60 degree rosette gage and the axial strain gages are at 120 degrees from each other; however, it is called a 60 degree rosette since one strain measurement is actually only 60 degrees from the adjacent measurement. These arrangements allow for a measurement of the complete stress field. The rectangular rosette is the most commonly used three element rosette for structural testing.

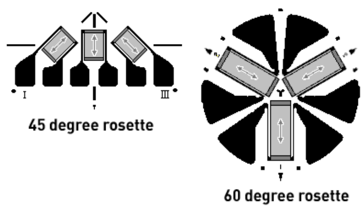


Figure 17.6.1-5 Examples of Three Element Rosette Strain Gages

The gage arrangement can have the gages stacked on top of one another or can have them tightly grouped, but separate, as shown in Figure 17.6.1-5. The tight grouping arrangement is the one typically used on aircraft structure as the strains typically don't vary significantly due to the small separation distance and sorting out the strains from the stacked configuration can add some complexity to the predictions and calculations. The relationship between the strains measured by the strain gage in Figure 17.6.1-6, shown in black, and the x, y and shear strains in the structure can be determined using a Mohr's circle transformation. The x-y element coordinate system is shown in red. If the FEA model strains are output in some coordinate system other than the element coordinate system, then the x-y axis represents the output strain coordinate system.

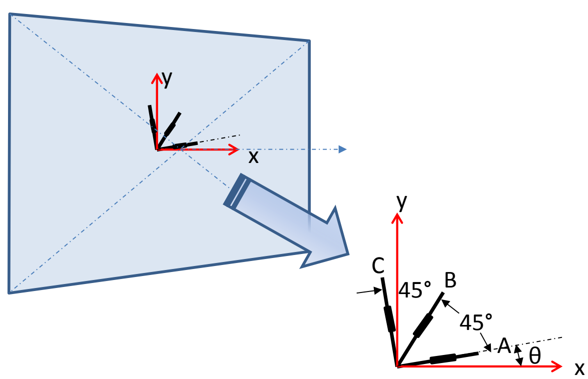


Figure 17.6.1-6 Rectangular Rosette Strain Gage Shown on a Shell-type Finite Element Model Element

The general case occurs if the rosette is rotated some angle, θ, relative to the x axis. To predict the strains in legs A, B and C of the strain gage using elemental strains ε_x, ε_y, γ_{xy}, the following equations apply

$$\varepsilon_A = \frac{1}{2}(\varepsilon_x + \varepsilon_y) + \frac{1}{2}(\varepsilon_x - \varepsilon_y)\cos[2(0+\theta)] + \frac{1}{2}\gamma_{xy}\sin[2(0+\theta)] \qquad \textbf{Equation 17.6.1-5}$$

$$\varepsilon_B = \frac{1}{2}(\varepsilon_x + \varepsilon_y) + \frac{1}{2}(\varepsilon_x - \varepsilon_y)\cos[2(45+\theta)] + \frac{1}{2}\gamma_{xy}\sin[2(45+\theta)]$$

$$\varepsilon_C = \frac{1}{2}(\varepsilon_x + \varepsilon_y) + \frac{1}{2}(\varepsilon_x - \varepsilon_y)\cos[2(90+\theta)] + \frac{1}{2}\gamma_{xy}\sin[2(90+\theta)]$$

where
ε_A, ε_B, ε_C are the strains in legs A, B, and C of the rectangular rosette (in/in)
ε_x, ε_y are the in-plane strains in the element x and y directions, respectively at the surface where the gage is located (in/in)
γ_{xy} is in-plane shear strain at the surface where the gage is located (in/in)
θ is the angle between the element x axis and leg A of the strain gage (degrees)

Given strain readings in legs A, B, and C for this arbitrarily oriented gage, the principal strains can be determined from

$$\varepsilon_{1,2} = \frac{1}{2}(\varepsilon_A + \varepsilon_C) \pm \frac{1}{\sqrt{2}}\sqrt{(\varepsilon_A - \varepsilon_B)^2 + (\varepsilon_B - \varepsilon_C)^2}$$
$$\alpha = \frac{1}{2}\tan^{-1}\left(\frac{\varepsilon_A - 2\varepsilon_B + \varepsilon_C}{\varepsilon_A - \varepsilon_C}\right)$$

Equation 17.6.1-6

where
ε_A, ε_B, ε_C are the in-plane strains in Legs A, B and C, of the strain gage, respectively(in/in)
ε_1, ε_2, are the maximum principal strains in the structure (in/in)
α is the angle between leg A of the strain gage and the principal axis (degrees)

Note that the angle α may be the same as the angle θ if the principal axis coincides with the x axis but it does not have to be.

From the principal strains, the stresses in the part can be calculated as

$$f_1 = \frac{E}{1-\nu^2}(\varepsilon_1 + \nu\varepsilon_2)$$
$$f_2 = \frac{E}{1-\nu^2}(\varepsilon_2 + \nu\varepsilon_1)$$

Equation 17.6.1-7

where
f_1, f_2 is the maximum and minimum principal stress (psi)
ε_1, ε_2 is the maximum and minimum principal strain (psi)
E is the Young's modulus (psi)
ν is the material's Poisson's ratio

Stresses can also be calculated using IFEM/STTGUI.

If leg A of the strain gage is oriented along the element x axis, *i.e.* θ=0, the strain predictions can be made from a simplified version of Equation 17.6.1-5.

$$\varepsilon_A = \varepsilon_x$$
$$\varepsilon_B = \frac{1}{2}(\varepsilon_x + \varepsilon_y) + \frac{1}{2}\gamma_{xy}$$
$$\varepsilon_C = \varepsilon_y$$

Equation 17.6.1-8

Similarly, to transform from test strains to elemental strains if the gage is oriented along the x-axis of loading

$$\varepsilon_x = \varepsilon_A$$

Equation 17.6.1-9

$$\gamma_{xy} = 2\varepsilon_B - \varepsilon_A - \varepsilon_C$$
$$\varepsilon_y = \varepsilon_C$$

Rosette gages are typically used on skins or spar webs where there are contributions from multiple load directions or in areas where there may be high stress gradients. Back-to-back rosette gages can be very useful in determining when a spar web or skin panel has buckled as the strain readings will show a departure from linear on the back-to-back legs. This configuration can also be useful for understanding strains due to pressure loads.

17.6.1.4 Two Element Vsette or Shear Gages

A two element shear gage, sometimes called a vsette gage, has two strain gages oriented at some angle, α, to one another. The difference in normal strain sensed by an arbitrarily oriented shear gage in a uniform field is proportional to the shear strain along an axis which bisects the included angle between the two gage legs. The geometry of this arrangement is shown in Figure 17.6.1-7.

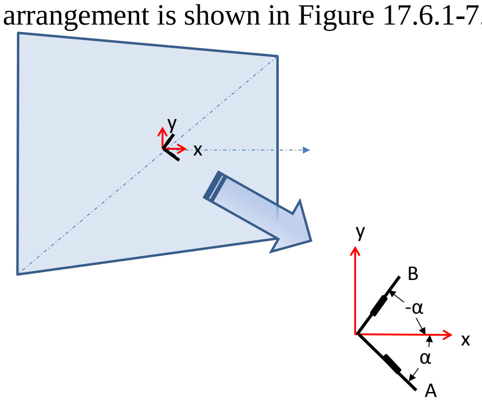


Figure 17.6.1-7 Two-Element Shear (Vsette) Strain Gage Shown on a Shell-type Finite Element Model Element

The strain prediction for legs A and B can be made from

$$\varepsilon_A = \frac{1}{2}\left(\varepsilon_x + \varepsilon_y\right) + \frac{1}{2}\left(\varepsilon_x - \varepsilon_y\right)\cos[2\alpha] + \frac{1}{2}\gamma_{xy}\sin[2\alpha]$$
$$\varepsilon_B = \frac{1}{2}\left(\varepsilon_x + \varepsilon_y\right) + \frac{1}{2}\left(\varepsilon_x - \varepsilon_y\right)\cos[2\alpha] - \frac{1}{2}\gamma_{xy}\sin[2\alpha]$$

Equation 17.6.1-10

where

ε_x, ε_y are the in-plane strains in the element x and y directions, respectively at the surface where the gage is located (in/in)

γ_{xy} is in-plane shear strain at the surface where the gage is located (in/in)

α is the angle between the element x axis and leg A of the strain gage (degrees)

The sign of the shear is very important in correctly predicting these gages, particularly for composite materials.

Taking the difference ε_A-ε_B and solving for shear strain results in an equation which can transform measured data into the shear state in the panel

$$\gamma_{xy} = \frac{\varepsilon_A - \varepsilon_B}{sin2\alpha}$$

For α=45:

$$\gamma_{xy} = \varepsilon_A - \varepsilon_B \qquad \textbf{Equation 17.6.1-11}$$

If the angle, α, is 45 degrees, the denominator evaluates to 1, then the shear strain is given as the difference in the strain measured in the two legs as shown in Equation 17.6.1-11. This is a very useful special case because if the two legs of the shear gauge are wired in the Wheatstone half-bridge as legs 1 and 2 or 3 and 4, Reference Figure 17.6.1-3, then the subtraction is done automatically and the output strain from the bridge is the shear strain. Similarly a full-bridge consisting of two vsette gages results in a higher sensitivity arrangement that reads the shear strain directly. This configuration is often used in flight test, after calibration, to measure the shear load at specific wing or fuselage station cuts for comparison with predicted loads. Refer to Section 17.10 for a discussion on flight test gage calibration and Section 17.2.3.5 for a discussion on Flight Test.

Vsette or shear type gages are most often used for flight test in areas where determination of shear load is required. They are of less use in determining the stress state in a structural part. A rosette gage is recommended for that purpose.

17.6.2 Deflection Transducers

Deflection transducers are devices that can measure relative displacement between two points on the test specimen or between a point on the test specimen and ground. Prior to making predictions, it is important to understand how the transducer is being used and what the reference zero location is.

A linear or rotary potentiometer can be used for large quasi-static displacements. These are simple devices which are inexpensive and are good for displacements of ¼ in or more and 15 degrees or more rotation. Their accuracy is also good.

A linear variable displacement transducer (LVDT) can be used to measure linear gaps and depending on the sensitivity of the device can measure small deflections as small as 0.005 inch as well as large deflections of 10 inches or more. It converts a position or linear displacement from a mechanical reference into a proportional electrical signal with phase and amplitude information. This is useful for measuring motion of one panel to an adjacent panel or structure.

An extensometer measures the linear change in length of the test specimen. These work not only for single specimens like a tensile test bar or stress strain measurements but can also be used to measure joint deflections. Extensometers also have a wider range of measurement capability.

17.6.3 Accelerometers

Accelerometers measure the acceleration of the object on which it is mounted. These devices are typically used in flight testing to obtain local acceleration data for various locations in the aircraft in the x, y, and z aircraft directions. Data is usually reported in g's, inches/sec^2, or ft/sec^2 for linear acceleration. They may also be mounted on equipment to measure the vibration of the equipment during flight test for comparison to the environments predicted in the aircraft's environmental criteria document.

17.6.4 Instrumentation Best Practices for Full-scale Aircraft Tests

Instrumentation of a test article provides invaluable information and, when compared to the cost of running a full-scale test, is a minimal investment. Of course, all tests have limitations so it is important to carefully select where instrumentation will provide the highest fidelity result, mindful of the test goals.

In addition to the cost of the gage and installation of the gage, instrumentation limitations may be due to the number of channels available on the data acquisition equipment, space constraints for the wiring for the instrumentation or, for flight test, limitations on the amount of telemetry data. So a compromise might be that there are more gages installed than can be acquired on a given test with a case-by-case selection process occurring based on the condition being run, load levels to be achieved, *etc*. Table 17.6.4-1 provides an overview of the instrumentation on a recent full-scale test program for the ground test airframes.

Table 17.6.4-1 Recent Full-scale Test Instrumentation Requirements

Test Article	Instrumentation
Full-scale Static Article	4000 strain gages 60 deflection transducers 250 load cells
Full-scale Durability Article	1400 strain gages 30 deflection transducers 250 load cells
Flight Test Loads Aircraft	400 loads bridges

Instrumentation for full-scale test articles should be located on the primary load paths at a number of section-cut locations away from stress concentrations, fasteners, and areas with high stress gradients. The goal of this set of instrumentation is for overall model correlation. An example of this would be for a wing:

- A number of wing stations (W.S.) are selected for instrumentation and axial gages are placed on all upper and lower spar caps, oriented in the span wise direction, at the same section cut, a rosette or vsette is placed at the center of each spar web and on the upper and lower skins. In this case, typically, a rosette is preferred by the stress engineers because the full strain state can be determined while a vsette is preferred by the loads engineers to determine shear for loads correlation.
- If the spar webs were in diagonal tension or if buckling is suspected, then each of the rosettes on the spar web should be backed up by a rosette, *i.e.*, back-to-back gages. This enables the user to look for nonlinearity in the strain readings indicative of buckling.
- If pressure pads are present, such that local pressure is being applied then if it is important to determine membrane or bending stresses, back-to-back gages on the pressurized surface is recommended.

A similar arrangement of strain gages at fuselage, horizontal and vertical tail station cuts can also be developed.

A subset of this primary load path instrumentation should be repeated on the durability ground test and loads and flutter flight test articles. These can be used to ensure the test articles are behaving in a consistent manner and provide confidence that external applied loads are consistent, independent of the manner in which the loads are introduced, for a set of critical conditions.

Having a subset of the total gages on any of the test articles symmetrically placed is strongly recommended. This can help in determining if the model response for any asymmetry in the structure is properly capturing the structural behavior or if the aircraft's actual behavior in flight test is matching the predicted loads. For the durability test article, all strain gages should be located symmetrically on the aircraft. Often this is not done, as a cost savings; however, symmetric gages can help in reviewing the trend data to determine if changes in strain levels are a result of cracking or some other anomaly such as broken fasteners, panel motion, *etc*. If there is a test anomaly, symmetric gages can help in determining the source and can potentially prevent a catastrophic failure.

Where additional gages are added beyond the section cuts, they should, in general, also be located on primary structure to get overall load distributions.

- Strain gages on these full-scale articles are not typically put on stress concentrations, even on the durability test article. Gages to determine stress concentration effects is generally better done in an element or component test. Gages may be placed near stress concentration areas to monitor the far-field strains or if a better understanding of the stress state at a detail is required.
- Strain gages, for full-scale tests, should not be routinely placed on secondary and tertiary structure with high margins and, commensurate, expected low strains.
- If a structural member has a low margin of safety for a predominant load component not repeated on the test article, *e.g.*, pressure, then an elaborate pattern of back-to-back gages is wasted and not necessary.

While it is important to locate the majority of the strain gages ahead of time, a number of channels should be held in reserve so that last minute gage additions can be accommodated. This might be needed in areas where the test strains are higher than predicted, test load anomalies are noted or a repair has been made.

Static and durability full-scale test articles have equivalent flight loads introduced at a small number of concentrated load fittings, straps and or pads. Occasionally where these load introduction points attach to aircraft structure, non-representative hot spots can occur. The addition of a gage to monitor the load introduction may be warranted to ensure there is not a failure due to local loading.

Deflection transducers should be located where overall aircraft deflection response can be measured, such as the wing tip. Compare the measured gross deflections to the results predicted by the finite element model. They should be very close. If not, investigate. Differences may be easily explainable but, if not, spend the time to understand what is occurring – it may mean the difference between a successful test and a test that is tainted because specimen constraints were not effective or appropriate for the condition.

When the installation of the strain gages occurs in the manufacturing flow is a much discussed topic. For gages in close-out areas that are inaccessible after the airframe is complete, the gages must be installed and wired prior to the completion of that assembly. All other gages can be installed by the test lab after delivery of the test article. This is the best choice, if the schedule allows, since it minimizes the potential for damage to the gages and the wiring. If the test lab installs the instrumentation and wiring on the test article in non-close-out areas while it is still being manufactured, there is a very high risk that many of the gages and/or wiring will be damaged inadvertently by the mechanics as they assemble the aircraft. This can result in significant rework of the instrumentation once the article is delivered to the test lab.

All instrumentation should be photographed in place, preferably prior to being obscured by sealing. The photographs should be reviewed real-time by program engineers to ensure there is sufficient information to determine the exact location of the instrumentation, if necessary, during correlation activities and to make sure the gage is oriented as expected.

Something that is often overlooked is that the instrumentation has to be connected back to the data acquisition system and the wire bundles can get large. On one full-scale fatigue test, the cables obscured a 16 inch long crack. The test lab should route the cables in less critical areas and be sure when performing inspections that areas under the wire bundles are, at a minimum, visually examined.

The test article is supposed to be representative of the production vehicle in both configuration and quality. Sometimes there are repairs or rework that has occurred during manufacture. For minor variations such as fastener substitutions, short edge distance or minor thickness variations, additional instrumentation is not required; however, if there is a substantial repair which has a potential effect on the load distribution, adding gages in the area and symmetric gages on the unrepaired opposite hand is desirable to aid in understanding the impact on the strains. This is particularly important on the durability article in the event of cracking due to the repair.

Thermal compensation of instrumentation is of paramount importance in full-scale testing and the approach varies, depending on the type of test being conducted. For ground test articles (static and durability) in addition to using temperature compensated gages, locate temperature and humidity measurement devices around the test articles and record the ambient temperature and relative humidity before each test and at regular intervals during cyclic tests. It is imperative that full-scale tests be conducted in stable temperature controlled environment.

Issues with thermal drift have been reported on full-scale durability article due to thermal cycling in the test hangar if heating or air conditioning is left off overnight or over weekends and then activated on just before start of testing for the day. Additionally,

- Deflectors should be provided for vents that blow directly on the test article.
- Opening of bay doors to ambient outside temperature and humidity can cause temperature related strains on static articles as well. Opening and closing of bay doors during or just prior to test should be discouraged.
- If the test article is located in a non-temperature controlled hangar, consideration should be given to the use of dummy gages in a Wheatstone half bridge for static ground articles. This allows for a much greater range of temperature compensation.

Flight test aircraft, as discussed previously, typically use the two active gage Wheatstone half-bridge or the four active gage Wheatstone full-bridge for both the temperature compensation as well as the signal sensitivity. This is not a place to cut costs. Flight test results for a modification program had to be discarded because temperature compensation was not used.

Note there can also be thermal drift on flight test aircraft if they are exposed to direct sunlight, particularly if they have dark or black composite skins. Aircraft should be sheltered from sun exposure prior to flight test so that when the gages are nulled they do not include thermal strains. See Section 17.9.3 for discussion on nulling of flight test gages.

17.7 Load Case Selection and Test Loads Development

Test loads development is the process of transforming the distributed flight loads which result from aerodynamic, inertia, fuel pressure and inertia, cockpit or cabin pressure, and point loads to a matching load set with a limited number of load introduction locations. Because there may be hundreds, thousands or tens of thousands of flight and ground load FEM cases, the first step in the process is down selecting to a manageable number of cases for test. There are typically no more than 20 flight cases and perhaps only 8-10 flight cases included in the set of static cases.
The cases selected typically include:

- Maximum wing up and down bending
- Maximum wing shear and torsion
- Several maximum fuselage cases – side bending, up bending, down bending, and torsion. There may be multiple sets of these cases depending on the construction of the fuselage, *i.e*., forward, mid and aft fuselage cases
- One or two landing conditions
- Maximum vertical and horizontal tail conditions
- Maximum hinge moment cases for control surfaces
- Carrier operations such a catapult launch, arrested landing, *etc*., as applicable

A reduced subset of these cases will also be used for the loads calibration testing and, may additionally be used as strain survey cases for full-scale durability article.

In addition, for the full-scale static article there may be a number (50-100) of local design conditions for which loads must be developed. These are cases which might design a specific area of the aircraft and include cases for the various landing gears, engine mounts, jack points, hoist points, stores hard points and control surfaces.

17.7.1 Static Test Article

For static testing a relatively small number of full aircraft load cases will be run to limit load and again to ultimate load. Note the test lab will view a limit test and an ultimate test of the same flight condition as two separate conditions because each must have a unique identifier for data acquisition and storage. Thus the test lab will view this as 40 test cases rather than 20 flight cases.

The cases may be selected by the external loads group based on envelope loads plots or they may be put forth as suggested cases by the IPT’s of each section. The goal in selecting the cases is to provide cases which exercise as much of the airframe as is possible and that test critical primary structure to ultimate load. Every structural part cannot and will not be tested to its critical load. That is not possible and is one of the primary reasons for the strain based certification approach discussed in Section 17.2.1.3.

The challenge is then to translate a fully distributed load set consisting of aerodynamic, inertia and pressure loads into a representative load case which can load the aircraft using a limited number of fittings, straps, pads and internally applied pressures.

For the full-scale static article, the first step in this task is for the stress and external loads engineers to collaborate to determine where and how concentrated loads can be input into the airframe. Maximum loads for each load introduction point are determined by the stress group to prevent local overload of the structure and provided to the external loads group. In addition, the IPT stress engineers provide input to the external loads engineers on what skins and internal areas will require pressurization. The potential fitting placements and maximum loads, skin pads and internal pressure requirements are also supplied to test engineering so that work can begin on the test fixtures, load trains, and whiffle trees and sizing of the actuators.

External loads engineers then iterate on possible combinations of load at the load introduction fittings to match the overall shear moment and torsion distributions of the selected load cases. In parallel, stress and design engineers design the load introduction fittings and analyze the aircraft back up structure. Typically the test lab engineers are responsible for sizing the load introduction fittings. As the load sets mature, there may be some iteration as increases in loads for a particular jack or set of pads are required to match the design load distribution and the stress engineers must reexamine the maximum loads. Or additional jacks, straps or pads may be required to match the baseline external loads case.

17.7.2 Loads Calibration Aircraft

For the loads calibration conditions, the process is very similar to that used for the static test article load cases; however, it is not uncommon for only a subset of the static test load introduction points to be used. The goal of the loads calibration test is to apply a full airframe condition and match the internal loads distribution at the specific section cuts of the airframe where the loads calibration gages are located. See Section 17.10 for further discussion. The load introduction points that are selected are common with the static test article and use the same fittings attached to structure.

Because fewer fittings are used, the cases must be re-derived for the loads calibration article. Unless this occurs prior to the development of the load maximums / fitting sizing for the static full-scale test or those maximums are exceeded, the stress group involvement may be limited.

17.7.3 Durability Test Article

For the durability article, the loads development process is repeated a third time; however, the maximum loads and load introduction fitting locations are more related to the life of the article rather than static strength. Some fitting locations may be common with the static article, but there may be others that are not. The loads task is also more complicated for the durability article since they must now generate a spectrum of loads representing the flight spectrum and not several dozen independent cases.

A reduced subset of the static test load cases may be added to the spectrum load set as reference conditions or may be used as strain survey cases for full-scale durability article. This allows for a set of cases with a known response to be used on the durability test article. Once again, these cases would need to be developed for the load introduction fittings present on the durability article.

Full-scale fatigue test (FSFT) spectra are typically sequences of individual flights where the mission types, severity, and durations are randomized. Each flight starts and stops with a taxi segment, and each flight has a mission flight time associated with it. The test spectrum's flight hours are a summation of the mission flight times. Measuring progress in a FSFT is based on the accumulated test spectrum flight hours. Different programs have used different acronyms for this measurement, *i.e.*, Equivalent Flight Hours (EFH), Cyclic Test Hours (CTH), or Spectrum Flight Hours (SFH). Test anomaly discoveries, such as cracking or delaminations, are then associated to the point in the spectrum where they were discovered, in spectrum flight hours.

The spectrum is typically created in blocks which are then repeated as required to achieve the life goal of the test. These blocks of loads may vary from 500 to 1000 flights or more depending on the type of aircraft. There may be flight segments alternating with buffet segments or other specialty high cycle loading. Figure 17.7.3-1 illustrates a notional block of flights.

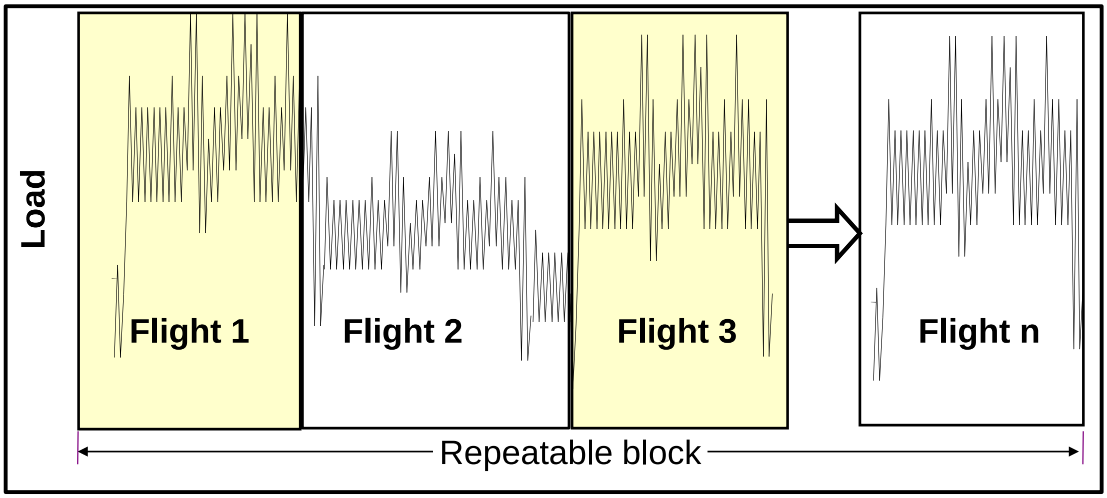


Figure 17.7.3-1 Sample of a Repeatable Block of Loads

Because the number of flight cycles determines the length of the test there is a desire to run sufficient cycles to adequately represent the real-world damage potential but no more than that. So often, the smaller magnitude cycles which have no effect on the fatigue life of the aircraft are removed from the test spectrum. This process is called spectrum truncation. In the process of spectrum development, truncation studies are performed in which all cycles below a certain magnitude are removed and a crack initiation analysis is performed at selected critical locations on the aircraft, called control points. These studies may have multiple iterations as the cycles to be removed are fine tuned. This culminates in coupon testing of baseline and one or more truncated spectra to see how the proposed truncation levels perform. See Section 17.5.3 for a discussion of coupons.

Another process which can be performed in test spectrum development is called spectrum clipping. This calls for the capping of very large magnitude cycles to some stress level (clipping level) in order to increase the test severity. The high tension cycles can have the effect of blunting the crack tip and retarding crack growth. A similar process to the spectrum truncation is used for the spectrum clipping studies; however, coupon testing is typically not performed. Spectrum clipping applies to metallic structure only and is not used by all programs.

Additionally, it is recommended that there be reference cases inserted in the spectrum for the purpose of health monitoring. These cases should be added in after a series of benign maneuvers in the spectrum. It is recommended that the cases are a subset of the static test or loads calibration load set at a level of 20 – 40 percent of design limit load. The load level is kept low to minimize the potential of impact to the durability life. These cases would include wing up- and down-bending, left roll, and right roll and key cases to exercise the fuselage. Extracting strains and monitoring these gages over the course of the test will provide an early warning to possible crack events.

Another set of cycles to consider for insertion into the spectrum are “rest cases”, taking the airframe back to a zero “g” condition at regular intervals as frequently as after every 5 flights. If there are many high cycle endpoints, such as for the buffet portion of the spectrum, then the rest cases would also be inserted after every 2000 endpoints. This provides for an adjustment offset to combat thermal drift in the gages, if necessary. Insertion of rest cases needs to be done in a mindful manner so as to not introduce an unrealistically high cycle such as a zero "g" case just prior to a maximum wing bending case.

All aircraft tests do not use all of these options in the final test spectra, but, as a minimum they should be explored as part of the spectrum development.

17.8 Test Predictions and Test Success Criteria

Predictions are necessary for any type of component, element, full-scale or flight test article for a number of reasons. These are explored in the sections below.

Prior to the start of test, the test goals should be clearly defined along with the pass/fail criterion. It is expensive to conduct testing and the engineer and customer need to have defined expectations and an identified success criteria documented in the test plan. This is true whether the test is an element test where a point design failure load is being determined, a full-scale test article where ultimate load must be achieved or a flight test vehicle where a specific maneuver is being demonstrated.

All predictions should be made using the material properties commensurate with the test environment. For most full-scale articles this will be room temperature ambient (RTA). Additionally, the predicted strains and failure loads shall be done using "typical" material properties. These are properties which have no statistical basis. For metallic materials, Section 3.3.3.2 discussed how these can be calculated if they are not available. For composite materials, typical properties are available within IDAT in separate material databases. If the typical-test environment approach is not used then the predictions will be in error and the actual failure load may be much higher than predicted. Note that no special action is required for the modulus of elasticity used in FEM property cards because typical values are used in design.

17.8.1 Laboratory Test Predictions

For laboratory tests, in order to properly size the jacks which will be applying the load – the maximum test load needs to be estimated / predicted. If the maximum load is overestimated the tolerance on the actuator may be too large to correctly apply the appropriate test load. If it is too small the test may need to be stopped to move to a larger jack and load line may change or test delays may result if a larger actuator is not available.

If the test is to be taken to failure at the end of test, the analysis to determine the needed load should have all conservatism removed including using the typical material properties and appropriate test environment. There have been a number of tests at Lockheed Martin where insufficient attention was paid to the failure prediction loads and the test had to be stopped prior to failure because the test rig was incapable of achieving the required failure load.

Deflections need to be predicted to ensure that there is sufficient space for a full range of expected motion. They also serve as a double check on the behavior of the specimen. If the actual deflections are not matching the predicted deflections, an investigation should determine why. On a major cantilevered wing box test, the deflections were showing to be 10-20% low relative to the finite element model. The span wise strains on spar caps were also below predictions. The input jack loads were verified for both the model and the test article. It was finally determined that the test-fixture restraints at the inboard end of the wing box were not sufficiently stiff to act as fully fixed and had to be redesigned. After redesign, the strains and deflections matched within a small percent.

Strain gages need to be predicted so that real time monitoring can be done to ensure the strain distribution is as expected and that nothing is overloaded. These same predictions are used post-test for model correlation. If the data acquisition system can also plot a not-to-exceed value for gages these values also need to be determined. Even if the data acquisition system cannot display the not-to-exceed values, the engineer monitoring the test needs to have that information readily available to make decisions if the strain readings are higher than expected. The not-to-exceed value should be scaled to the maximum load level of the test. For example if the test is a limit load test, the not-to-exceed values should be scaled to limit and clearly marked as such.

Static test predictions should be made for each load case tested for all full-scale component or airframe level tests. There may also be predictions required for a few unit cases to verify polarity of the gages and allow for a check of gage sign convention. It can be viewed as a time/cost savings if only the conditions of interest for a particular structure have predictions and only strain not-to-exceed values are provided for the remaining conditions. However, this approach can result in confusion during monitoring when the actual strain readings do not in any way correspond to the cutoff values. If the customer gets a full post-test instrumentation dump, many times the review of the data will be automated to provide a report that only shows a list of gages with differences from predictions of a certain percent, such as 10 or 15%. Thus, if the gage has no prediction or if the prediction is a strain cutoff value it will end up on this report and then prior to the start of the next test sequence each prediction variation must be explained.

For full-scale durability tests, predictions are typically made for a set of check cases or exercise cases which are often a subset of the loads calibration full-aircraft conditions. These are typically run to only 40-60% of design limit load to prevent contamination of the durability test results but provide a measurable link to aircraft response of other test articles. These cases will also be run at various times during the durability test as discussed in Section 17.7, after a shut down for inspection, after a repair, *etc*. Test predictions are not made for the cyclic strain levels.

Predictions for coupon, element and small component testing are often made by hand using free body diagrams and the strain equations discussed in Section 17.6. Predictions for full-scale test articles which can be very complex are usually made using a finite element model to aid in the internal load distribution. These can be made by hand or through the use of IFEM/STTGUI discussed in Section 17.15.1. Predictions are typically done at the ultimate load level and then scaled as appropriate. If significant nonlinearity is expected, the effects should be included in the strain gage predictions and made at the appropriate test load level.

17.8.2 Loads Flight Test Predictions

For flight test, prior to the start of the test, the test engineer should have a clear idea of the expected behavior of the test aircraft to ensure that the test is conducted safely while achieving all of the test goals.

For each test performed, predictions of loads should be made. These may be based on theoretical predictions and wind tunnel and/or CFD data for early flight testing, but as more data is obtained in testing with actual aircraft response, these predictions are adjusted with flight measured data.

Note that for flight test, individual strain gage predictions, as is done for ground testing, are not done except for a few critical gages which might be monitored to prevent overload. These may not be monitored for every test and may not be the same gages every time. In general the majority of the flight test predictions are for the load bridges. The load equations and strain gage combinations for the load bridges are determined during loads calibration testing. See Section 17.10 for more discussion. The predictions are made for the parameters of the load case the pilot is supposed to fly. Because it can be difficult for the pilot to achieve that exact set of parameters, *e.g.*, center of gravity location, fuel weight, fuel distribution, g-level, speed, etc., after the test the prediction process may need to be repeated by the program external loads engineers using the exact parameters the pilot flew which would result in a revised set of predicted loads for correlation.

In addition to predictions for each of the loads bridges, 100% allowable load values are provided. These are used for determining if possible damage to the aircraft has occurred during a flight maneuver. If these levels are encountered on any of the safety of test load bridges during a flight test, the test is terminated and some type of inspection occurs. See Section 17.9.3 for further discussion.

17.9 Test Monitoring and Procedures

During the conduct of the test, teams of structural analysts will be monitoring the data from the test instrumentation in real time. This is done to

- Minimize the possibility of premature failure
- Ensure that meaningful data is collected from the test
- Allow for better understanding of the behavior of the structure under load

Depending on how the data acquisition system works, all instrumentation data may not be available real-time and the analyst may need to prioritize what is viewed. Typically all remaining data is available post-test but prior to the start of the next condition.

Before the start of test the test lab or flight test instrumentation engineers will report on any gages which are not functional for the upcoming test. Gages are fragile instruments and there can be a number of things that go wrong from a short in the gage to a loose wire to failure of the adhesive holding it to the test article. If the gage is installed in a “wet” area these failures are more frequent occurrences, in spite of the sealing. The cognizant engineering group, depending on the type of test, will need to make a decision if any of the gages which are not functional need to be repaired prior to the start of the test. If the gage is on the static article but the gage is a loads flight test gage, the loads group should also be consulted. If a repair is required, the test may be delayed for several hours or longer, depending on the number of gages requiring work. If the case to be run is critical for the structure with the failed instrumentation, then repairing it may be crucial. If it is not a critical case, then testing without that gage and having it repaired during the next test break may be acceptable. It is a judgment call requiring some flexibility on the part of the engineer. Even if it is not expected to have a critical strain reading, if the gage is important to understanding the distribution of strain in the area, *i.e.*, it is part of a group of gages, then repair may be necessary.

Each of the different types of test has different procedures and although these may vary by program the sections below describes the general approach to each.

17.9.1 Static Full-Scale Test

In the weeks leading up to the start of static test, there will be a test readiness review (TRR) or test safety and readiness review (TSRR), typically involving the customer which will deal with the safety aspects of the test set up as well as a discussion of the load cases, load case sequence, load level sequence and may contain a lab procedures briefing. The overall test load case sequence is typically discussed well in advance of the testing with less critical cases completed before critical wing up- and down-bending cases, though not always. The TRR is the time when the sequence is finalized. All test load cases will be taken to limit load before any case is taken to ultimate load. For some programs, all full-aircraft test load cases may be taken to 60 or 80% DLL before any cases are taken to limit load based on the perceived risk to the test article.

Once the testing begins, at the beginning of each static test condition there will be a number of events that will happen prior to “start of test”. The load system will be turned on, and gages will be “zeroed”. This is the process the test lab uses to remove resistance tolerances and strain resulting from installation of the strain gage. This can also be called nulling the gage. On a full-scale test article, involving many gages, this is typically done in software.

The next step is to tare and balance the test article to put it in a zero “g” state. Tare loads are the loads required to just balance the weight of the airframe and balance loads are the loads to just balance the weight of the load fixtures (fittings, whiffle trees, actuators, etc.). A second zero after tare and counterbalance is typically done and then the test article is ready to be loaded for the test condition.

A typical test condition will go to a low load level, back to zero to look for hysteresis, and then up to maximum test load in even increments. Loading of the article will be done in increments of 10% or 20% of DLL. For the first tests, typically caution is used and the load increment is 10%. Later in the test cycle and the engineers get accustomed to the strain levels and response, 20% increments are commonly used.

So, for instance, if the increment is 20% DLL, the test will go 0, 20% DLL, pause for strain gage review, 40% DLL, pause for strain gage review, 0 looking for hysteresis, pause, 20% DLL, pause for strain gage review, 40% DLL, pause for strain gage review, 60% DLL, pause for strain gage review, and continue up to the maximum load level in alternating 20% load increments, pause for strain gage review steps. This is illustrated in Figure 17.9.1-1 for a limit load test.

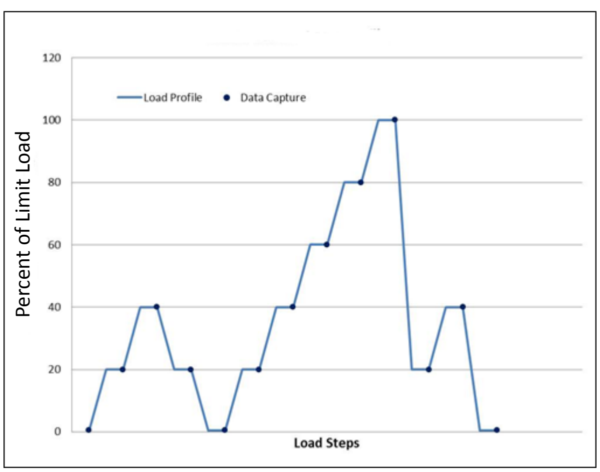


Figure 17.9.1-1 Load Profile for Design Limit Load Test

As shown in the sequence, after each load increment, the test is paused to allow the engineers who are monitoring the gages to review the data. At lower load levels the engineers may take as long as they wish, within reason, to view the strains. Once the test article gets to about 80% DLL or design limit load and beyond, the review of strains should be made quickly, typically in a minute or less, so that the test article is not sitting for long periods under load. As the test approaches ultimate load, the hold/review time may be further reduced. In the past, a number of test articles failed just below ultimate load as the test paused under load waiting for review of gages, as result, engineers no longer hold at high load levels and pause only long enough for the data acquisition system to record the strain data.

Quick review can be aided by a graphical display of measured strain and prediction versus load level, so that it is easily apparent if the strain is tracking the prediction and what the strain level at limit (or ultimate) load will be. It can be further aided at load levels above approximately 130% DLL, by only focusing on the critical strain gages in real time. All data will be available after the test condition for leisurely review.

Early in the test sequence, engineers may take a day to review the strain data for a given case / test level before going to the next condition. It is important that the engineers monitoring the test understand the structural behavior and if the response is not as predicted – it is important to understand why before moving to the next case. Things to be considered: is the variance a general trend, indicating that the loads are not being applied properly or the restraints are slipping or is it a single gage or set of gages, perhaps indicating they aren't installed in the correct location or are near a stress concentration. While this is an important learning opportunity for less experienced engineers it is also crucial that there is oversight by experienced engineers to ensure there isn't a failure that could have been avoided.

Typically the overall static test sequence for full airframe conditions is as follows:

- Strain surveys are performed for each load case to 60%-80% of design limit load. This data is compared to predictions to look for overall response of the airframe to loading, hot spots where strains are higher than anticipated and to exercise the structure. Between test points, engineers monitoring the test should review the strain data from the previous test to gain understanding of the test article behavior.
- After the strain surveys are complete and the stress group has had time to review the results, the test article will be loaded to limit load for each load case and the strain gages monitored. Between limit and ultimate load tests, investigations of any significant deviations of strains from predictions should be accomplished and, if necessary, the strain prediction for ultimate adjusted. Pay particular attention to unexpected non-linearity in the gages.
- Finally the test article will be taken to ultimate load for a limited number of cases, which have been sequenced to minimize risk to the test article. Ultimate load is held for a minimum of 3 seconds or the amount of time required to capture all instrumentation data, typically on the order of 30 seconds or less.

Local conditions may be run before, after or in between full airframe conditions.

When monitoring testing, keep in mind the magnitude of the strain when looking at overshoots or undershoots during all phases of testing. For instance a difference of 100 microstrain on a 100 microstrain (very low) strain prediction at limit load is likely not of concern during test, although it will need to be investigated for the correlation effort. However, a difference of 500 microstrain on a 3000 microstrain reading at limit load may indicate a potential test problem at ultimate load.

If the test article survives the ultimate test, by mutual consent of customer and contractor the test may be loaded to failure for the most critical condition. Or the test article may be held in reserve for future tests.

17.9.2 Durability Full-scale Test

The full-scale durability ground test for new airframes and the service life assessment test for in-service airframes are run over a period of several years in order to load the airframe with a minimum of 2 lifetimes of cyclic loads. The test article is mounted in a test frame and loaded via fittings, straps and actuators in a similar manner to the static ground test article. It typically has fewer fittings and almost never has external pads to simulate local aerodynamic pressure on skins. It may, however, use pads over substructure for load introduction.

The cockpit or cabin is usually pressurized to normal operational or maximum operational pressure with the pressure cycled based on the altitude of the specific load being applied. Additionally the fuel tanks may be pressurized. If so, the minimum of the maximum pressures is used to prevent overloading the upper surface structure and there may be only a limited number of or a single fuel pressure level(s) applied. If the pressurization is done using compressed air, often, as a safety measure, the test lab will want to fill the pressurized area with foam pads to take up some of the volume.

At the start of test, typically a subset of the limit load full aircraft conditions which were developed for the static test / loads calibration test articles is run on the durability test article to 40% of design limit load. These are often referred to as the strain survey conditions. Conditions included would be wing up- and down-bending, fuselage up- and down-bending and wing roll left/roll right cases. These may be monitored real time by engineering representative from stress and DADT or the data may be reviewed post-test. It is recommended that the first time the article is loaded that the gages be monitored real-time. Past strain reading from the static and loads calibration aircraft should be available for comparison and there should be predictions for these cases using the durability test finite element model and loads. The expectation is that the cases will give approximately the same strains on the durability test article as they did for other tests. The strain survey conditions should be run every time the test is started up after a loads dump, after extended downtime for inspections or maintenance and in the event of repairs to ensure that the test article is responding as anticipated.

The same type of tare and counterbalance is performed for the durability article as for the static article and the gages are zeroed using zero-g strain offset value read after tare and counterbalance. To minimize the hysteresis in the zero-g offsets used to zero the gages, the article should be exercised before taking the offset at the start of cycling or after a test load dump. Typically the test article is cycled through one cycle starting at zero-g, a maximum spectrum wing down-bending condition, a maximum spectrum wing up-bending condition, and then back to zero-g. The up- and down-bending cases are taken to only 20-40% of design limit load. This is shown graphically in Figure 17.9.2-1. The wing bending conditions are chosen because the wing is the structure, due to its flexibility, most prone to hysteresis.

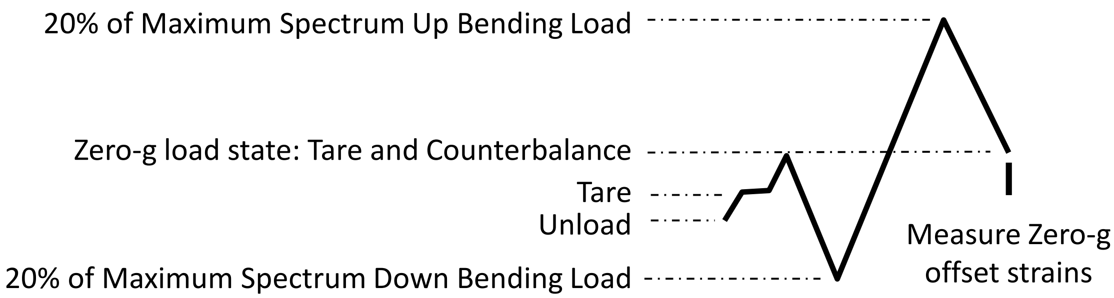


Figure 17.9.2-1 Offset Cycle to Minimize Hysteresis

Once the strain surveys have been completed and the data reviewed, the cyclic loading can begin. Initially the cyclic rate will be very slow to ensure that the jacks work together and no unusual motion results. The cyclic rate will then be ramped up to a steady state value that will vary by test article.

Strain gage data is accumulated virtually continuously generating large amounts of data and so rather than individual values, trends are monitored. This is done by plotting the strains from each load endpoint for a given gage on the same plot. Over time, a band of strains will develop. If that band stays approximately the same width on an approximately horizontal mean, the test is cycling with no anomalies. Over time, the band may expand or narrow and the mean may start sloping up or down indicating a change in the test article. A number of test related anomalies can be indicated by a change in the trending of a particular gage. These are discussed in detail Section 17.13.3.

Figure 17.9.2-2 shows some of the trends that might be seen. Strain gage A is exhibiting normal behavior – the average line shown in red is horizontal with small excursions and no change in slope. This is what would be expected if the test is cycling with no anomalies.

Strain gage B has a red line that is also mostly horizontal but with much larger excursions. This is behavior that might be indicative of a test anomaly and an inspection might be warranted. Then at about 8600 units there is a definite shift in strain level indicating an anomalous situation. At this point the test should be stopped and inspected in the area where this gage is located looking for possible causes.

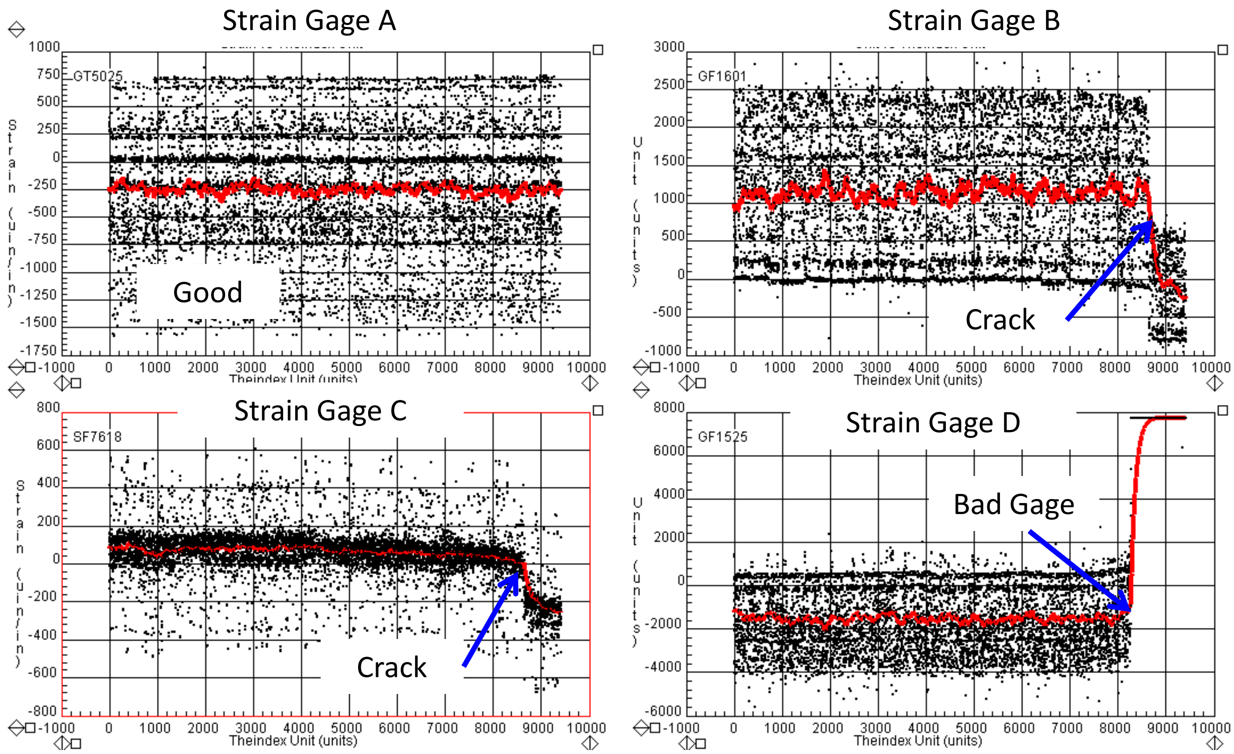


Figure 17.9.2-2 Durability Test Strain Gage Trends

Strain gage C has a red line that shows a definite downward slope change indicative of possible anomalies. Again at about 8600 units there is a jump in strains and the test should be stopped and the area around strain gage C inspected.

Finally strain gage D shows a horizontal line with small excursions and then jumps to a large opposite sign stress and has no further excursions. While this should be investigated as a possible anomaly, this behavior is due to gage which stopped functioning.

With durability testing, because the test can be cycling 24 hours a day 7 days a week, there is special emphasis placed on the automatic trend monitoring of strain gages. If a threshold trend variation is seen, the test article is unloaded and shut down. Even with automated trend monitoring, there should be an engineer reviewing the trends and data on a daily basis. If an anomaly is seen, the area of the article around the anomalous gage should be, at a minimum, visually inspected and possibly NDI inspected. Additionally, some test programs have designated some or all of the strain gages as safety of test gages. If their strains exceed a certain value then the operator is notified, an entry is placed in the operator's log, and/or the test is held or unloaded in a controlled fashion until they can be reviewed and inspected. Typical safety-of-test gages include major load paths or gages placed in an area where a suspected crack is located. This gage would not be attempting to monitor the strains at the crack but looking for changes in the strain field in the area of the crack to confirm its presence.

Figure 17.9.2-2 uses a 100 point moving average of endpoint strains looking for a change above a given threshold. If the threshold is exceeded, the test unloads and shuts down. The data shown in in Figure 17.9.2-2 has been post-processed to superimpose the red line averages on the strains. Alternately, sometimes test data can be reviewed "on the fly." Note that when the gages are monitored in this fashion, they are not zeroed and the strain values will be different than that seen after the gages are zeroed. The important thing for this type of monitoring is watching the gage trend.

An example of “on-the-fly” output is shown in Figure 17.9.2-3. Note that only the endpoints can be shown as in Figure 17.9.2-2 or the endpoints can be connected as in Figure 17.9.2-3. That is a function of the software and sometimes the preference of the person monitoring the output. While the averages are not shown in Figure 17.9.2-3, the eye can spot the trends.

Desirable behavior is a band that is of uniform height and whose overall slope is zero. For instance gage E is trending down toward a higher negative strain from left to right which could indicate some type of test anomaly. Strain gage F is showing about the same on the lower side (small negative strains) and a lower upper strain on the high side. That would also indicate a downward trend in the slope and possible anomaly. Finally strain gage G is trending up to a higher positive strain and the band is getting wider, also indicative of a possible anomaly.

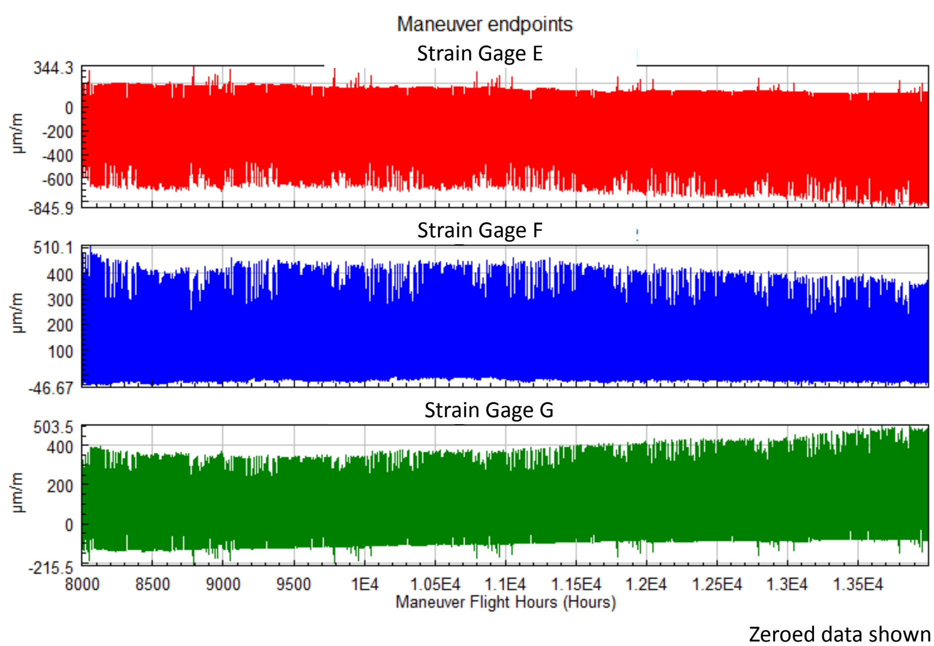


Figure 17.9.2-3 Strain Gage “On-the-Fly” Trends

Another method of monitoring the output is to filter and plot the same case over time. If the strain survey cases are inserted into the spectrum, as discussed in Section 17.7.3, these are obvious choices since there is a baseline from the beginning of the test. If not, then maximum or minimum spectrum load would be appropriate. Figure 17.9.2-4 illustrates this type of output for a single condition for six different gages. Gages A and F are located on the web, shown, and gages B-E are located elsewhere on the test article. Gages B-E show very uniform results for the single load case with no change in slope. Gage F shows irregular strain readings and Gage A shows a sudden, dramatic shift in slope. In this case it is indicative of crack formation and growth.

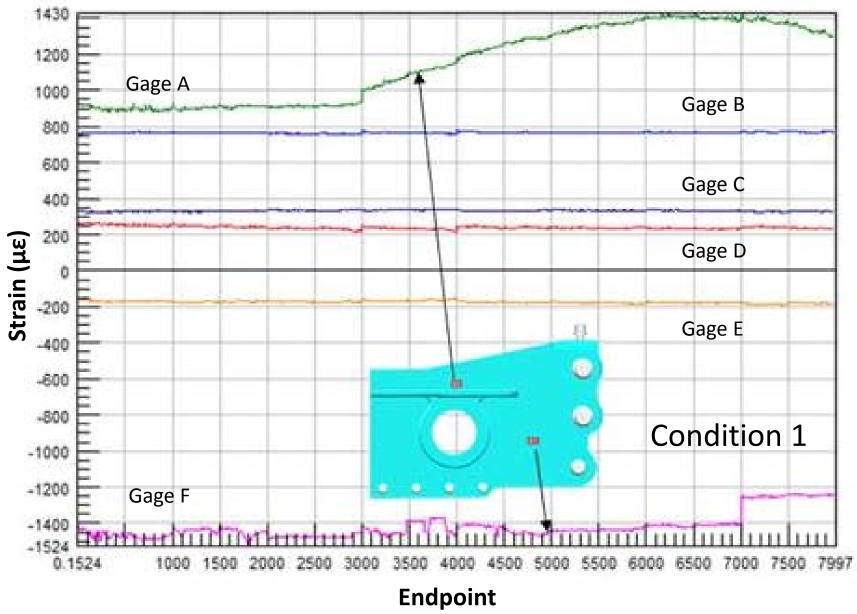


Figure 17.9.2-4 Plot of Condition 1 over Time for Multiple Gages

In addition to inspections which may be triggered by strain gage drift, there are predetermined inspections which are performed at preset intervals throughout the test. These may be after every block of testing, after each life and at end of test. The extent of the inspections may also vary. For instance, after each block, there may be close visual inspection, with NDI at certain critical locations and a small number of fasteners pulled for bolt hole eddy current. At the half-life and full life inspections, there may be many more NDI inspections added with additional fasteners removed for eddy current inspections of holes. After the end of the test, there is also a teardown/disassembly of the article with a significant number of inspections in critical areas including NDI and fractography.

One recent full-scale durability test program used the durability and damage tolerance (DADT) engineers to perform the visual inspections allowing them to get to know the airplane and to gain a better understanding of the hardware. In addition, because they performed the analysis they have a greater appreciation of where problems may occur. If an indication was found, then the NDI engineers were called in to officially perform the NDI. Having the DADT engineers interacting with the hardware as much as possible reduces the risk of a catastrophic failure and reduces the cost of inspection.

17.9.3 Loads Flight Test

Loads flight testing involves flying one or more instrumented fully functional test aircraft over a period of months or years to gather data on the external loads applied to the aircraft by the aerodynamics, inertia loads, maneuver response, landing and ground conditions throughout the design envelope. Additionally the flight test article is used to demonstrate that the designed aircraft can achieve the extreme points of the flight envelope, thus providing the information necessary for aircraft certification.

The overall flight test program is based on the flight test plan. The plan has all the maneuvers sequenced for overall flight test certification and represents the preferred order for accomplishing all of the flight test points; however, there are times when the sequence is interrupted – due to issues with the aircraft, availability of stores, temperatures, overloads/maintenance, or just sequencing of another group’s flight testing requirements.

The test plan has a published "band of goodness" or tolerance band required for all points to determine if the particular flight has met the criteria to be deemed a successful test. This variation might be in terms of a speed tolerance, an altitude tolerance, weight and center of gravity tolerance, or other flight parameters. As each test point is flown, based on these tolerance values, it can easily be determined whether or not the point has met the criteria or whether it needs to be adjusted and repeated.

In general, the flights for a particular test are sequenced to start in the middle of the envelope. The points flown will then expand outward to more severe conditions. For instance, altitude may be reduced; speed or dynamic pressure increased, or angle of attack increased or combinations of all. This represents a rational build-up of the condition types to the maximum edge-of-the-envelope conditions. A typical expansion sequence might include 1g sideslip conditions, 360 degree rolls, wind-up turns and then finally elevated-g rolls.

Based on the overall test plan, each flight test point is listed on a flight test card and these are assembled into a flight test deck representing one day's activity. There may be several points that make up a maneuver or there may be only a single point. Some of the considerations which go into the planning of the flight test decks include the complexity of achieving the points, *i.e.*, where in the envelope is it and the type of data to be collected. The loads flight test engineer, supporting a particular day's test, must understand the current issues of the day. What testing is being done? What is unique about that type of testing? What are the underlying risks? What makes it complicated?

The following is a general overview of a day of flight testing. It may vary by program:

- Early preflight planning, occurring a week or month before the test day, is a review of the flight deck to ensure that the individual flight cards are accurate, all of the groups get the information and data they do need and that there is not data collected or point flown that are not needed.
- Preflight tasks, in the day to week before a particular deck is flown include
    - Checking that the correct predictions are available for the upcoming planned card and that the predictions have been adjusted with any flight measured data, as necessary.
    - The limits applicable to each card, *e.g.*, airspeed, N_z, interceptor inputs, *etc*, are added and checked for accuracy.
    - Checking/preparing the electronic displays to ensure the right data is being represented on the screens which will be monitored. This includes choosing the correct bridges, making sure the predictions are available and correct as well as the 100% load limits for the appropriate bridges.
- Complex, high risk or edge of the envelope flight cards are flown in the simulator in the days leading up to the test, by the actual test pilot with key members of the team who will monitor the test flight simulating the monitoring task. This is so that the entire team knows what to expect during the test.
- The night before a planned flight test, a schedule of events will be released. It will include a tentative timeline for the pre-mission brief, control room standup meeting, and takeoff. The day of the flight, the hotline is monitored for any changes or updates to the plan. Changes or updates may be due to weather, maintenance issues, *etc.*
- The pre-mission brief will cover the test cards for the day's flight, general test procedures, flight limits for the day, potential hazards, and weather.
- If the flight is a "go", then the first thing that happens is to set up the instrumentation:

  - The first check is a strain gage functional check. With the aircraft on the ground, the pilot will move the stick to the four corners and activate the rudder pedals. This perturbs the strain gages enough to check that they are outputting a signal.
  - Before every flight, gages are "nulled" to get to a zero g condition and remove installation strains by either nulling to a given load or by nulling to bridge.
    - Typically used for wing structure, a strain correction is applied to the gages based on the known weight of the structure plus fuel plus stores.
    - Typically for control surfaces, the gages are nulled based on information gathered from the loads calibration aircraft for those bridges.
    - For loads that are unknown once installed on the aircraft, an ambient bridge value, or "bridge zero", is taken ahead of time in a known, typically uninstalled, state. The load is then calculated by applying the calibration coefficient to the current value of the bridge subtracted by the bridge zero. One example of where this type of initialization is used is on landing gears.
  - The final check is an in-flight set of scripted maneuvers that are flown before starting any test cards for the day. These standard maneuvers allow the engineers to see that the response from these gages is consistent with previous day's performance.
  - If any required instrumentation is not working, the aircraft will be returned to base to get the appropriate gages operational
- Then the flight test deck is initiated

During the actual test, the loads flight test team is responsible for monitoring the flight parameters as well as loads time histories of specific loads bridges to ensure the safety of the airplane from the loads perspective. The flight test team does not monitor all loads bridges, only those designated as safety of flight. The data for all loads bridges is available after the flight and is transmitted to the program external loads engineers for review and further post processing.

- The duties of the flight test loads lead are to monitor the speed, angle of attack and other flight parameters as well as the quality of the maneuver. He is also responsible for the safety of the flight and making sure it fits within the maneuver parameters. It will later be his responsibility to designate whether the test point was "good" meaning it met the necessary parameters for a successful test.
- Additional flight test loads engineers monitor loads calculated from load bridge outputs for different components of the aircraft such as wing, horizontal and vertical tails, control surfaces, doors (if opening) and stores (if a stores flight). These individuals will typically monitor 6-8 loads bridges via a reconfigurable electronic screen. The display would include the 100% load limits as well as the flight measured data. Their responsibility is to monitor the safety-of-test loads and to ensure that none of the limits are exceeded. Typically the loads engineers will monitor the same set of loads for an entire deck, but when a new deck comes up they will switch components. This maximizes the versatility of the flight test engineers by exposure to all areas of the airplane and keeps the engineers alert because they are not monitoring the same loads for long periods of time.

If the measured loads exceed the predictions, the flight test loads engineers review the data and make a determination if it is safe to continue the flight test point or deck. If the flight measured loads exceed 100% of the predetermined allowable load for that aircraft location, it is the responsibility of the loads monitors to notify the loads flight test lead who then notifies the test conductor. The test is halted and a chase plane is sent to take a close look at the test aircraft. Should the flight measured load exceed 105% of the predetermined allowable load, the test aircraft must return to base and undergo additional inspections.

After the flight test is completed, there is a post-test debrief. This is a general discussion of the test that was conducted: what was done, any concerns about the aircraft or the actions of anyone and whether or not the test met the criteria established for a successful test. Most importantly, this is a chance to bring up any lessons learned during the test. Everyone is encouraged to speak freely to ensure nothing important was missed to improve future flight tests.

Finally the last responsibility of the day is to fill out a summary report. This contains information on the aircraft number, what the test consisted of, what was interesting from the perspective of the represented discipline, load levels, *etc.* There is a standard format used by each flight test program. Depending on the program, each report is then archived individually and, later, may be assembled into a formal report and submitted to the customer at the end of the flight test program.

17.10 Loads Calibration

The primary purpose of strain gages on the loads flight test aircraft is to measure the load distribution in the aircraft at selected locations for correlation with predicted loads, *i.e.*, overall shear, moment and torsion. This validates the airframe external load prediction methodology which is a very important part of the certification process. Additionally there is real-time measurement of in-flight strains to ensure the safety of the aircraft.

The measured parameters, per Reference 17-4, include shear, moment and torsion at multiple wing stations, shear and bending moment at multiple fuselage stations, and root shear, moment and torsion for vertical and horizontal tails, and hinge moments for control surfaces.

In order to translate the measured strains into meaningful loads, prior to flight, the aircraft undergoes “loads calibration” in which a set of known loads are applied to the aircraft and the strains are measured. There are three types of loads applied during calibration:

- Isolated loads
- Combined loads
- Distributed loads

Isolated single jack loads are applied to the test airframe and strain gage readings recorded. These strains are used to determine which gages should be electrically networked together to develop the loads equations (coefficients) through the solution of simultaneous equations by a least squares technique. The resulting load coefficients are then used to calculate resistor values so that selected individual bridges can be combined into summing networks that electrically simulate the loads equations. This technique involves combining outputs of different loads bridges in the proper proportion by weighting outputs with attenuating resistors and provides a single channel for the measurement of each desired load.

Combined sets of jack loads are next applied to the test airframe and strain gage readings recorded. This is the next increment in the calibration process. The equations, based on the single load calibration, are reviewed for behavior when multiple loads are applied. This step is used to further refine the equations to match the aircraft response.

The final check is the use of distributed full airframe load cases for calibration which are typical external load cases which would be expected to be encountered during loads flight testing such as critical wing up- and down-bending cases, a maximum roll maneuver, a maximum sideslip maneuver, etc. These full aircraft distributed loads cases are applied, using all available jacks, to the test airframe and strain gage readings recorded. The results are used to verify the load equations resulting from the application of the isolated and combined load sets.

Eight to ten cases are usually selected for the all-airframe loads calibration conditions and during the calibration test, these loads are applied to a maximum load level of 60-80% of design limit load. These cases will later be a part of the static test load set and may also be used, at lower load level on the durability test article as check cases before start of cyclic testing. This set of cases becomes the ‘go-to’ set for checkout of the aircraft if an anomaly arises in test or in the aircraft and are sometimes referred to as the strain survey cases.

All loads are applied in a test rig using jacks, straps and pads similar to what is used for static testing, but the test rig and number of load inputs are usually reduced to minimize the amount of reconfiguration required to get ready for flight. Figure 17.10.0-1 shows an example of jacks and straps on the S-3SLAP test article.

Figure 17.10.0-1 S-3A Airframe in Ground Test Jig

During the calibration loading test the gages are checked for linearity and repeatability and the magnitude of the bridge response. A greater response is desirable since it will have more signal to noise response in-flight. The output from the strain readings of the calibration conditions are used to formulate a set of load equations of the form

$$\{L_j\} = \{\beta_i\}[\varepsilon_{ij}]$$

where
L is the array of load sources. This is a general symbol to represent shear, moment or torsion.
ε is the matrix of strain readings for the i strain gages (in/in)
β is the array of correlation coefficients for i strain gages

The correlation coefficients can be programmed into the flight test instrumentation system so that the flight test engineer can view, directly, the measured loads for comparison with predicted load for the specific flight test point.

The general theory behind this can be found in Reference 17-11.

17.11 Correlation of Test Data / Validation of the Air Vehicle Finite Element Model

One of the key steps in the structural certification process is the correlation of the test measured results with the analytical predictions and validation of the air vehicle level finite element model. The tests that are generally considered in the correlation effort are the static strength, proof, and strain surveys associated with the fatigue tests and the loads calibration tests. Correlation of the crack initiation and crack growth resulting from the durability test to the analytically predicted crack initiation and crack growth is also an important part of the post-test analysis but will not be covered in detail in this section. This section will focus on the static strength test which is used for validation of the AVFEM.

Detailed structural analyses, in the form of fine grid finite element models, classical stress analysis methods, and standardized automated stress analysis tools are used to develop strength margins of safety. Fine-grid finite element models (FGFEM) are used to address structure affected by geometric and material nonlinear behaviors, large displacements, local structural details, or other behaviors not captured by the linear air vehicle finite element model. Fine grid models are used in conjunction with the AVFEM to develop more detailed internal loads for use in structural analyses.[7]

Validation of detail stress analysis methods and FGFEMs is achieved by demonstrating that the internal load assumptions are consistent with the validated internal load distributions from the AVFEM and the stress analysis margins of safety accurately or conservatively represent observed behavior of the static test article. Figure 17.11.0-1 is a flow chart describing the process of correlation and structural analysis validation. Implicit in the approach is a requirement for a philosophical consistency in the approaches for the AVFEM, the FGFEMs and the analyses as they build on one another and validation of the structural integrity of the airframe is inextricably linked to this connectivity. As the certification analysis is prepared, based on the results of the correlation and validation effort, it is anticipated that the majority of the design analysis provides a validated basis and that areas where the analysis and/or models have to be modified are rare.

Recall in the discussion from Section 17.2.1.3 Strain Based Certification and 17.2.1.4 Certification Analysis Requirements that the design analysis correlated to the test results is the basis for the certification analysis. The full-scale ground structural testing is accomplished over a range of conditions and condition types as a means to validate the structural analysis and demonstrate airframe performance. Reference 17-3 provides the basic guidance on the customer's expectations in Paragraphs 5.3 Full-scale

[7] Reference 17-15

Testing (Task III), 5.4.1 Certification Analysis (Task IV) and 5.5.7 Recertification (Task V). Reference 17-14 provides insight and guidance on how the correlation effort can be accomplished.

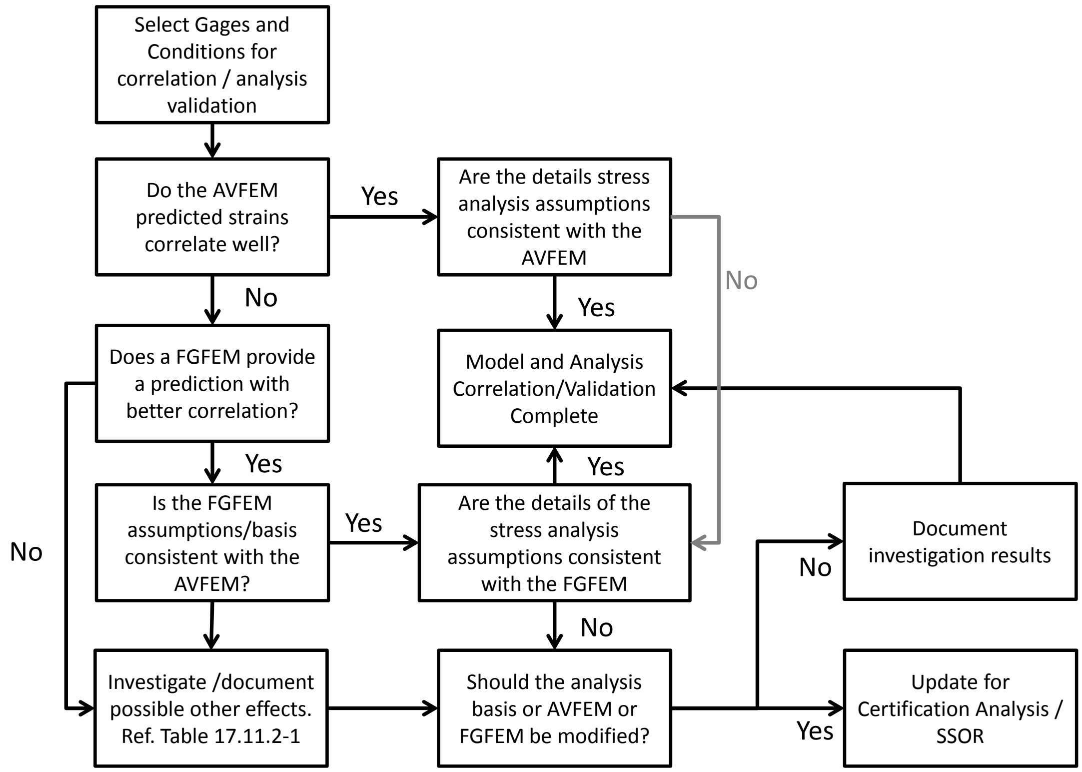


Figure 17.11.0-1 Flow Chart for Strain Gage Correlation and Analysis Validation[8]

Correlation of test results is made easier by the proper selection and placement of instrumentation. Section 17.6.4 discusses best practices for the placement of instrumentation on full-scale aircraft. Many of the guidelines presented there are a result of lessons learned during the correlation efforts of past aircraft programs.

There are several steps involved in the correlation effort which will be discussed below. First the individual gages must be correlated and any issues with the correlation evaluated and resolved. Then the analysis must be viewed as a whole to determine if the analysis is valid and, if not, what additional action must be taken.

Some aircraft programs have taken the position that correlation and, thus, finite element model validation will be done only on a subset of all gages including

- Primary load path structure
- Critical or Representative Aircraft Section Cuts
- Load Introduction Locations
- Gages having strain values over a certain amount, for instance 25-50% of material yield or in the case of composites 16-33% of ultimate.

Other aircraft programs have provided correlation for all gages.

[8] Derived from Reference 17-15

Some guidelines which have been used on past programs to select FEM Validation gages focus on the selection of a sufficient number of gages to investigate the load distribution in major structure including:

- Major fuselage shear and bending load paths
- Major wing bending, shear, and torsion load paths
- Vertical and Horizontal Tail bending, torsion, and interface loads
- Horizontal tail attachment
- Door attach locations
- Control surfaces (Rudder, Flaps, Elevators, *etc.*)

17.11.1 Correlation Criteria, Sample Strain Plots and Correlation Discussion

Plotting the strain gage information is the first step in both monitoring the strains as well as in performing the correlation. If predefined error bands are included as a part of the plot then which gages will require additional work for correlation becomes immediately apparent. Typically an error that is no greater than ±5 percent on single load path safety-of-flight structure and ±10 percent on non-safety-of-flight structure is acceptable. Other limits may be used depending on program and customer concurrence. For gages which fall into the prescribed error bands, reviews of trends and strain gage linearity is typically the only correlation effort required. This will be discussed more below. If the errors are larger than these limits some degree of investigation is required and will be discussed in Section 17.11.2. Actual error band limits will be set by the individual program with customer concurrence.

A sample plot is shown in Figure 17.11.1-1. This plot was drawn with a ±5 percent tolerance band on strains. This type of plot should be generated for each load case for each strain gage to be correlated based on the program criteria and philosophy.

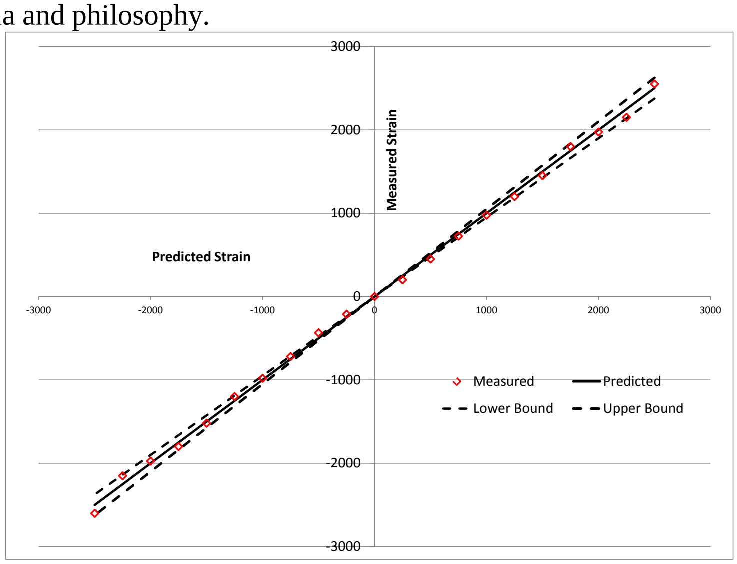


Figure 17.11.1-1 Sample Strain Plot with Upper and Lower 5% Error Bands

The correlation of the measured strains with the predicted strains, for this example, is good at higher strains. Below about 500 microstrain the measured values fall outside of the 5 percent error band.

Note that in the type of plot shown in Figure 17.11.1-1 if there is a change in sign between the predicted and measured, it will show up because the second and fourth quadrants are shown. Any changes in sign, unless the strain is an exceptionally small value should be investigated. It could be a simple problem with the polarity of the instrumentation or the gage factor entered into the data acquisition program both of which can be easily fixed or it could be a symptom of a significant problem with the model/analysis that needs to be addressed.

If specific errors need to be calculated for individual strain gages, this is typically done assuming the predicted strain is the baseline value for comparison. This is given by

$$E_{pct} = \frac{\varepsilon_{measured} - \varepsilon_{predicted}}{\varepsilon_{predicted}} \cdot 100$$

where
E_{pct} is the percent error between the measured value and the predicted value (baseline)
$\varepsilon_{measured}$ is the test measured strain
$\varepsilon_{predicted}$ is the test measured strain

If the measured is greater than the predicted then the percent error is positive and if the measured strain is lower than predicted, the percent error is negative. A similar equation can be used for load cells and deflections. This is the preferred equation for the calculation of error per Reference 17-14.

An example calculation is provided, using values from Figure 17.11.1-1

Example error calculation From Figure 17.11.1-1 at maximum load:	
$\varepsilon_{measured}$	2550 microstrain
$\varepsilon_{predicted}$	2500 microstrain
E_{pct}	$E_{pct} = \frac{\varepsilon_{measured} - \varepsilon_{predicted}}{\varepsilon_{predicted}} \cdot 100 = \frac{2550 - 2500}{2500} \cdot 100 = 2\ \%$
For this strain gage the variation between the measured and predicted is that the measured strain is 2 percent higher than the predicted value. This is within the acceptable error band.	

In some cases, error bands will be drawn as a constant offset from the prediction line forming a correlation band, as is shown in Figure 17.11.1-2. This is not the preferred method for displaying the error since it is based on a constant percent of maximum load. This results in the error band for small strains to be overstated. However, some programs prefer to use the constant offset bands since the area of focus for correlation is for strains over a particular magnitude as is discussed below,

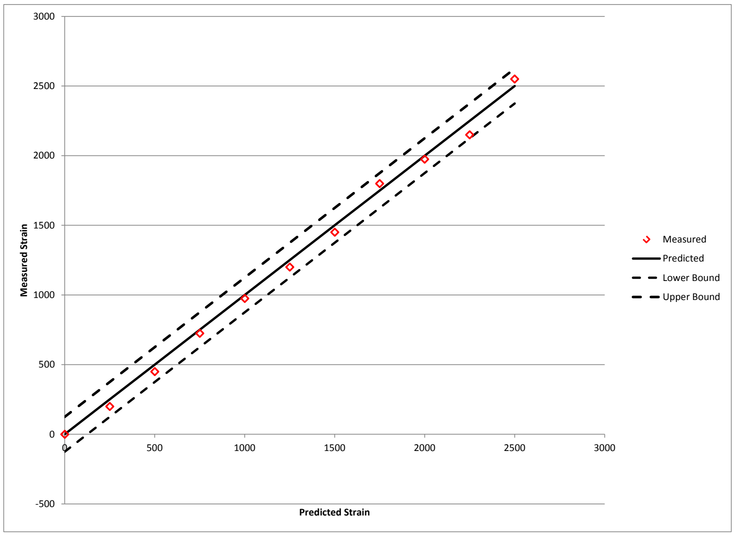


Figure 17.11.1-2 Sample Strain Plot with 5% Correlation Bands

Additionally if the plot includes strain thresholds below which correlation is less important due to the magnitude of the measured and predicted strains, then the correlation task can be prioritized, if not further reduced. These thresholds are set at a small strain value, typically on the order of 25% of material yield or in the case of composites 20% of the minimum ultimate strain which sized the part, *i.e.*, not the unnotched allowable. Other programs have used an arbitrary, conservative cutoff of 500 to 1000 microstrain. Figure 17.11.1-3 is the same plot as is shown in Figure 17.11.1-1 but with a threshold cutoff of 1500 microstrain plotted, based on a 25% of yield for an aluminum part.

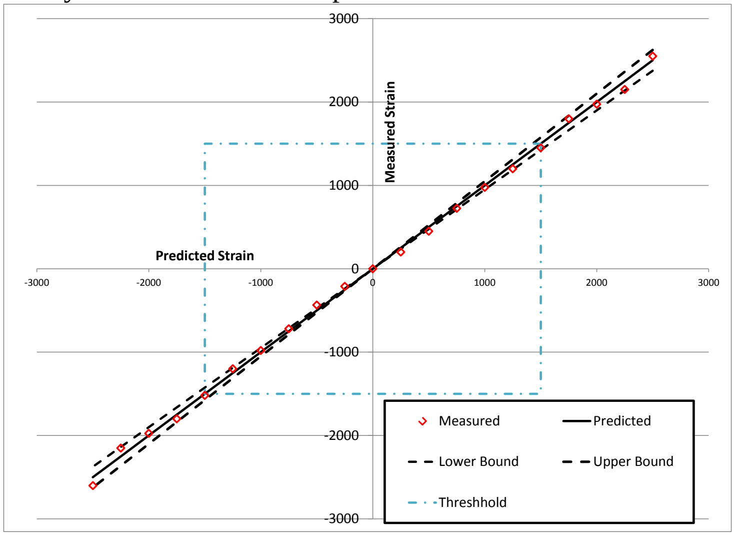


Figure 17.11.1-3 Sample Strain Plot with Upper and Lower 5% Error Bands and Threshold Strain

Thus when looking at Figure 17.11.1-3, strains inside the threshold box which are outside of the strain error band are not of a concern because they are low relative to part strength. Once the strains exceed the threshold box, they are within the 5 percent error band and thus are providing good correlation between the predicted and measured values.

Once the strain gages are examined for relative correlation, the task is not complete. The measured strains plot must also be examined for trends which could be indicative of nonlinear behavior. In Figure 17.11.1-3, the measured strains show variability from predictions without a discernable pattern. In some cases the prediction at one load level is above the measured value and at a different load level is it below. This is acceptable behavior and could be caused by variability and tolerance in the actuators applying the test loads. Figure 17.11.1-4 is another variation of the sample strain plot shown in Figure 17.11.1-3 which has the same 5 percent error bands and 1500 microstrain (10^{-6} inch/inch) threshold values. However, the measured compression strains have been modified. Instead of the random variability illustrated in Figure 17.11.1-3, this figure shows a consistently reducing but slight curling of the compression strain from the straight line prediction which might be indicative of buckling. If this is a limit load plot, examining the strains at ultimate load might provide more insight as buckling should be more pronounced. In addition, examining any adjacent substructure gages for strain increases could also be useful in understanding the behavior.

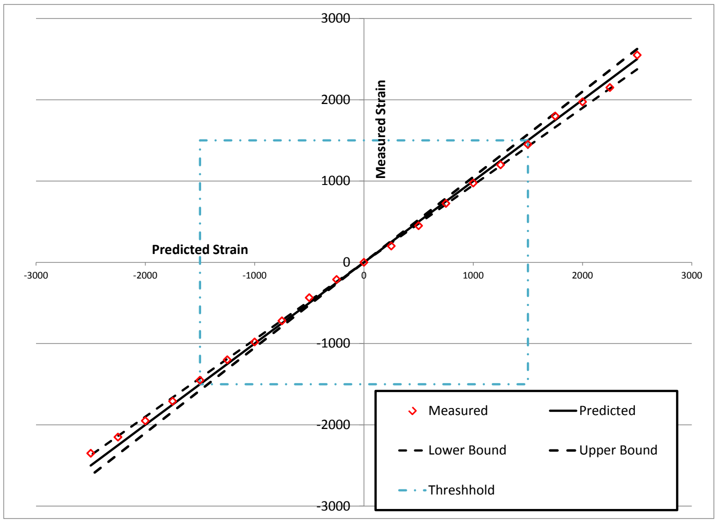


Figure 17.11.1-4 Sample Strain Plot with Nonlinear Trending in Compression

If nonlinear effects are present and the strain predictions do not include those effects, the predictions should be adjusted to include them. If they were not omitted intentionally or are otherwise not taken into account in the design analysis, it will need to be adjusted to include non-linear effects.

Figure 17.11.1-5 is a plot of a strain gage that is outside of the error bands for most of the load levels.

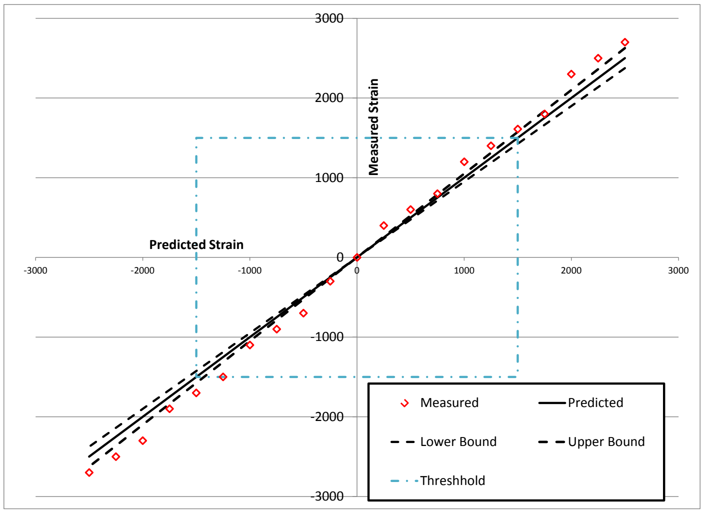


Figure 17.11.1-5 Sample Strain Plot with Strains Consistently Outside Error Bands

This plot shows predictions too low in both the tension and compression behavior. This might be indicative of predictions based on the wrong part thickness or some other FEM anomaly which would need to be investigated. It could be something specific to the test article such as a material review discrepancy or a repair. Once the root cause is determined, a determination of the impact to the design analysis would need to be assessed.

17.11.2 Correlation Issue Resolution

Any issues which are discovered during the correlation effort must be resolved. Some of the plots in the previous section were shown with correlation anomalies and there was a general discussion about possible causes. For a meaningful correlation effort, issues need to be investigated and a determination made on the impact to the design analysis. Sufficient time must be included in the schedule to allow for this investigation and documentation of the results.

There are three primary categories of correlation issues:

- Test Discrepancies
- FEM/Test Article Discrepancies
- Nonlinearities, secondary effects, *etc.* better represented in a fine grid finite element model (FGFEM)

Test discrepancies can be a result of instrumentation errors such as an incorrect calibration, gage factor or polarity; measurement errors such as a bad gage or a gage that has incomplete or nonexistent thermal compensation or a gage located in the wrong position or incorrectly oriented; test errors such as incorrect loads applied, in general, or at a local actuator; or a hardware anomaly such as a repair or other material review salvage action.

It is necessary to approach a possible test discrepancy correlation issue in an organized fashion and work through and eliminate each possibility. Figure 17.11.0-1 describes the overall flow of the process for strain gage correlation and a checklist of other possible sources of error and items to investigate is given in Table 17.11.2-1.

Once the root cause is determined, then a corrective action assessment can be made to determine if the correlation differences and root cause signify that a change in the design analysis is warranted. Typically this is only required if it can be shown that the air vehicle finite element model (AVFEM) did not adequately represent the load distribution in the airframe because a load path was not represented or so poorly represented (relative model properties, material properties, constraints, *etc.*) as to influence the overall distribution or if significant unanticipated buckling, diagonal tension or membrane response occurred which was not accounted for in the analysis of adjacent affected substructure. Although the linear AVFEM would not correctly predict buckling or membrane effects, many times those effects are present and accounted for in the fine grid finite element models often used to support detail analysis or the secondary effects were addressed using hand analysis or other computer tools. This needs to be discussed and documented as part of the correlation and validation effort and would not result in a requirement to modify the AVFEM or design analysis.

Many of the other issues may require changes to the test FEM sizing and material properties, including modeling of significant test article repairs, applied loads, test FEM constraints, and rerunning the model and to update the strain gage predictions. Any “final” predictions should also account for Item 17 in the checklist of Table 17.11.2-1. This type of change would also not propagate into changes to the AVFEM, loads or design analysis.

Table 17.11.2-1 Checklist for Determining Root Cause of Model Correlation Issues

No.	Suggested Check	Finding
1.	If the gage is mirrored on the opposite side of the aircraft – is the correlation better for the mirrored gage?	
2.	If the gage is back-to-back, are the strains the same or is there indication of bending, buckling, increased load or decreased load in both?	
3.	If there are strain gages on similar nearby structure, does the overall strain/load picture make sense or is there an anomaly? Here the task is to look for load redistribution or a possible load path that has not been accounted for.	
4.	Use the photographs or visit the test article to examine if there is a repair in the area, and that the gages are located and oriented per the drawing. Look for stress concentrations which may be affecting the strains.	
5.	Are the assumptions used in the predictions consistent with the test article?	
6.	Have the test lab verify polarity of the gage if there are indications there could be an issue?	
7.	Is there a trend in the correlation of other similar gages on similar structure that might indicate an overall behavior?	
8.	Have the test lab engineers verify the loads applied to the test article / have the FEM group verify the loads applied to the test FEM? Do they match? Does the test FEM need to be rerun with different applied loads?	
9.	Does the FEM model match the test article with load introduction fittings, dummy parts, and removed structure (if any)?	
10.	Review any Quality Action Reports and Dispositions in the area	
11.	Verify the thickness / areas / moments of inertia / skin effectivity in the model/ analysis used to make the prediction match the structure and are correct	
12.	Verify the material properties used in the model including stiffness matrices for composite materials and that appropriate temperature corrected material properties were used.	

13.	Verify that the load introduction fittings/straps, and pads, within the resolution of the model accurately represent the test article parts.	
14.	Verify correct boundary conditions	
15.	Is the mesh size sufficient? Issues can arise from mesh density both too refined and too coarse.	
16.	Is the mesh uniform (no triangles) with elements with appropriate aspect ratios? Predictions should not be made using CTRIA3 elements.	
17.	Was there a hand redistribution of loads or accounting for secondary effects in the design analysis that is not reflected in the test predictions that should be accounted for?	

17.11.3 Correlation Examples

The plots provided in Section 17.11.1 were simple examples to illustrate the correlation approach and technique. This section will provide some examples from a recent program with discussion of the results.

Fuselage structure, outside of the wing carry-through area is notoriously complicated for the predictions and correlation effort since the structure is highly redundant, pressurization and the resulting secondary effects that are not well represented in the AVFEM are present and some of the structure, such as landing gear and door hinge back-up structure, can see locally high strain gradients. Another complexity is the presence of access panels which may have multiple effectivities as the loads increase and the fasteners in oversized holes transition from carrying load via friction to the fastener bottoming out in the hole and the load carried in bearing. Below are a look at some examples of fuselage gages.

Figure 17.11.3-1 represents a fuselage station cut and is a plot of all gages at that specific location for all static test load cases. The predictions came from the AVFGM.

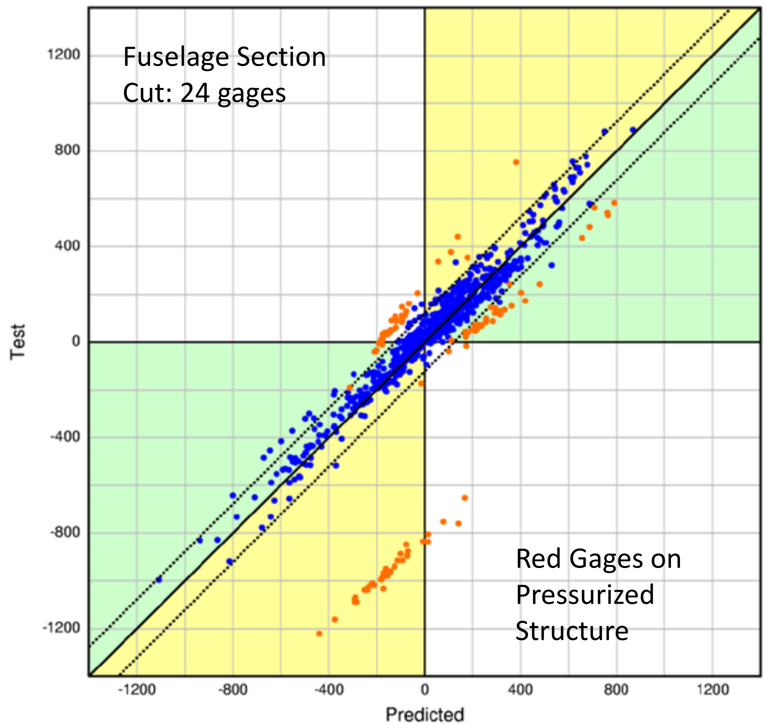


Figure 17.11.3-1 Fuselage Station Cut, All Strain Gages, All Conditions

There are 3 groupings of gages that show very poor correlation. These gages are on pressurized structure with nonlinear membrane effects which cannot be adequately predicted based on the coarser AVFEM. These local effects are accounted for in detailed stress analysis. When the predictions were performed using the FGFGM for these three gages the correlation was very good. The remaining strains, in blue, showed good correlation between test and predicted.

Figure 17.11.3-2 also represents fuselage gages but located on frame and bulkhead caps at multiple locations. Of the 39 gages included in this plot, seven gages did not correlate well. Four of them, identified as gage 1 through 4, are discussed below.

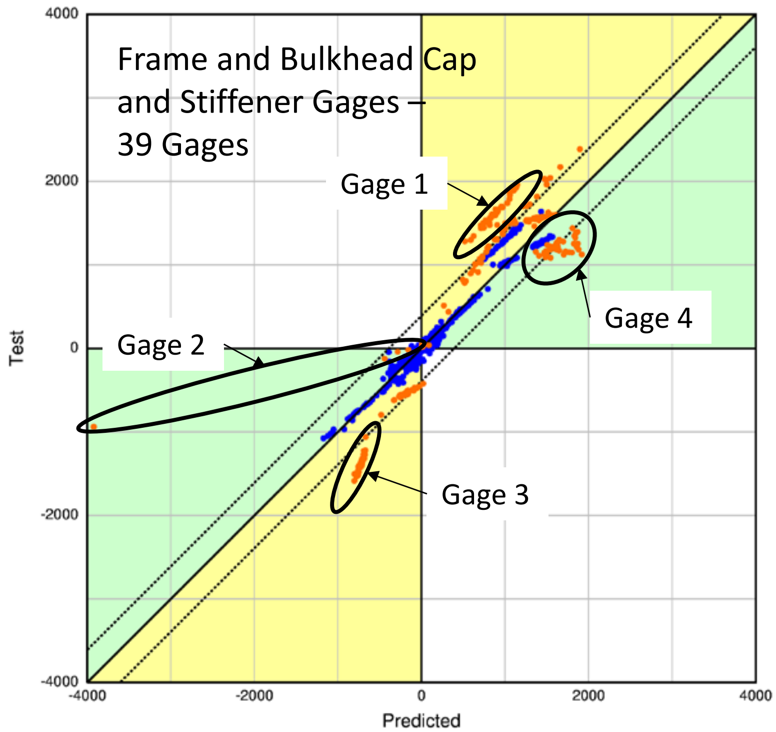


Figure 17.11.3-2 Fuselage Frame and Bulkhead Caps, Multiple Stations, All Conditions

Gage 1 is located on a stiffener below a longeron whose loads are primarily due to pressure. The modeling of the vertical stiffener, as a single shell element captures the axial load but does not adequately capture the strain distribution. Hand calculations properly predict the strain and the design analysis accounts for this effect.

Gage 2 lies in an area of high stress gradients for certain conditions and the AVFEM in this area does not have sufficient mesh density to capture the gradients for these conditions. That is why, for conditions without the high gradients, the correlations look good. The design analysis takes these gradients into account.

Gage 3 is at a joint between fore/aft structure and a frame where there is load transfer from the frame into the longeron structure. The cap element selected for use in the model prediction is coincident with the element representing the fore/aft element; however the gage is located before the joint, so the load is still in the frame cap at the gage location. An adjacent gage, after the joint, was examined and shows good correlation. Design analysis of the area takes into account the details of the load transfer.

Gage 4 is located in an area of the model where the average thickness of multiple layers of material is modeled as a single element. When the actual area of the structure is used with the model internal loads, the gage shows good correlation. The design analysis is based on actual structural area.

Although these four gages show poor correlation between the AVFEM and the measured results, after investigating, it is determined that no further action need be taken to modify the model or the detailed analysis approach. The differences are a result of local effects which are not typically captured in AVFEM analysis; however, they are captured in fine grid models and the design analysis. The load paths are correct and adequate and the analysis does account for the local effects through the use of fine grid models or classical analysis techniques. The correlation report should include, as a minimum, a discussion of how the local effects are accounted for in the design. Preferably, it would include test predictions accounting for the local effects in the same manner as the design, thus substantiating the approach.

17.12 Analysis Validation

Each step in the validation process builds on the previous. At the most simple level, coupon testing is performed to determine the fundamental material properties which are used in the analysis as allowable material properties are used in tuning the analysis tools to predict a particular failure mode. At the next level, analysis is performed using rational engineering assumptions coupled with generic test or theoretical data and then the analysis result is validated by element or component testing. This may result in the addition of correlation factors to the analysis to improve the predictive capability of the analysis. This forms the basis for the verification of the design stress analysis methods and assumptions.

Once the design analysis is complete, stress analysis validation continues with the validation of the AVFEM by correlation to the full-scale static test article measured data. Geometric and material nonlinear behaviors, large displacements, local structural details, or other behaviors not captured by the linear air vehicle finite element model are correlated to the test measured data through the use of FGFEMs or hand analysis techniques. The flow chart of Figure 17.11.0-1 is used to guide in the validation of the design analysis based on this correlation activity. It is implied that prior to use in design analysis these FGFEMs have been compared to the parent AVFEM and any differences understood and documented.

The final validation step occurs by obtaining flight measured loads for correlation with the predicted loads. This correlation is used to calculate a final set of aircraft loads for use in certification analysis which forms the basis for the Strength Summary and Operating Restrictions report. The SSOR defines the final validated flight envelopes.

17.13 Reporting, Database Development and Archival

A tremendous amount of data is generated during an entire aircraft test program and how the data is archived is a very important aspect of the test. The data is not collected just for the immediate need but also forms the basis of substantiation for the certification of the aircraft. The data is the foundation for the statistically based material properties, the fatigue crack initiation and growth properties, point design allowables, verification of design, correlation and validation of the finite element model, stress and durability and damage tolerance analysis and tools and finally verification and validation of the aircraft loads. Because the expense of developing material properties is so high, the data derived from one program can also form part of the certification basis for the next aircraft program and is also important in the certification of modification, derivative and block upgrade programs. Furthermore, it may form the basis of analysis methods far into the future, thus it is imperative that it be preserved.

In short, the ability to access, retrieve, understand, and create reports of the test data gathered during a typical aircraft building block test program is invaluable. Creating an archive which can be referenced and is easily accessible makes good business sense and cannot be emphasized enough. Lessons learned from past programs indicate this has not always been well thought out or rigorously implemented on some programs within Lockheed Martin. This results in the need to recreate data that is simply lost.

Computer systems and software programs evolve, software companies come and go, so this document will not recommend a particular software package but rather provide some guidelines on the required data in the following paragraphs. However, as a test program winds down, one thing to consider is that no matter what archival software was used, archiving a duplicate back-up copy of the database in an ASCII text-readable flat file may be prudent. In that way the data can be imported into a new software with a minimum amount of work.

17.13.1 Coupon Level Test Archival Guidance

ALL material coupon test data which support the development of statistically based material or joint allowables should be stored in a database (not just the composite materials). Some of the information required includes:

- Coupon test specification and documentation of any deviations from the specification
- Test fixture descriptions and photo
- Test frame location and identification
- Test operators name and contact information
- All coupon measured dimensions
- Coupon and material information: *e.g.*, heat, lot, grain direction, measured thickness, batch, composite laminate definition, ply rosette, fastener type, fastener size, hole dimensions, countersunk head depth, nut, buck tail size, formed tail size, *etc*.
- Failure loads
- Load-stroke and strain curve point data
- Strain gage point data
- Description of failure, other test results and measurements, and photographs
- All other test unique measurements
- Test report number

The lab conducting the tests should be able to provide the majority of this information in electronic format. At the beginning of the program, prior to any testing, the digital format should be predetermined and flowed to the test house as part of their requirements. The data required may change depending on the type of testing and the materials involved; however, using a generic format that can accommodate the variations is recommended. The development and use of a test-neutral hypertext mark-up language (HTML) may be useful in this process. By using a common format for all test labs the information is ready for storage in a data repository database when it is received. It is prudent to have a preprocessing step to validate the data format received from the test house or to reformat as required in order to minimize the possibility of invalid data being added to the database.

On a previous program, all composite coupon level test data was consolidated into an MVISION® database and was available for the next generation program. All metallic data was stored in a series of Excel spreadsheets which have subsequently been lost, resulting in a requirement to repeat some of the metallic coupon testing for the next generation program.

17.13.2 Element and Subcomponent Level Test Archival Guidance

How the information is archived for this level of test is dependent on the test requirements and goals. The geometry and results including load levels, instrumentation readings, failure loads, and failure modes can be archived in a database similar to the coupon level testing. These database entries should be accompanied by an officially released, numbered test report so that an engineer in the future can understand exactly how the test was conducted and what the goals and results were. The test report number should be a part of the database information for easy retrieval and the report should be available in electronic form.

Depending on the complexity of the test, there may be two test reports required – one written by the laboratory and one written by engineering. For simpler tests, these may also be combined into a single report with the test lab information contained in an appendix.

The test lab report contains the basic test results, specimen geometry with photographs of the specimen in the test fixture and/or failed, test set-up, fixture information, etc. Much of this information should be generated from the electronic data submitted for the database.

The engineering report contains the engineering interpretation of the test including any analysis methods or correlation coefficients which may have been developed and conclusions. If the test configuration was modeled with a finite element model, correlation of the test results with the finite element model would also be included. Information on the model and constraints should also be a part of this report. If the test is used to develop or substantiate point design allowables, then those allowables should be reported, including any restrictions on their use.

17.13.3 Full-scale Component or Full-scale Aircraft Ground Test Archival Guidance

The complexity of these types of tests are such that archiving all necessary and pertinent data in a database for later retrieval is not possible; however, there are some types of data that can and should be archived in a database such as loads, strain gage locations and instrumentation drawings, predictions and results (strain survey or conditions only for the durability article), deflections, and temperatures. It is not necessary to archive every run, but only the final runs which also include date and time information. Additionally, for a durability article, additionally the cyclic endpoints are recorded, typically every endpoint during the maneuver flight portion of the spectrum and on a sample basis during the buffet portion of the spectrum due to the high number of cycles.

Anomalous events in testing must be carefully documented as they may require action, further inspection or repair. A test anomaly is a crack, rupture, deformation, impact, or other physical damage on the structural test article. Any newly discovered cracks or impact events should be documented on an NDI damage screening report. There are four classifications of anomalies described here and the reporting requirements for each are discussed in Table 17.13.3-1

- Test fixture anomaly – an anomaly that is restricted to the non-test portion of the test article, load introduction fittings, dummy structure, such as landing gear or engines, or any other test lab equipment to load the test article. Test fixture anomalies are generally dispositioned for corrective action/repair by test lab engineering in consultation with a designee from program engineering. Typically the customer is not notified for this type of anomaly unless significant down time is required for its resolution.
- Instrumentation anomaly – an anomaly resulting from unusual or suspicious strain gage, deflection, load cell, or load bridge measurement. Strain gages that develop problems or which are replaced / repaired should also be documented in the Master Instrumentation List. Strain gages on a durability test article which appear anomalous due to trend changes will require inspection of the surrounding area for a possible cause. Repair of instrumentation can occur immediately, if the gage is designated by engineering as critical for the next load case or load sequence or may wait for a test article down time between tests, during inspections or during

repairs. Typically the customer is not notified for this type of anomaly unless significant down time is required for its resolution.

- Minor structural anomaly – an anomaly in a part that can be replaced with a similar part or which requires a minor repair that does not affect the load path and load distribution. This might include a loose or failed fastener, damaged non-critical structure such as fairings, clips or brackets, scratches which can be blended, small composite impact damage requiring no repair or a fastener repair. Minor structural anomalies should be dispositioned by the designated program engineer. Typically the customer is not notified for this type of anomaly but will see them as a part of the itemized inspection report.
- Structurally significant anomaly – this type of anomaly would be a crack, failure, rupture, or plastic deformation of Class I primary structure or fracture critical or durability critical structure. In durability testing, most cracks fall into this category. Structurally significant anomalies shall be evaluated and dispositioned by program engineering. These types of anomalies also need to be assessed for their impact to safety-of-test (SOT) and safety-of-flight (SOF) (if applicable). Typically, the customer is notified for this type of anomaly. Furthermore, if an anomaly is assessed to be SOF or SOT the program Chief Structures Engineer should brief the customer.

In addition there are some other documents, reports and logs that are recommended for full-scale test. These are applicable to static, durability, service life assessment program (SLAP) tests or full-scale static or durability component tests. These are summarized in Table 17.13.3-1.

Table 17.13.3-1 Recommended Reports, Documents and Logs for a Typical Full-scale Test Program

Report Name	Description	Static	Durability	Responsible Engineer	Comments	Example Shown in Figure
Test Operators Log: “Test Log”	This is a running record of significant test activity. It is used to record the day-to-day activities such as load application, instrumentation, data acquisition, inspections, repairs, etc. This log will also contain record of test fixture, test article and instrumentation anomalies	x	x	Test Conductor		
Anomaly Squawk	Documentation of a new anomaly. The anomaly squawk sheet contains an informal description of the anomaly, an engineering disposition, and a description of completed inspection, rework and repair.	x	x	Any	Anomalies might include broken fasteners, abnormal strain gage readings, test fixture anomalies or crack indications which are not yet confirmed, etc. The anomaly squawk sheet, if not maintained electronically (preferred), should be scanned and added to test record archive.	17. 16.0-1
Damage Screening Report (DSR)	Anomaly inspected and documented. Used for new crack indications and impact events (composite materials)	x	x	NDI Inspector	Used to convey initial information to engineering. For re-inspection of existing cracks or delaminations any growth should be documented in the crack log.	
Inspection Checklist	For documenting pretest inspections, periodic test inspections, and post-test inspections		x	Program Engineering; NDI Inspection	Checklists prescribing required inspections, completed inspections, findings, NDI report numbers, DSR numbers, and anomaly squawks. It should also note who performed the inspection.	

Report Name	Description	Static	Durability	Responsible Engineer	Comments	Example Shown in Figure
Damage Log	This is a single page description of each crack, delamination or other significant damage, the location, part number, and pertinent size, number of hours at discovery (durability test) or load condition (static test) and any other information. It should have photographs of initial and the most current state. This is a tool for the engineers to systematically monitor the cracks/delaminations/damages and any changes. The damage log also has the up-to-date disposition of the damage either directly in the log or through reference to a Structural Test Memo.	Note 1	x	Program Engineering	All test induced structural damage will have a log sheet. Additionally if a SLAP article, damage existing prior to the start of test will have a log sheet. Subsequent inspections/growth is documented on the damage log. The damage is given a sequential number and if multiple damage locations are in the same area they are given letter designators, *e.g.*, Damage 10A, 10B, etc.	17. 16.0-2
Damage Tracking Spreadsheet/ Database	Key information from each damage log sheet should be entered into the Damage Tracking Spreadsheet or Database. The following data should be included: • Damage ID No. • Component Name or Description • Location: FS, BL, WL • Component Part No. • Reference Documents • Inspection Item • Test Anomaly Report Number • Test Flight Hours or Test Load Case at Discovery	Note 1	x	Program Engineering	This tracking spreadsheet or database is an easily searchable summary of all cracks, delaminations or damage. It can also be used as a summary list for final documentation.	

Report Name	Description	Static	Durability	Responsible Engineer	Comments	Example Shown in Figure
	• If SLAP article, Component Delta Flight Hours • Crack Length versus Test Flight Hours • Repairs and test flight hours (or condition) when accomplished					
Ground Test Summary	This is a one page report, typically filled out post-test by IPT test monitors, summarizing each test condition and findings. Information includes load case, date, load level, instrumentation issues, test issues and a results summary.	x		Program Engineering	These are collected, electronically, by the program test coordinator and will be assembled into the test results report. There is one per each major aircraft section.	17.16.0-3
Pre-test Inspection Report	Used for summarizing the initial condition of the test article prior to lab testing. It will include the results of visual and NDI inspections for any cracks, corrosion, repairs, delaminations or non-conformances.	x	x	Program Engineering; NDI Inspection	Any crack found during the pre-test inspection should be the first items listed on the crack log. For newly built articles, this pretest inspection is typically done by cognizant program engineers looking to see if there is anything unexpected, structure missing or if there is undocumented damage.	
Structural Test Memorandum (STM)	This is a formal written communication between program engineering and the test lab and is used to implement any changes to the test, loads, define any repairs and/or modifications. It will have a sequential STM number and should be electronic and archived in the test documentation archive.	x	x	Program Engineering		17. 16.0-4

Report Name	Description	Static	Durability	Responsible Engineer	Comments	Example Shown in Figure
Summary Inspection Report (SIR)	The SIR is a summary of all events, major and minor inspection findings, special inspections, deferred work, changes to the test spectrum or loads, and instrumentation trend monitoring results. This is provided to the customer to status and document test progress.		x Note 2	Program Engineering	This is a summary report developed from other documents, (test operations log, crack log, and structural test memos) periodically during test, typically after each block of loading.	
Teardown Inspection Report	This report documents any crack findings as a result of disassembly and cut-up of the test article. The areas to be examined are documented in the test article teardown and inspection plan.		x	Program Engineering; NDI Inspection	Data recording of findings would follow the same procedures documented in this section.	
Drawings	<u>Configuration Drawing</u> to document the configuration of the test article. It should include any repairs made during salvage operations in the factory or in the field. <u>Instrumentation drawing(s)</u> to document the detail placement of the strain gages and other instrumentation.	x	x	Program Engineering	The instrumentation drawing should take into account when in the manufacturing process gages in limited access areas have to be installed.	
Test Anomaly Report (TAR)	Test anomalies that require investigation and analysis by program engineering are typically documented on a TAR, which is a numbered report.	Note 1	x	Program Engineering	Not all anomalies require TARs. In general, it would be limited to structurally significant anomalies and some minor structural anomalies. Other classes of anomaly are typically dispositioned on the anomaly squawk. See Section 17.3.4 for a detailed discussion of TARs	17.16.0-5
Notes:						

Report Name	Description	Static	Durability	Responsible Engineer	Comments	Example Shown in Figure

1. These items are typically used for cyclic loading tests. However, static tests may also have damage and/or anomalies which need to be documented and these forms may be used.
2. A final test operations and inspections report will be a compilation of all of the SIRs generated at the end of each block of testing for the durability test article.

Below is a list of topics that should be covered in the full-scale test reports. Some of these topics such as the test correlation effort or the teardown inspection may be the subject of separate reports, while other topics may be included in a single over-all report.

- Descriptions of the test article configuration
- Description of the test facility and test setup including loading and restraint system
- Test Procedures
- Instrumentation summary and references to instrumentation drawings, photo archives, etc, if a separate document
- Data acquisition system and data management
- Test conditions (static) or test spectrum (durability)
- Applied load by condition (static)
- Test correlation results, AVFEM model validation, and summary of impact to the design analysis
- Test results
    - Static: Compilation of ground test summary reports
    - Static: Location of strain gage results files
    - Durability: Summary Inspection Reports
    - Durability: Test Anomaly Logs
    - Durability: Damage Log
- Compilation of Structural Test Memorandum
- Pre- and Post-test inspection reports
- Teardown Inspection Results
- Test Adequacy Discussion

The test labs will also publish a test report summarizing the test article, test frame, jack information and loads and the general conduct of the test.

The results of the strain gage correlation and model validation effort will be used to update the final certification analysis in conjunction with the flight test adjusted external loads as discussed in Section 17.2.1.4.

17.13.4 Test Anomaly Report

Test anomalies which are significant enough to require further engineering investigation are documented on a Test Anomaly Report (TAR). The flow chart shown in Figure 17.13.4-1 provides a decision tree for use in determining if a TAR is required.

Note that a TAR is typically required for any part that has cracking, disbonds, or delaminations . Part of the information documented on the TAR includes the crack correlation analysis. The TARs are then collected and included in the overall test report and are a self-contained investigation and analysis of significant test anomalies.

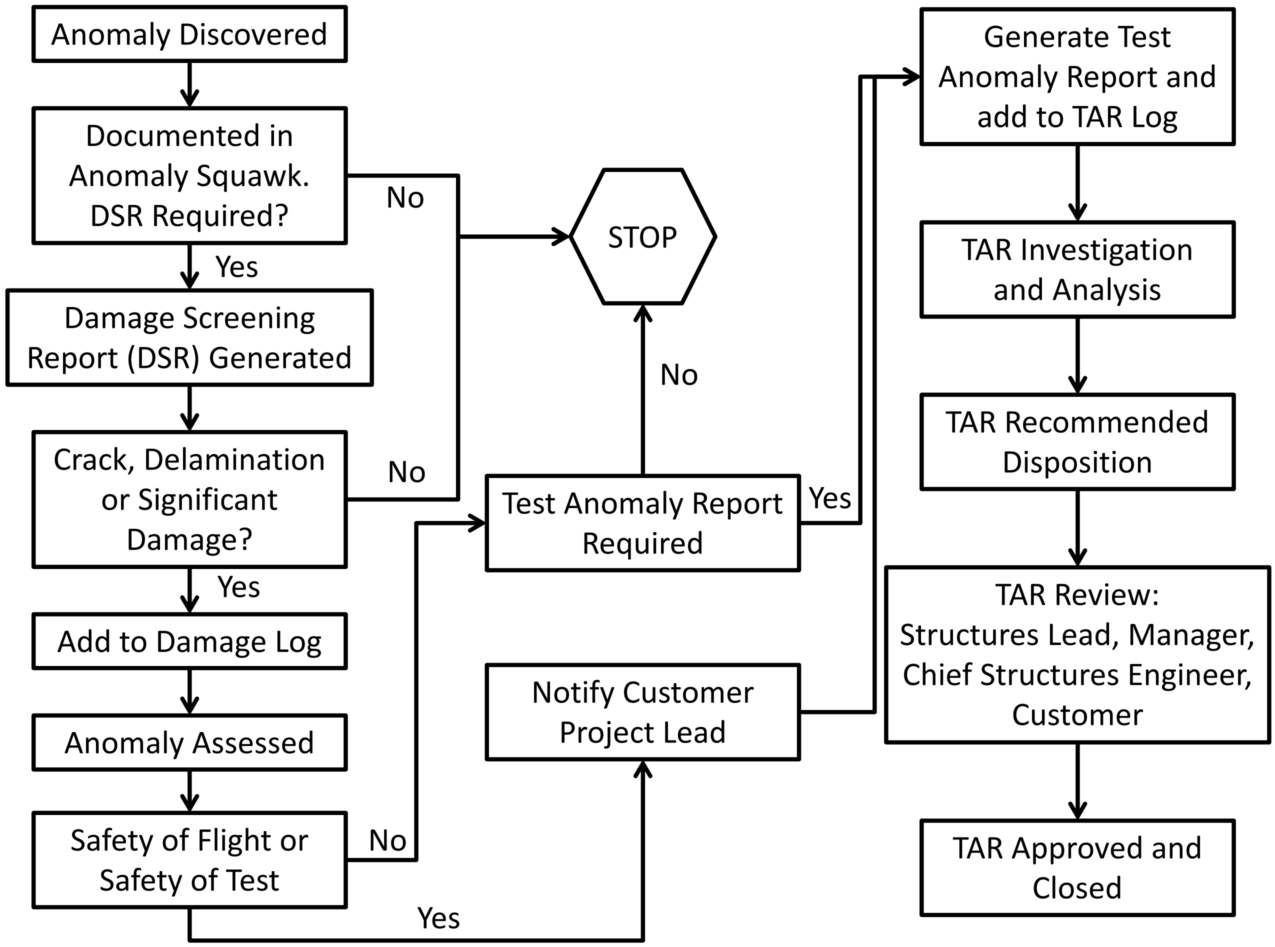


Figure 17.13.4-1 Test Anomaly Report Decision Tree and Process Flow

17.14 Experimental Stress Analysis

Experimental stress analysis is typically part of a design/test/redesign program. While some of the element and subcomponent level testing for point design allowables may fall into this approach, for aircraft structural design, the approach is to design, analyze, test, correlate and validate the analysis and redesign if something was missed or if the analysis was shown to be too conservative.

For aircraft programs, the experimental-stress-analysis-only approach is often taken for electronics, antennae and radome suppliers. The test results and validation of design is reported in a qualification test report which must be reviewed by stress, dynamics and system integrity engineers. Many times the report contains no analysis or limited, post-test analysis and may attempt to qualify the item by similarity to an item used on another aircraft platform. In order to mitigate program risk and prevent requalification, it is imperative that the affected analysis organizations review and sign off the qualification test plan PRIOR to start of testing.

See Reference 17-2 PM4056 Section 18 for a discussion of radome testing.

17.14.1 Electronic Equipment

It is important for the reviewing engineer to understand how the item will be mounted in the aircraft, the specific aircraft environments and the fundamentals of the structural aspects of the design. As the qualification test report is reviewed it is his responsibility to ensure that the test adequately simulates the structural attachment, the actual aircraft environment in terms of local maximum accelerations, vibration levels, acoustic levels, thermal environment, *etc.*, and if important, the stiffness of the attaching back-up structure. For electronic equipment mounted in the aircraft, the testing is often done to specification levels on a centrifuge, assuming rigid back-up structure as-installed. There are two primary specifications used: MIL- STD-810 and RTCA-DO160. The former is for military equipment and most of the required testing will be more severe than would be required for most military aircraft use. The latter is used for much commercial-off-the-shelf equipment (COTS) and is for the testing of electronics mounted in commercial aircraft for a large variety of environments. As many military customers are migrating to the use of COTS equipment to reduce costs, the use of RTCA-DO160 is becoming more commonplace in military contracts. The requirements for equipment under this specification are often less stringent than what would be required per MIL-STD-810 and may be insufficient for use on a modern military aircraft.

Equipment qualified under RTCA-DO160 may need to have additional tests performed to ensure that it will stand up to the environment of specific military aircraft.

Qualification by similarity for the structural aspects of the equipment requires that the equipment be of the same general size, shape, weight, center of gravity and construction, using the same attachment scheme and qualified to acceleration, vibration, shock, and acoustic levels which meet or exceed the current aircraft's requirement. If the qualifying levels are lower than the current specification, additional testing may be required.

To prevent misunderstandings, as early as possible in the equipment development cycle, the types of testing, test levels and criteria for qualification by similarity should be agreed upon and documented in the equipment procurement specification.

17.15 Computer Tools

17.15.1 CAT/IFEM/STTGUI Instrumentation Prediction

The common analysis tool suite (CAT) IFEM has a tool specifically to aid the analyst in predictions and post processing of instrumentation for structural test. Structural Test Tool GUI (IFEM/STTGUI) is designed to analyze and post-process structural test predictions and test lab data for strain, load and displacement gages. Its primary purpose is to support the static structural test and certification process. It interfaces with the TMP/Vision and SLIM finite element visualization and loads database tools.

STTGUI enables:

- Visualization of gages and their attributes with respect to a finite element model (FEM).
- Display of predicted and measured strains on a FEM, in XY graphs and tabular formats
- Post-processing, analysis and correlation of predictions with test measurements.

STTGUI consists of a graphical user interface that integrates a TMP/Vision viewport and an XY Graph window with a tab-based menu system.

STTGUI supports the creation of biaxial, rosette, uniaxial, vsette, displacement, load and grid point force instrumentation (gage) types. The gages are associated to specified elements of the FEM. They can be placed at any location on a bar/beam element, shell element, or solid element face and may be located at the center of the element or at a location other than the center and on top or bottom surface.

Predictions can easily be made for one load case or a number of load cases and the program has the ability to do sensitivity studies on the location of the instrumentation. The program also allows the user to read in actual test data and compare to predictions and perform comparisons and correlation. It has a number of options for visualizing and reducing the data.

17.16 Sample Forms

Included in this section or a sampling of forms discussed in Section 17.13.3 and Table 17.13.3-1 for use in documentation of the full-scale test programs.

Squawk Date	Test:	☐ Test Fixture
		☐ Instrumentation
SFH:	Test Anomaly Squawk	☐ Structural
Inspection:		☐ Other

Condition:

Prepared by: ____ Date:_____________
Time:_____________

Disposition:

Engineer: ____ Date:_____________
Time:_____________

Resolution:

Completed by: ____ Date:_____________
Time:_____________

Figure 17.16.0-1 Test Anomaly Squawk

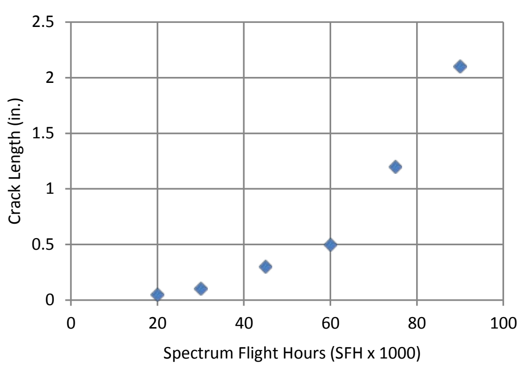
Test: _____________ Durability Test Damage Record

Component & Location				FS			TAR #		Damage ID	
				WS or BL		☐ L ☐ R	Date		Test SFH Discovered	
Part #		Reference Documents		WL			Inspection Item		Component Delta SFH	

SFH	Crack Length	Inspected by	NDI Report	Remarks	Disposition	Engineer

Location Illustration	Initial Finding
Sketch of Aircraft Location	Photo of Finding at Discovery

Crack Growth History



Current Finding

Most recent photo

Figure 17.16.0-2 Damage Log Form

Ground Test Summary		Program:
A/C:	Test Condition Description:	Test Date:
Test Condition No.		Test Observer:
Aircraft Subsection/IPT:		Test Coordinator:

Instrumentation Issues: *This section is used to describe any instrumentation anomalies or instrumentation that was non-functional.*

Test Issues: *This section is used to describe any issues with the test article/ loads/ load jacks or any noteworthy issues that occurred during the test.*

Test Results Summary: *This is a short summary of the test. If the test was not critical for a particular IPT, it would be noted here, if there were strains higher than predicted or failures, it would be noted here, etc. Typically anything that might be of interest downstream would be included in this discussion.*

Figure 17.16.0-3 Ground Test Summary

Structural Test Memo

To: Ground Test Laboratory
From: Test Coordinator

STM Number: 001
Request Date:
Need Date:

Subject: Inspection for *Structural Part Name*

Distribution: Provide Standard Distribution List

Background: *Provide a short summary of the background for this specific issue*

Action: *Describe the action the test lab must take*

____

Joe Engineer Date
Program Test Coordinator

Figure 17.16.0-4 Structural Test Memo Format

LOCKHEED MARTIN

TEST ANOMALY REPORT

Page 1 of 1

Title:		TAR Number:			
		Crack Log #			
		Date / Revision			
Part Numbers:		Safety of Flight:	☐Yes ☐No		
Inspection Documents:		Component SFH:			
Reference Documents:		FS	WL	☐CWS/BL ☐OWS	☐L ☐R
Reviewed Test Lead:		Approved DaDTA:		Approved Manager:	

Section 1 - Anomaly Description	Engr.		Email		Date	

1.1 Anomaly Description: *Include under what circumstances the anomaly was discovered and any relevant history of the areas. Include copies of relevant documentation, photos, and figures where appropriate. Attach NDI reports and methods, FPI photographs, and data on crack growth as a function of spectrum flight hours. Descriptions of repaired anomalies must also contain the repair information.*

1.2 Revision History: *This section will also show revision history and include the appropriate revision letter, date of revision, and spectrum flight hours. It will include all documentation relevant to the anomaly but not previously included in the initial Test Anomaly Report such as new information, documentation, or history that was not known or was unavailable at the time the Test Anomaly Report was written.*

Section 2 – Anomaly Investigation	Engr.		Email		Date	

2.1 Investigation: *Provide detailed description of the investigation to determine the cause of the anomaly. Include copies of metallurgic studies and fractographic analysis that may be performed and any relevant documentation appropriate for the investigation.*

2.2 Analysis: *DaDT analysis will include correlation analysis of cracks to determine a predicted life, a correlated life, and an equivalent initial flaw size (EIFS). The DaDT analysis methodology and the variables used in the analysis will be documented.*

2.3 Conclusions: *Summarize the results of the investigation and the conclusions drawn, including the impact to the test article and a SOF assessment.*

Section 3 – Recommendation	Engr.		Email		Date	

Recommendations to resolve an anomaly may include repair recommendations, redesign recommendations, or recommended imposition of inspections including methods and frequency on the fatigue test article and/or in-service production aircraft.

If it is determined that an anomaly will not impact the service life of the wing, and will not have an economic or mechanical impact to the fleet other than what is normally expected, then the recommendation should be that no action be taken for the reasons given.

There is no implied requirement for implementing the TAR recommendations by LM Aero. The recommendations are made for the consideration by the USG customer and the LM Aero C-130 Program.

Figure 17.16.0-5 Test Anomaly Report (TAR)