AIR FORCE STRUCTURES

Structures Bulletin

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Number: EN-SB-11-001

Date: 24 June 2011

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

References:

1. MIL-STD-1530C, *Aircraft Structural Integrity Program*, 1 November 2005.
2. MIL-HDBK-516B, *Airworthiness Certification Criteria*, Department of Defense, 4 February 2010.
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, strain surveys associated with fatigue testing and loads calibration testing.

Introduction:

This bulletin provides guidance and outlines procedures for correlating structural ground test results with analytical predictions. The United States Air Force (USAF) approach to aircraft structural certification is accomplished primarily by analysis validated by test, and is referred to as “Certification Analyses” in MIL-STD-1530C (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 on correlation of instrumentation measurements obtained during structural ground testing (static strength, proof, fatigue, and loads calibration) with FEM-based predictions. This bulletin includes test planning considerations for instrumentation and loading, correlation criteria, correlation evaluation, and correlation issue resolution.

Discussion:

MIL-STD-1530C (Reference 1) provides the basic guidance for evaluating test data and correlation with analysis in Paragraphs 5.3, 5.4, and 5.5 (references to figures and other paragraphs are omitted for clarity).

> 5.3 Full-scale testing (Task III)
>
> "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 USAF. Test results shall be used to validate analytical design data and to verify requirements are achieved."
>
> 5.3.7 Interpretation and evaluation of test results (Task III)
>
> "Each structural problem that occurs during the tests described by this standard shall be analyzed to determine the root cause, corrective actions, force implications, and estimated costs. Examples of structural problems include but are not limited to: analytical shortfalls (measured loads, stresses, vibrations, etc., which differ from predictions), failures, cracking, yielding, corrosion, etc. The scope of and interrelation between the various ASIP tasks within the interpretation and evaluation effort are illustrated on figure 2 and figure 3. The results of these evaluations shall define corrective actions required to demonstrate that the strength, rigidity, damage tolerance, and durability design requirements are met and the associated risk reduction is achieved. The cost, schedule, and other impacts which result from correction of structural problems shall be used to make major program decisions such as major redesign, program cancellation, awards or penalties, and production aircraft buys. Structural modifications or changes derived from the results of the full-scale tests to meet the specified strength, rigidity, damage tolerance, and durability design requirements shall be substantiated by subsequent tests of components, assemblies, or full-scale article, as appropriate."
>
> 5.4.1 Certification analyses (Task IV)
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> "The design analyses described in 5.2 shall be revised to account for differences revealed between analysis and test. Selected design development tests described in 5.2, the full-scale tests described in 5.3, and the interpretation and evaluation of test results described in 5.3.7 shall be used in the certification effort. The design analyses correlated to ground and flight testing establish structural certification and are herein referred to as "certification analyses." The certification analyses provide the engineering source data for the Technical Orders that document the operational limitations/restrictions, procedures, and maintenance requirements to ensure safe

operation. Approval of the certification analyses shall constitute aircraft structural certification, a critical step in achievement of airworthiness certification for the aircraft in accordance with procedures outlined in MIL-HDBK-516 (Reference 2)."

5.5.7 Recertification (Task V)

"Recertification of the aircraft structure shall be performed if significant deviations from the certification baseline occur. Such deviations may include changes to usage, damage, and/or service life expectancy. The recertification analyses shall provide the engineering source data for revision of Technical Orders which document the operational limitations/restrictions, procedures, and maintenance requirements to ensure continuing safe operation. Recertification efforts should consider all ASIP tasks and elements and may require an additional full-scale static and/or durability test."

Correlation of analysis with test data is a common theme throughout JSSG-2006 Appendix A (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

In order to properly establish analysis to test correlation guidance, some of the 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 software programs such as MSC NASTRAN, Patran, ABAQUS, etc.

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 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 that structure whose failure could cause loss of the aircraft or aircrew, or cause inadvertent store release. The loss could occur either immediately upon failure or subsequently if the failure remained 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 so as 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 of potential correlation issues. It must be understood that 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:

- Types
  - Rosette, axial, shear, deflection, etc.
- Quantity
  - Number of channels, consideration for back-up gages, etc.
- Locations
  - Left side and right side, primary load paths, back-to-back, etc.
- Provisions for Additional Instrumentation
  - Spare channels, extra data storage capacity, etc.
- Calibration
  - Manufacturer requirements, thermal compensation, etc.
- Accuracy
  - Manufacturer certification, range of applied loading, etc.
- Linearity Checks
  - Automated evaluation and reporting of issues
- Data Collection Sample Rate
  - Storage buffer, rate during applied loading, etc.
- Data Storage
  - Capacity, time history, load cell feedback, etc.

2) Test Loading Considerations:

- Load Levels and Increments
  - Maximum % limit load, % limit load increments, hysteresis check
- Load Case Selection
  - Loading conditions which provide meaningful instrumentation measurements, etc.
- Load Application and Distribution
  - Whiffle trees, formers, hard points, etc.
- Test Article Restraint
  - Boundary conditions, constraints, load introduction fixtures, transition structure, etc.

Correlation Criteria

The correlation of analysis predictions to structural ground test measurements must consider many factors. Since measurement of strain is 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. Good and bad correlation
2. Higher and lower priority issue resolution efforts
3. Good and bad 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 a correlation is successful is the percentage of error between the analysis and test values. There are four possible equations to calculate the percent error based on what is considered the “truth data” (measured or predicted). 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%

$$(1)\ \%\ \text{Error} = \frac{\text{Measured-Predicted}}{\text{Predicted}} \text{x}100 \qquad (3)\ \%\ \text{Error} = \frac{\text{Measured-Predicted}}{\text{Measured}} \text{x}100$$

$$(2)\ \%\ \text{Error} = \frac{\text{Predicted-Measured}}{\text{Predicted}} \text{x}100 \qquad (4)\ \%\ \text{Error} = \frac{\text{Predicted-Measured}}{\text{Measured}} \text{x}100$$

When performing a correlation effort it is extremely important to know which of the four possible equations is being used to calculate the error. In general, most structural models and analyses are thought of as the truth data, and the test data is collected to validate that the model is predicting correctly. As such, Equation (1) is commonly used since it overstates the % error for measurements higher than predicted and understates the % 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”. Therefore Equation (1) is the preferred choice for computing % error.

A correlation that gives errors no greater than +/- 5% for SOF structure and no greater than +/- 10% for non-SOF structure is generally considered acceptable and therefore further evaluation is limited to the review of trends (see Figure 3 below) and strain gage linearity for stability-critical structure. Errors greater than these limits require correlation issue resolution described below. Acceptable error limits may be subject to debate in an effort to minimize cost and schedule associated with correlation issue resolution. If increasing the acceptable error limits is considered, a careful evaluation of all implications must be performed on a case-by-case basis. For example, considering the increase of a limit for a structural component due to high static strength margin must consider that the: static strength analysis may be incorrect, durability and damage tolerance analysis may be more sensitive to errors, buckling analysis may be more sensitive to errors, etc. The error limits included in this bulletin attempt to account for these variable issues and therefore are the recommended values to be used in the correlation evaluation described below.

An example plot in Figure1 shows data for gages on an aircraft component for all test load conditions. The plot shows that the majority of the data is within the acceptable error bands and shows 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 % error bands are drawn at 5%. Note that this type of plot also makes data above and below predictions obvious and makes reversals of data clear.

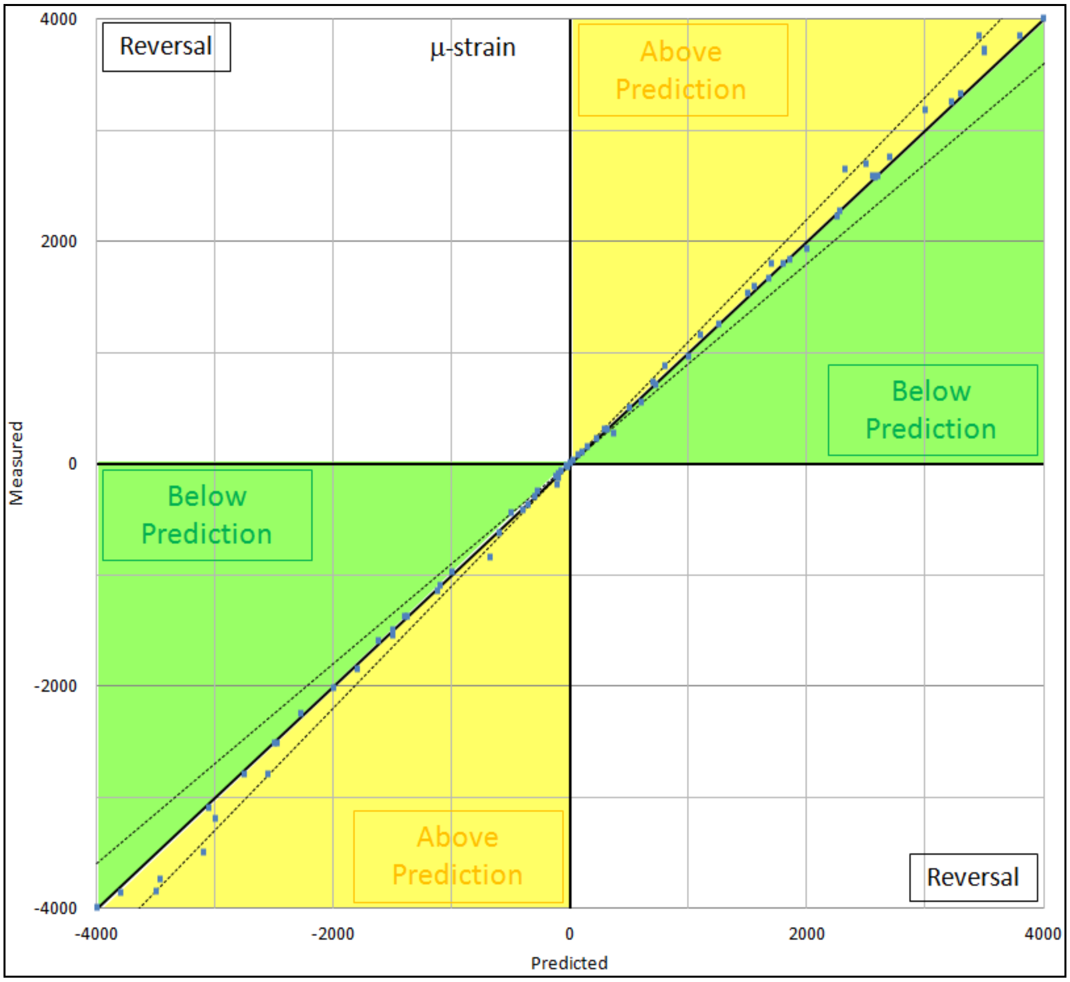

Figure 1 – Sample Correlation Plot with Error Bands

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 use of correlation bands versus percent error bands is shown below in Figure 2. For this example, the actual percent error is 19% at 2000 micro-strain, although it would be shown within a 10% correlation band.

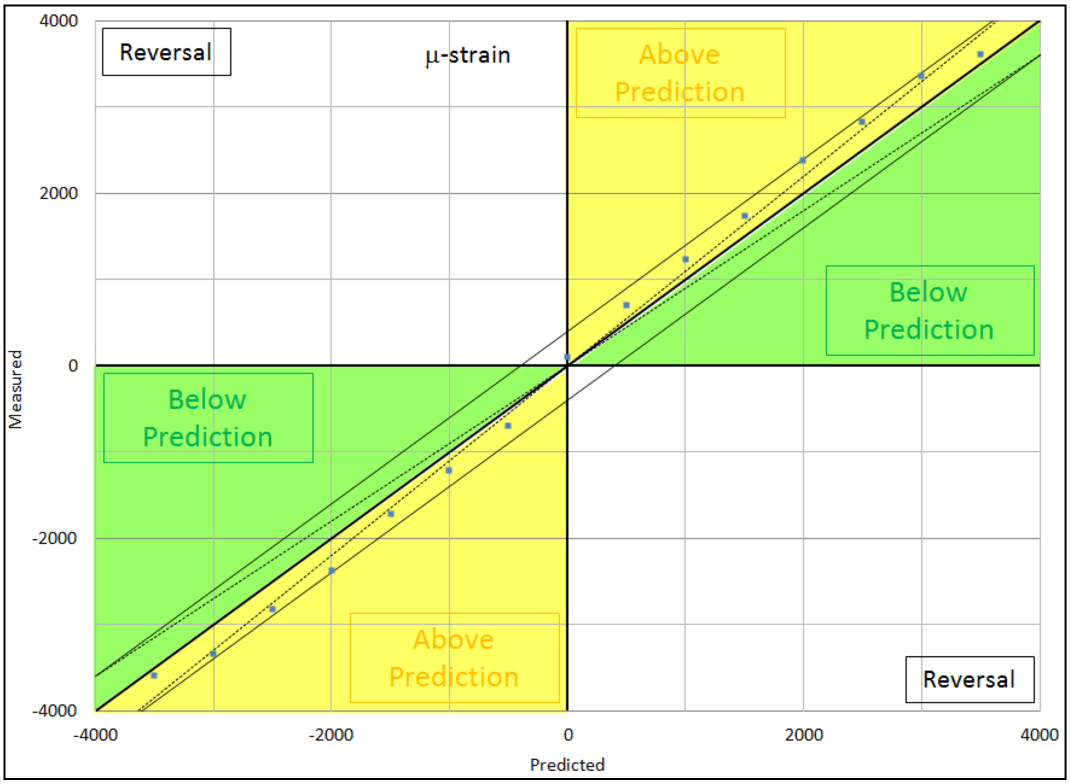

Figure 2 – Sample Correlation Plot with Correlation Bands and Error Bands

(2) Strain Threshold

Below certain thresholds, strain measurements become less reliable and less important. For these reasons, strain thresholds should be established below which the percent error calculations that exceed the acceptable error limits stated above should be given a lower priority for issue resolution. For purposes of FEM correlation, a strain threshold of 25% of the material yield strength shall be utilized. It should be noted that not all strain gages will be loaded above the strain threshold for all loading cases. The example below shows a single structural element that is fabricated from a material with a yield strain of 5000 micro-strain, and therefore the strain threshold is 1250 micro-strain.

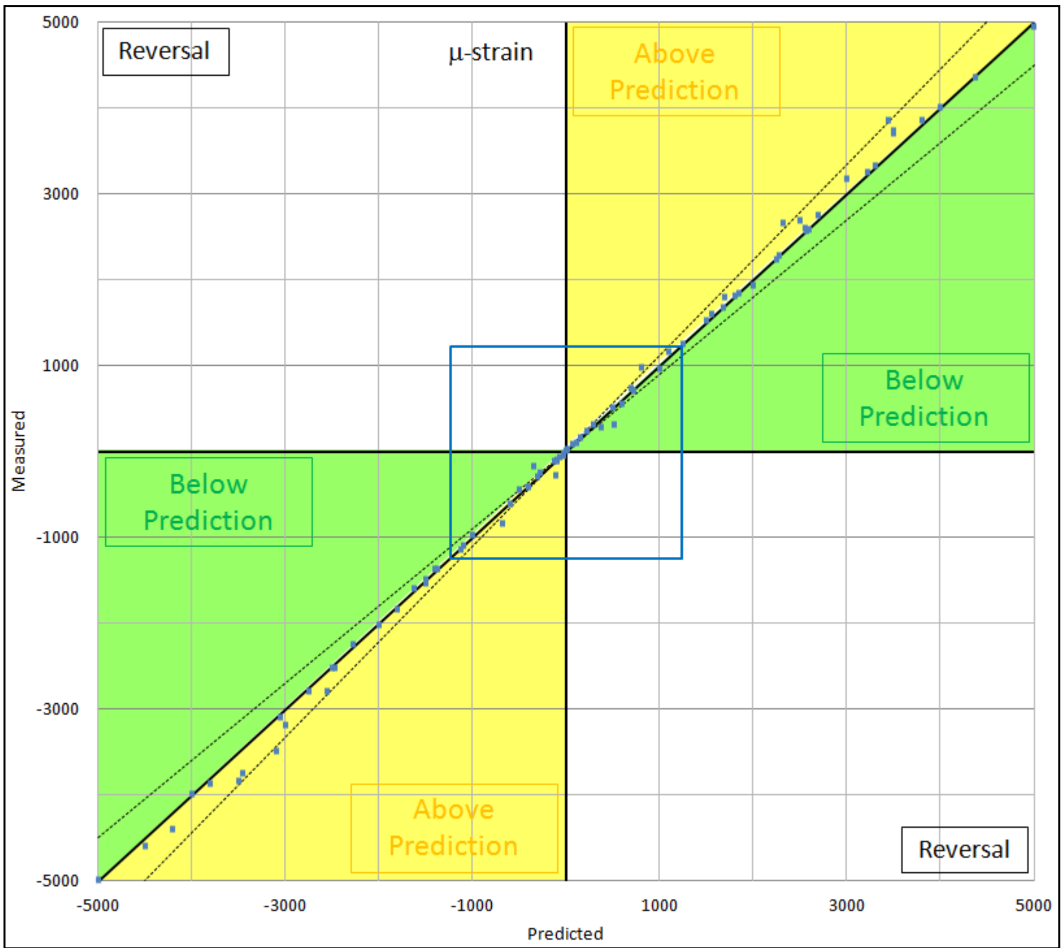

Figure 3 – Sample Correlation Plot with Strain Threshold Box for the Material

(3) Trend

Trends should be examined in SOF multiple load path structure 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 4 below is an example of a strain gage that meets the acceptable error criteria; however, it indicates a trend that warrants investigation into unanticipated internal load distribution of adjacent structure (see Correlation Issue Resolution).

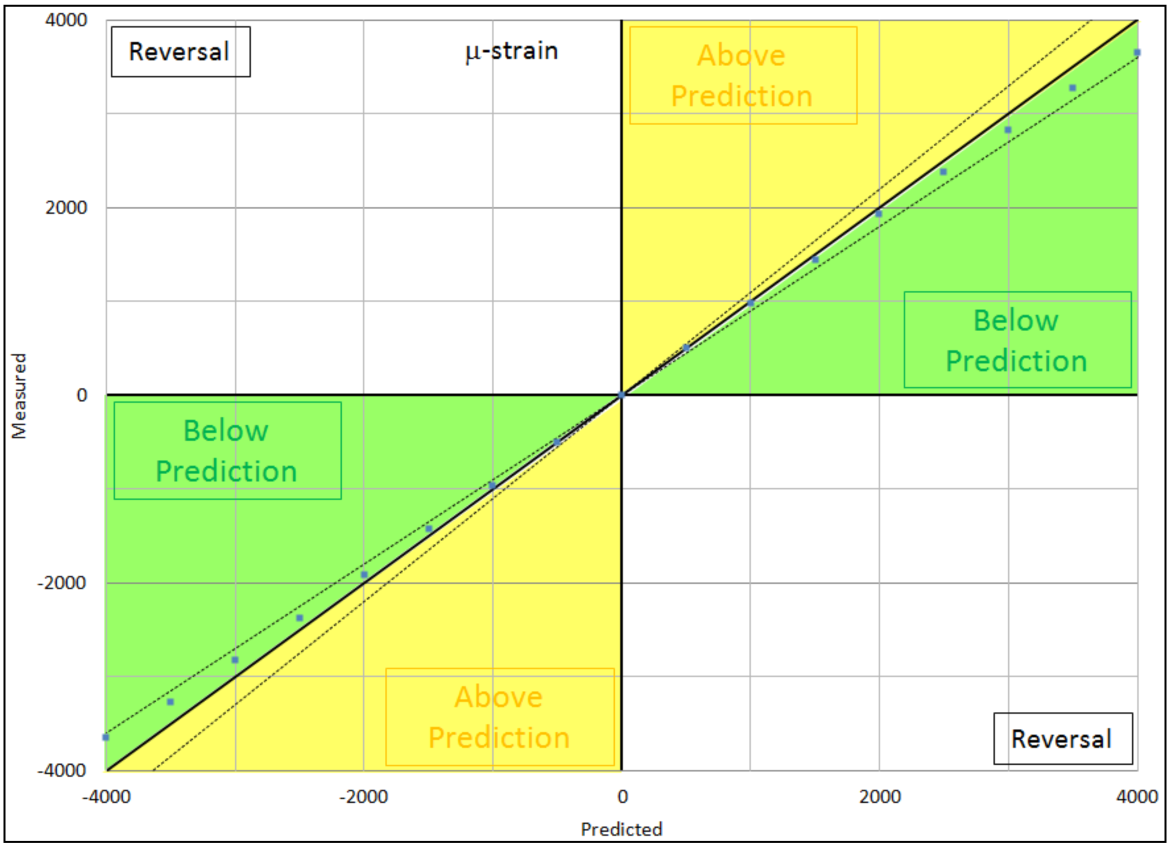

Figure 4 – Sample Trend Plot for Single Gage

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 criteria are not met, certain steps must be taken to resolve the differences. The following logic diagram (Figure 5) describes an approach that should be followed to evaluate the FEM correlation.

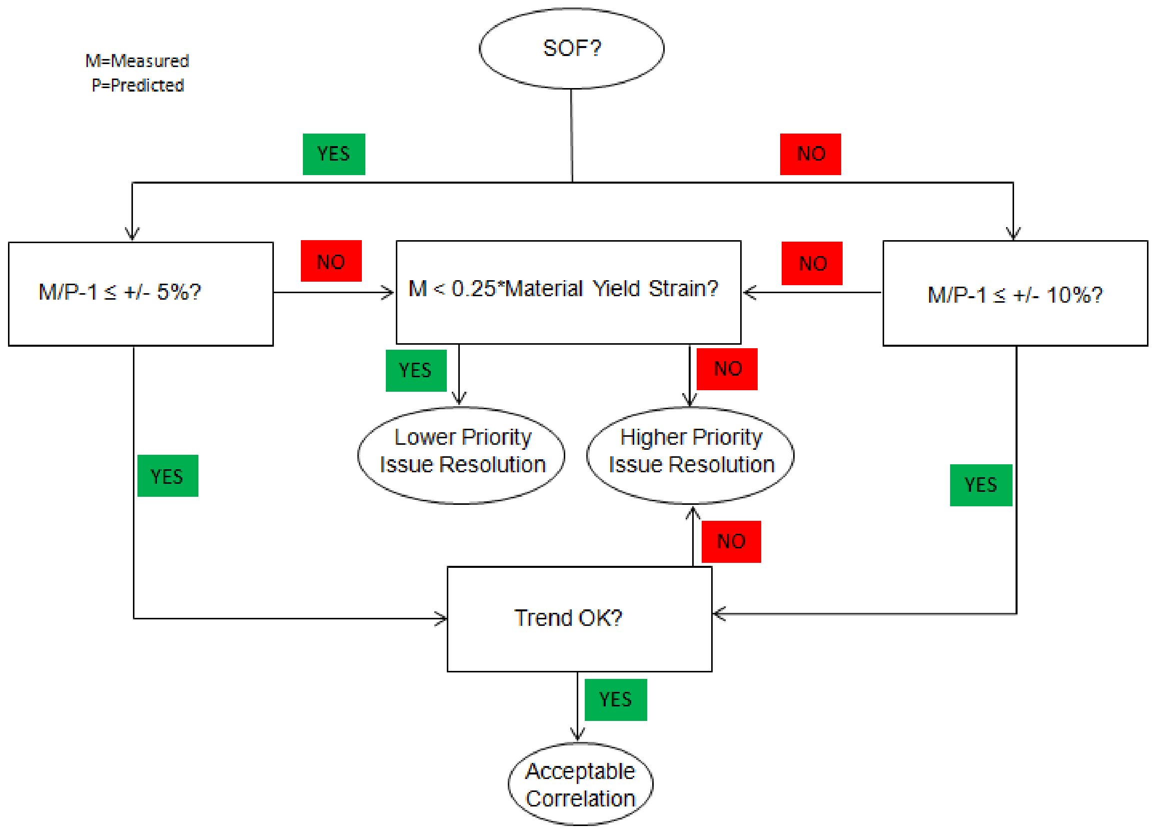

Figure 5 - Guidance for Evaluating a FEM Correlation Effort

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. Suggested checks to determine if the correlation issue is due to test, analysis, or both are provided below.

1) Test Discrepancies

The following are suggested checks to consider that may identify the root cause to be a measurement discrepancy:

- Is the gage location/orientation per the drawing?
- Does a gage located on the same structural member on the opposite side of the aircraft provide a similar result?
- Does a back-to-back gage on the same structural member provide a similar result?
- Do Measured/Predicted results for other gages on the same structural member (e.g. – spar cap) provide similar results?
- Do Measured/Predicted results for the other gages on the aircraft component (e.g. – wing) provide similar results?
- Were the test loads applied as expected?
- Is the test article geometry/configuration the same as used in the FEM?

2) FEM Discrepancies

The following are suggested checks to consider that may identify the root cause to be an analysis discrepancy:

- Are the correct material properties used?
- Are boundary conditions applied correctly?
- Are the test loads applied to the FEM correctly?
- Are proper elements used (beam, bar, plate, etc.) to represent the structure
- Is the mesh size sufficient?
- 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?

Summary:

This bulletin provides guidance and outlines procedures for correlating structural ground test results with analytical predictions. The USAF approach to aircraft structural certification is accomplished primarily by analysis validated by test. The focus of this bulletin is on correlation of structural ground test results with 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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