Structures Bulletin

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Subject: Guidance on Correlating Finite Element Models to Measurements from Structural Static Tests

References:

1. MIL-STD-1530D Change 1, *Aircraft Structural Integrity Program*, 13 October 2016.
2. AFI 62-601, USAF Airworthiness, 12 May 2001.
3. Joint Service Specification Guide 2006*, Aircraft Structures*, Department of Defense, 30 October 1998.

Purpose:

To provide guidance on correlating finite element models (FEMs) used to determine internal loads, local stresses and strains, and deflections with instrumentation measurements obtained during structural ground tests. For the purpose of this bulletin, applicable structural ground tests include: static strength testing, proof testing, and strain surveys associated with fatigue testing and loads calibration testing.

Introduction:

This bulletin provides guidance and outlines procedures for correlating structural ground test results to analytical predictions. The United States Air Force (USAF) approach to aircraft structural certification is accomplished primarily by analysis validated by test, as identified in Section 5.4.1 in MIL-STD-1530D (Reference 1). Structural testing is primarily accomplished as a means to validate that analytical predictions are reliable and accurate over the full range of structural loading, as well as to provide demonstration of performance. The focus of this bulletin is the correlation of instrumentation measurements obtained during structural ground testing (static strength, proof, fatigue, and loads calibration) with the FEM-based predictions. This bulletin includes test-planning considerations for instrumentation and loading, correlation criteria, correlation evaluation, and correlation issue resolution.

Discussion:

MIL-STD-1530D (Reference 1) provides the basic guidance for evaluating test data and correlating with the analysis in paragraphs 5.3 and 5.4 (references to figures and other paragraphs are omitted for clarity).

> 5.3 Full-scale testing
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> "The objective of this task is to assist in the determination of the structural adequacy of the design through a series of ground and flight tests. Test plans, procedures, and schedules shall be approved by the procuring agency. Test results shall be used to validate or correct analysis methods and results and to demonstrate requirements are achieved."
>
> 5.3.7 Interpretation and evaluation of test findings
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> "Each finding that occurs during the tests described by this standard shall be analyzed to determine the root cause. Examples of findings include but are not limited to: higher than predicted loads, strains, stresses, displacements, vibrations, weights, different than predicted stiffness, frequencies or mode shapes, yielding, failures, cracks, delaminations, disbonds, onset of WFD, corrosion, wear/galling, bushing migration, and improper drain paths. The test results shall be used to revise the analyses described by this standard until an acceptable correlation is achieved. The revised analyses shall be used to determine if corrective actions are required to achieve the strength, rigidity, durability, damage tolerance, and other specified requirements. For each corrective action required, cost, schedule, and aircraft availability impacts shall be determined for options to resolve the issue and risk analysis shall be performed to establish the operational limit (for example, g-restriction, weight restriction, airspeed restriction, reduced certified service life) before the corrective action is implemented."
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> 5.4.1 Structural Certification
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> "The design analyses described in 5.2 shall be revised to account for differences revealed between analyses and testing in 5.2 and 5.3. Design development tests described in 5.2, the full-scale tests described in 5.3, the interpretation and evaluation of test-identified issues described in 5.3.7, and the resolution of test identified issues described in 5.3.8 shall be used in the structural certification effort. The design analyses correlated to ground and flight testing shall be used in the structural certification as an integral part of the airworthiness certification procedures established in AFI 62-601."

Correlation of analysis with test data is a common theme throughout Appendix A of the JSSG-2006 (Reference 3) where it frequently states:

- “The validity of the analytical models shall be demonstrated by correlation with testing.”
- “Structural analyses shall be validated and updated for all testing such that the predictive methods ensure adequate strength levels and understanding of the structural behavior.”
- “Measurements of stress and strain distributions on major components obtained from static tests need to be correlated with analytical distributions.”
- “Laboratory load tests of instrumented airframe and major parts shall verify that the airframe structure static strength requirements are met. This instrumentation is required to validate and update the structural strength analyses.”

Terminology

To properly establish analysis to test correlation guidance, some key terminology is defined below:

Analytical Tools: Any software program used to perform computations for a structural analysis. In the context of this bulletin, analytical tools are commercial software programs such as NASTRAN, Patran, ABAQUS, etc. as well as proprietary software tools for structural analyses.

Structural Model: A computer based model created to predict the behavior of a structure. In the context of this bulletin, structural models are used to obtain internal load, stress, strain, and displacement predictions for applied loading of complex structures. An example of a structural model is a FEM.

Safety-of-Flight (SoF): Safety-of-flight structure is structure whose failure could cause loss of the aircraft, or cause severe injury or death, or impair a safety critical function, or cause inadvertent store release. The consequences could occur either immediately upon failure or subsequently if the failure remains undetected.

Verification of Analytical Tools**:** Verification is an action to establish the truth, accuracy, or reality of something. In the context of this bulletin, verification of analytical tools is associated with the accuracy of the analytical tools used to develop a structural model.

Correlation: Correlation is to set forth to show a relationship. In the context of this bulletin, correlation is the process by which the analytical results of a structural model are compared with test data. This activity is typically referred to as "correlation", and is the primary focus of this bulletin.

Validation: Validation is an effort to support or corroborate on a sound or authoritative basis. If something is valid it implies that it is well grounded or justifiable. In this bulletin, validation refers to the process of confirming that the structural model represents the behavior of the structure being evaluated within acceptable level of accuracy.

Verification of Specification Requirements**:** In the context of this bulletin, verification of specification requirements constitutes the work required to accomplish structural certification.

Test Planning Considerations for Instrumentation and Loading

Planning for structural ground test programs should include consideration for potential correlation issues. Instrumentation and test loads can directly impact correlation efforts and it is prudent to carefully evaluate their contribution during the test planning effort. However, this bulletin does NOT provide sufficient information to develop detailed instrumentation and test loading requirements. A list of considerations for both instrumentation and test loading are provided below.

1) Instrumentation Considerations:

- Selection of transducers
  - Measurement type: strain, displacement, acceleration, pressure, etc.
  - Gage size (averaging), local stiffening, etc.
  - Range: strain (linear, non-linear), displacement amplitude, acceleration magnitude, pressure magnitude, etc.
- Quantity
  - Sufficient transducers to capture response of complex structure
  - Number of channels, consideration for back-up gages, etc.
- Locations
  - Left side and right side, primary load paths, back-to-back, etc.
  - Distribution and density to capture response of complex structure
- Provisions for Additional Instrumentation
  - Spare channels, extra data storage capacity, etc.
- Calibration
  - Manufacturer requirements, gage factor, etc.
  - Temperature compensation and environment for balancing bridge
- Accuracy
  - Manufacturer certification, range of applied loading, etc.
  - Excitation voltage, local heating, etc.
  - Data filtering, skewing, expected error, etc.
- Linearity Checks
  - Automated evaluation and reporting of issues
- Data Collection
  - Sampling rate, storage buffer, rate during applied loading, etc.
  - Sequencing, simultaneous sample and hold, etc.
  - Conditioning: digital, analog, amplification, saturation
- Data Storage
  - Capacity, time history, load cell feedback, etc.
  - Raw, conditioned, filtered, etc.

2) Test Loading Considerations:

- Load Levels and Increments
  - Maximum % limit load, % limit load increments, hysteresis check

- Load Case Selection
  - Loading conditions that provide meaningful instrumentation measurements, etc.
- Load Application and Distribution
  - Whiffle trees, formers, hard points, etc.
  - Weight, center of gravity, stiffness effects
  - Simulated (dummy) components
  - Counter balance requirements, load jacks, test hardware, etc.
  - Points versus distributed loads
  - Load vector changes with large deflections
- Test Article Restraint
  - Boundary conditions, constraints, load introduction fixtures, transition structure, etc.

Correlation Criteria

Because strain measurements are the most common data collected during structural ground testing, this bulletin will focus on the correlation of strain gage data with analysis predictions.

The most useful method to compare measured and predicted strains is to plot the results. A plot of measured versus predicted strains that contains (1) pre-defined acceptable error bands and (2) strain thresholds below which correlation issues are less important can be displayed to provide a quick-look at the correlation results. The plot readily illustrates strain gage measurements with:

1. Acceptable or poor correlation
2. Higher and lower priority issue resolution efforts
3. Demonstration of trends

The plots should be constructed for the correlation criteria listed below and described further in the following sections:

1. Acceptable error
2. Strain threshold
3. Trend

(1) Acceptable Error

An important factor in determining if test and analysis data have an acceptable correlation is the percentage of error between the analysis and test values. There are four possible equations to calculate the percent error. See example calculations in Table 1.

Table 1 – Possible Error Calculations

M (μ-strain)	P (μ-strain)	(M-P)/P (1)	(P-M)/P (2)	(M-P)/M (3)	(P-M)/M (4)
2000	1810	10.5%	-10.5%	9.5%	-9.5%
1810	2000	-9.5%	9.5%	-10.5%	10.5%

(1) $\%\ \text{Error} = \left(\frac{\text{Measured}}{\text{Predicted}} - 1 \right) \times 100$

(2) $\%\ \text{Error} = \left(1 - \frac{\text{Measured}}{\text{Predicted}} \right) \times 100$

(3) $\%\ \text{Error} = \left(1 - \frac{\text{Predicted}}{\text{Measured}} \right) \times 100$

(4) $\%\ \text{Error} = \left(\frac{\text{Predicted}}{\text{Measured}} - 1 \right) \times 100$

When performing a correlation effort, it is extremely important to know which of the four equations is being used to calculate error. Equation (1) is commonly used since it states a higher percentage error for measurements higher than predicted and states a lower percentage error for measurements lower than predicted. The equation also produces positive errors for measurements that are "high" and negative errors for measurements that are low, relative to predictions. Therefore, Equation (1) is the preferred choice for computing percentage error.

A correlation that gives strain error limits no greater than ±5% for SOF structure, or no greater than ±10% for a non-SOF structure is recommended. Further evaluation of data meeting this criteria can be limited to the review of trends and strain gage linearity for a stability-critical structure. Errors greater than these limits require correlation issue resolution and should follow the process described below. Careful evaluation of all causes and consequences for poor correlation must be performed on a case-by-case basis if increasing the acceptable error limits is considered. For example, increasing the acceptable strain error limit for a structural component must consider that the poor correlation may be due to errors in the internal load distribution. An incorrect internal load distribution can have detrimental effects on the static strength and durability and damage tolerance of neighboring structural components. Therefore, increasing the allowable error limit is in general not appropriate. The recommended error limits identified above are used in the correlation evaluation described below.

Figure 1 shows example data for gages on an aircraft component for all test load conditions. The plot shows that the majority of the data is within the recommended error bands and that several anomalies exist that require correlation issue resolution. This type of plot should be constructed for all loading conditions and all gages in the test article, major components (e.g. wing), and individual structural elements in a major component. In this example, the percentage error bands are drawn at ±5%. Note that this type of plot also makes test data above and below predictions obvious and reversals of data clear.

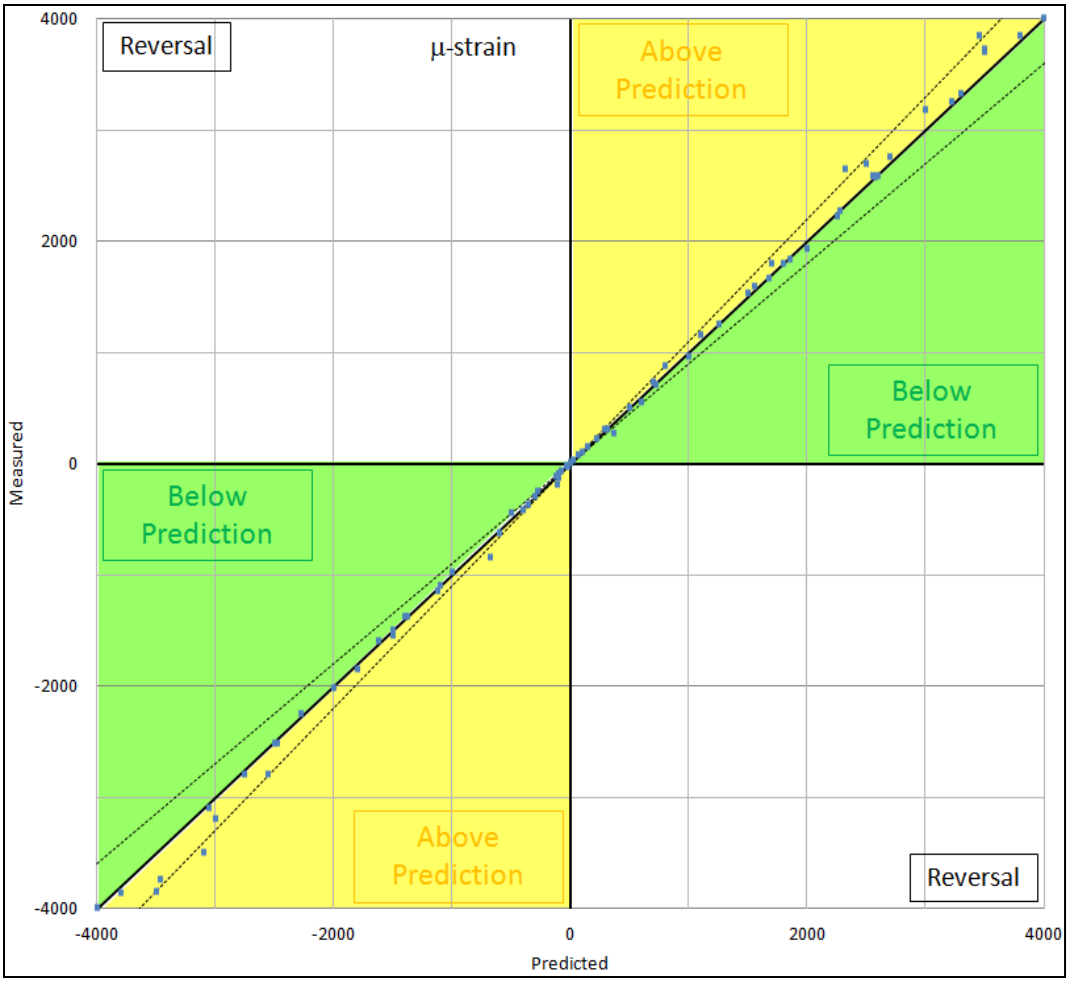

Figure 1 – Sample Correlation Plot with Error Bands

Frequently, predicted versus actual strain readings for structural ground tests are plotted on a chart with correlation bands. These (usually ±5% or ±10%) bands are typically based on the maximum predicted strain reading. Therefore, these bands allow for increasing percent error as values approach zero and therefore can be misleading.

A comparison of correlation bands (based on maximum predicted strain) versus percent error bands (based on local predicted strain) is shown in Figure 2 below. For this example, the local measurement error is 19% at 2000 micro-strain, although it would be shown within a ±10% correlation band.

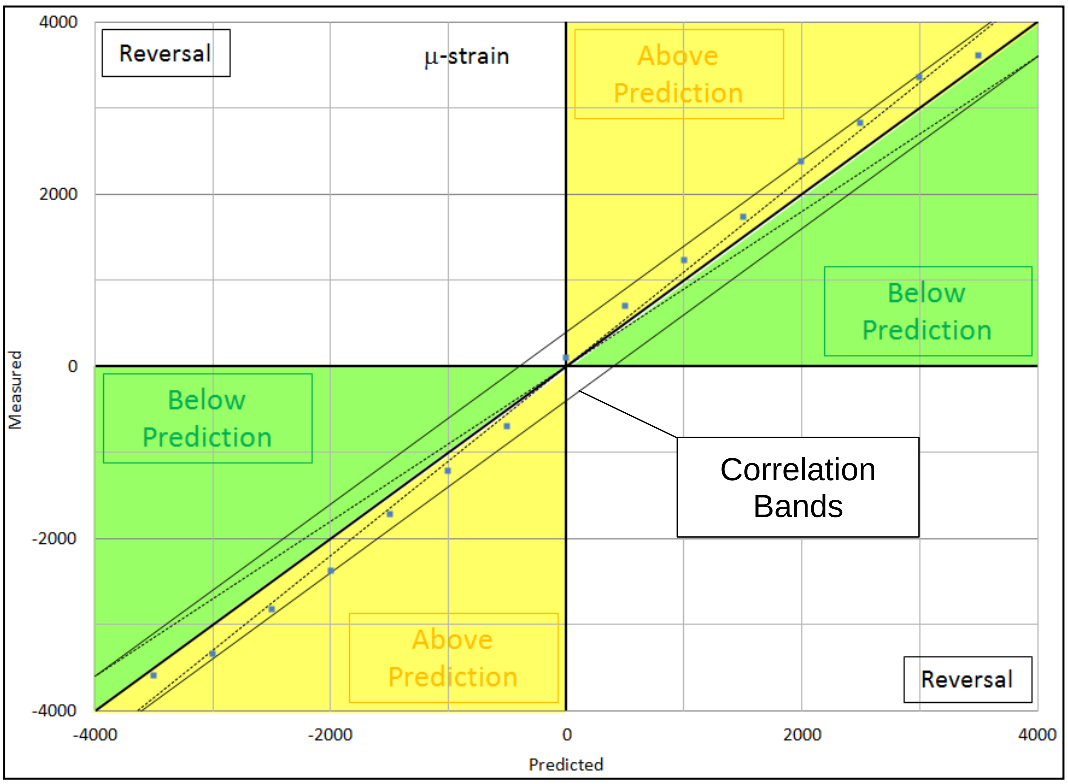

Figure 2 – Sample Correlation Plot with Error Bands and Correlation Bands

(2) Strain Threshold

Strain gage measurements below certain strain thresholds become less reliable due to offset error and desensitized data signals inherent in resolving small changes in the gage resistance for small strain levels. Additionally, any minor compliances in the loading fixture or structure itself that are not modeled in the analysis or other differences between the aircraft structure and the engineering approximations of that structure may render strain readings at low load levels unreliable. For these reasons, strain thresholds should be established below which the percent error calculations that exceed the recommended error limits stated previously (±5% for SOF and ±10% for non-SOF structure) should be given a lower priority for issue resolution. For purposes of FEM correlation, a strain threshold of 25% of the material yield strength is recommended. It should be noted that not all strain gages will be loaded above the strain threshold for all loading cases. Figure 3 shows an example of a single structural element that is fabricated from a material with a yield strain of 5000 micro-strain; therefore, the strain threshold is 1250 micro-strain. So as not to dismiss significant correlation excursions within the strain threshold region, a correlation band can be used in this region. The correlation bands should be based on the maximum predicted strain at the threshold boundaries. Figure 4 displays the strain threshold region of Figure 3 zoomed in and without error bands.

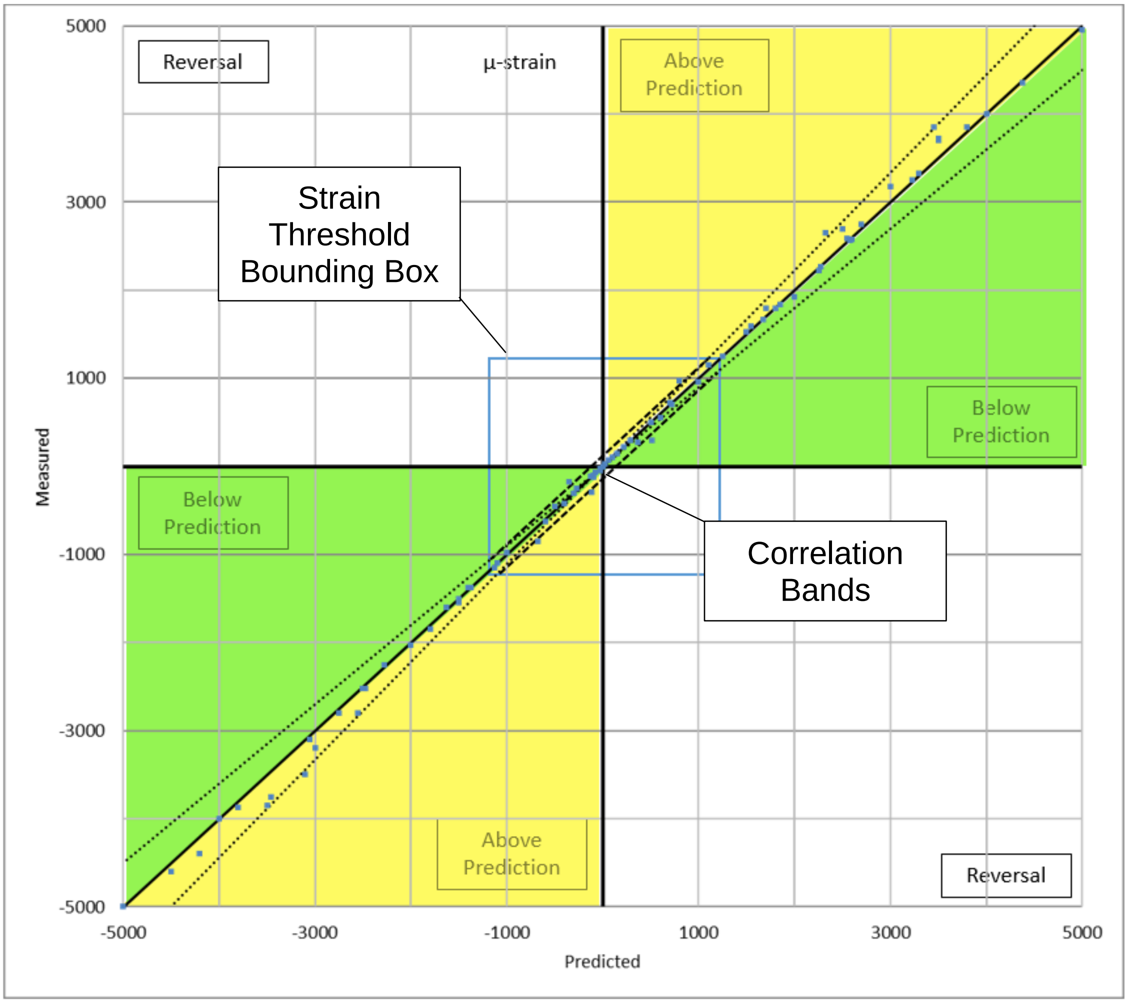

Figure 3 – Sample Correlation Plot with Error Bands, Correlation Bands, and Strain Threshold Box for the Material

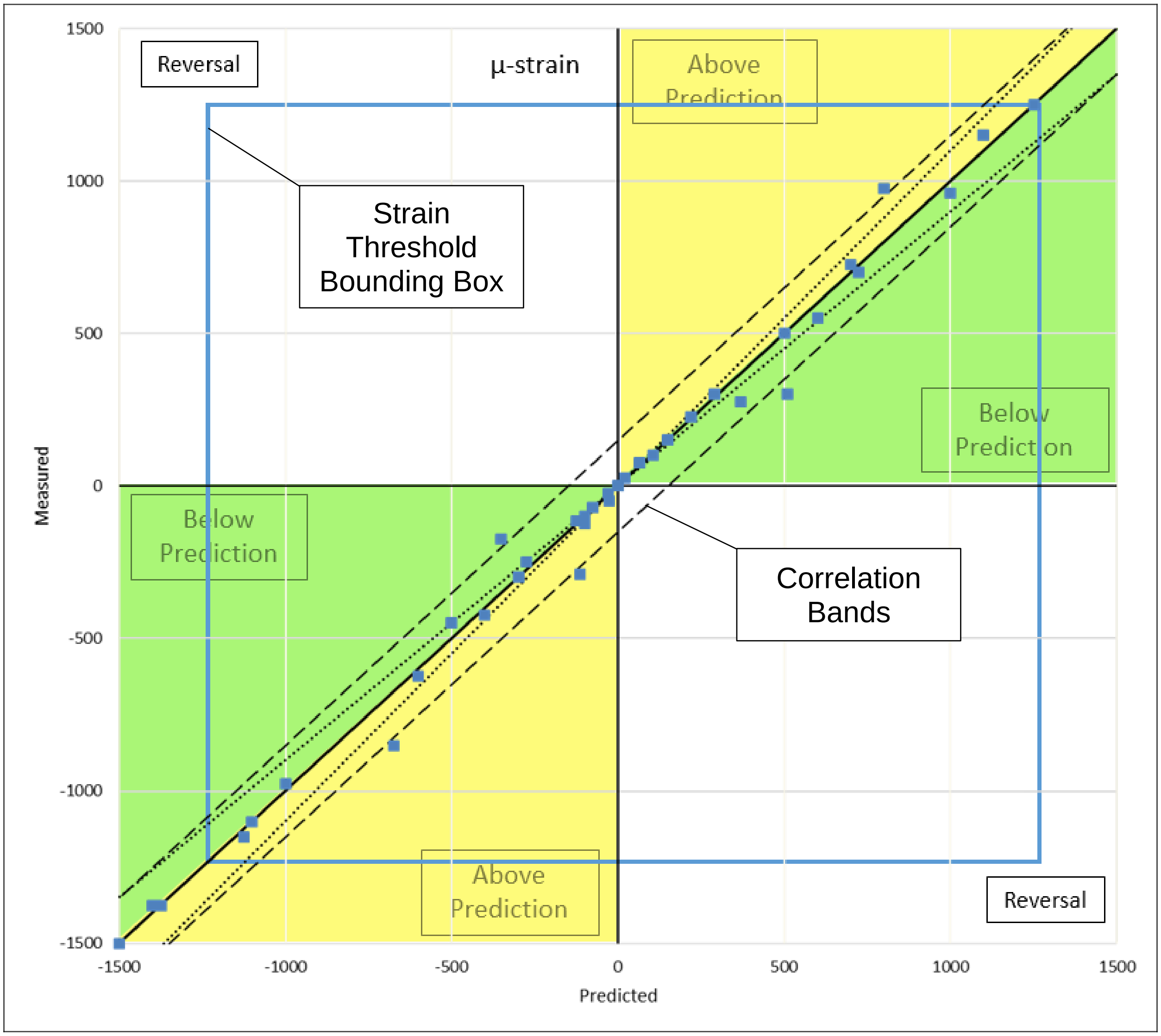

Figure 4 – Zoomed in Sample Correlation Plot with Correlation Bands, with focus on Strain Threshold Box for the Material

(3) Trend

Trends should be examined in SOF, multiple load path structures to ensure that the internal load distribution is well understood. This can be accomplished by plotting the measured versus predicted strain as a function of load level for each individual strain gage and examining the slope of the data. Figure 5 is an example of a strain gage that meets the acceptable error criteria; however, it indicates a trend that the analysis consistently over-predicts the magnitude of the measured strain and warrants an investigation (see Correlation Issue Resolution).

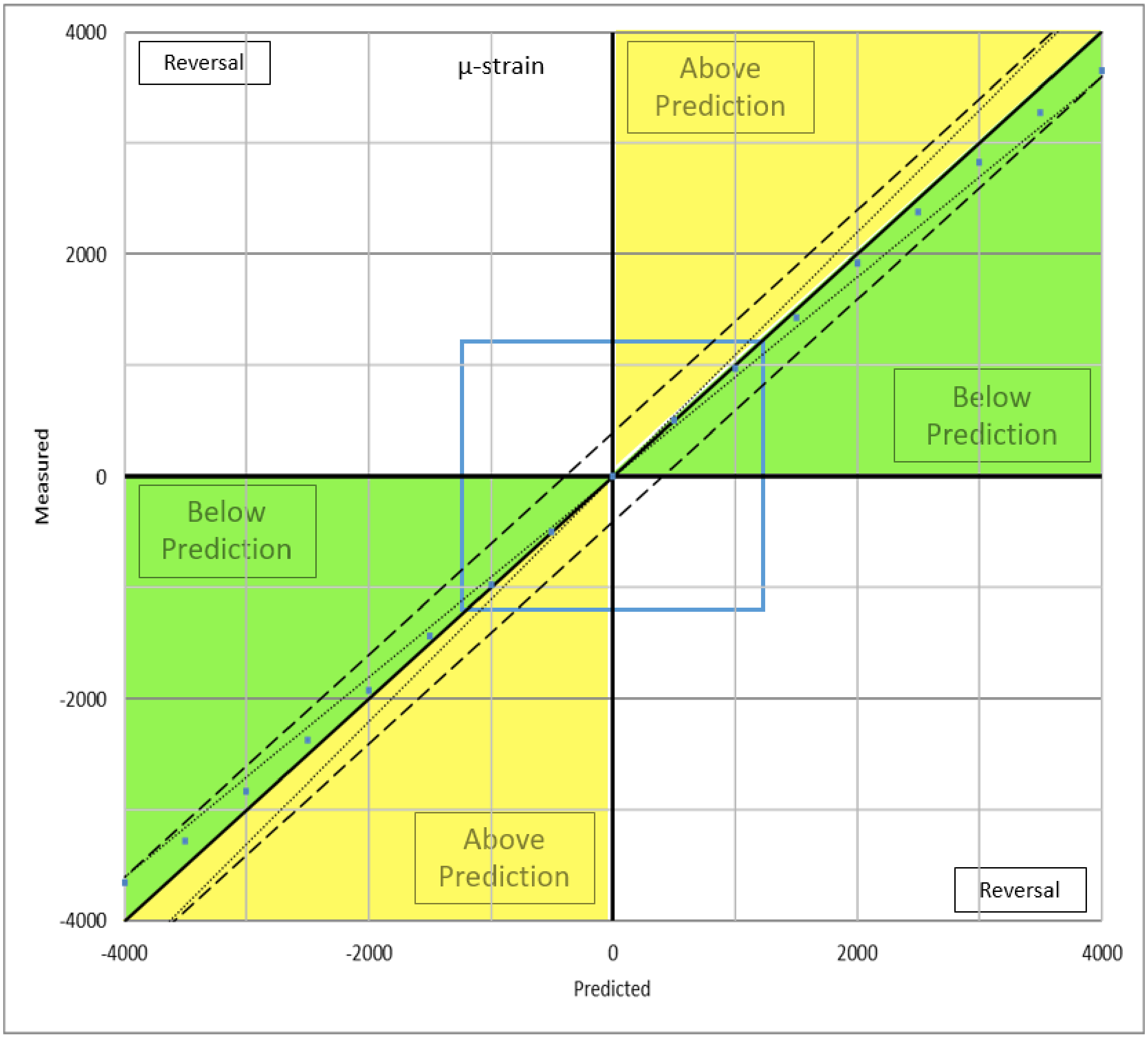

Figure 5 – Sample Trend Plot for Single Gage

Correlation Evaluation

After the initial analysis and test correlation effort has been completed, it must be evaluated to determine if the analysis is valid. If the recommended limit of ±5% for a SOF structure, or ±10% for a non-SOF structure are not met, additional steps must be taken to resolve differences. The following logic diagram (Figure 6) describes an approach that can be followed to evaluate the FEM correlation.

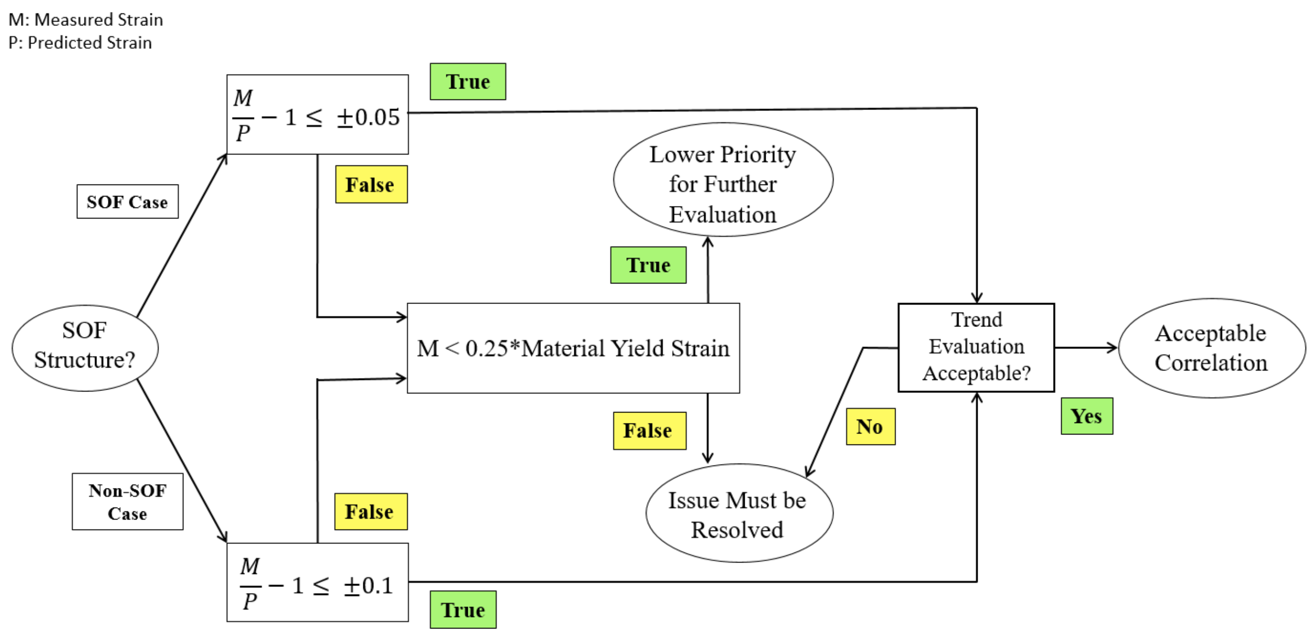

Figure 6 - Guidance for Evaluating a FEM Correlation Effort

Correlation Issue Resolution

If issues are discovered during the correlation effort, they must be resolved. Since errors are likely to exist in either the analysis, the test data, or both; it is important to identify the primary source(s) of error. Common sources of error introduced during test and analysis that can result in correlation issues are provided below.

1) Test Discrepancies

The following are potential sources of correlation error to consider that can be introduced during test and may aid in identifying the root cause of a measurement discrepancy:

- Is the gage location/orientation per the drawing? Were the individual transducer wires checked point-to-point to verify the transducer number matches the transducer location?
- Does a gage located on the same structural member on the opposite side of the aircraft and loaded symmetrically about the two gages provide a similar result?
- Does a back-to-back gage on the same structural member and loaded symmetrically about the two gages provide a similar result?
- Were gages installed on preloaded structure? What state was the structure in when gages were zeroed? How was structure supported/shored when gages were zeroed? Were any gages replaced mid-test such that they were zeroed separately from the rest of the gages?
- Do measured/predicted results for other gages on the same structural member (e.g. – spar cap) provide acceptable correlation results?
- Do measured/predicted results for the other gages on the aircraft component (e.g. – wing) provide acceptable correlation results?
- Were the test loads applied as expected?
- Were there any load cell calibration or drift issues?
- Were load fixtures adequately counterbalanced?
- Was temperature compensation provided or might there be an influence from temperature changes?
- Is the test article geometry/configuration the same as used in the FEM?

2) FEM Discrepancies

The following are potential sources of correlation error to consider that can be introduced in the FEM and may aid in identifying the root cause of an analysis discrepancy:

- Are the correct material properties used?
- Do the boundary conditions match the test article boundary conditions?
- Do the test load application locations and directions match those in the analytical representation, i.e. FEM?
- Are the elements used in the FEM (beam, bar, plate, etc.) representative of the structure
- Is the mesh size density sufficient to demonstrate solution convergence?
- Are modeling assumptions (e.g. – moments of inertia, effective skin width, end fixity, etc.) verified?
- Is the FEM geometry/configuration the same as the test article, including minor details that may influence the results?
- Are built-in residual stresses due to fabrication accounted for in the analysis?
- Are geometric nonlinearity effects accounted for in the analysis?

Summary:

This bulletin provides fundamental guidance and outlines procedures for correlating structural ground test results to analytical predictions. The USAF approach to aircraft structural certification is accomplished primarily through test-validated analysis. Structural testing is primarily accomplished as a means to validate that analytical predictions are reliable and accurate over the full range of structural loading as well as to provide demonstration of performance. The focus of this bulletin is the correlation of structural ground test results (static strength, proof, fatigue strain survey, vibration, and loads calibration) with the FEM based predictions. This bulletin includes test planning considerations for instrumentation and loading, correlation criteria, correlation evaluation, and correlation issue resolution.

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