Designation: F3601 – 23

Standard Practice for Structural Finite Element Model Verification and Validation[1]

This standard is issued under the fixed designation F3601; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice provides guidance for verification and validation of structural finite element models (FEMs) that are used to support showings of compliance with Civil Aviation Authority (CAA) regulations. This encompasses FEM predictions of internal loads, displacements, strains, stresses, stability, and post-buckling loads.

1.2 This practice applies to normal category aeroplanes with a certified maximum take-off weight of 19 000 lb (8618 kg) or less and a passenger seating configuration of up to 19. Use of the term aircraft throughout this specification is intended to allow the relevant CAA(s) to accept this practice as a means of compliance for other aircraft as they determine appropriate.

1.3 Code verification for FEM software is not included in the scope of this practice. It is expected, however, that the developer of software that is used to support showings of compliance has applied appropriate software quality assurance and numerical algorithm verification processes, including benchmark cases, to verify the accuracy and consistency of the solutions. Evidence of these activities should be recorded and documented and made available to the applicant and CAA upon request.

1.4 The applicant for a design approval should verify CAA acceptance of this practice before using it to support showings of compliance. For information on which CAA regulatory bodies have accepted this practice (in whole or in part) as a means of compliance to airworthiness standards: normal category aeroplanes (hereinafter referred to as "the Rules"), refer to the ASTM F44 webpage (www.ASTM.org/COMMITTEE/F44.htm), which includes CAA website links.

1.5 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

F3060 Terminology for Aircraft

F3114 Specification for Structures

2.2 *Federal Standard:*[3]

14 CFR Part 23 Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes

3. Terminology

3.1 *Definitions*— The following definitions are a selection of relevant terms. See Terminology F3060 for more definitions and abbreviations.

3.1.1 *external loads, n*—loads, external from the structure or what is being modeled, that are applied to the structure or finite element model (FEM) as a real-life event or part of a *load condition* (see 3.1.6).

3.1.2 *finite element model, FEM, n*—mathematical approximate representation of a real structure.

3.1.2.1 *Discussion*—The structural stiffness of the part or parts are represented as an equivalent stiffness matrix. A numerical solution is performed on the FEM to determine output given imposed loads, displacements, and boundary conditions.

[1] This practice is under the jurisdiction of ASTM Committee F44 on General Aviation Aircraft and is the direct responsibility of Subcommittee F44.30 on Structures.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from Federal Aviation Administration (FAA), 800 Independence Ave., SW, Washington, DC 20591, http://www.faa.gov.

3.1.3 *finite element model (FEM) validation, n*—task of demonstrating that the FEM predicted internal loads or deformations or both match or conservatively predict the real structure internal loads or deformations or both as measured in a test article or as predicted by other analytical means within an acceptable range of accuracy.

3.1.4 *finite element model (FEM) verification, n*—task of demonstrating that the FEM represents the engineering defined structure that is being analyzed to the degree necessary to obtain the desired results.

3.1.4.1 *Discussion*—This includes ensuring the FEM solver does not produce errors based on the input. The errors could be computer "run errors" or errors from improper or incorrect modeling. The input includes all items defined by the user, such as the node and element definitions, material properties, loads, boundary conditions, and so forth. The verification should include any variations of the FEM (including variations to match validation testing).

3.1.5 *internal loads, n*—loads (forces and moments), internal to a structural element regardless whether that element is a part of the FEM or the real structure.

3.1.5.1 *Discussion*—This is terminology commonly used by a stress analyst to distinguish from external loads (such as aerodynamic pressures, actuation loads, temperatures, and so forth).

3.1.6 *load condition, n*—set of external loads (forces, moments, pressures, temperatures, and so forth) applied to a FEM or real structure to simulate a real-life event, for example, a vertical gust or maneuver.

4. Significance and Use

4.1 This practice provides guidance for verification and validation of structural FEMs that are used to support showings of compliance with CAA regulations.

4.2 This practice is a companion to Specification F3114.

5. General

5.1 Experience has shown the finite element technique, in a general sense, to be a reliable method of internal loads analysis for aircraft structures.

5.2 Experience has also shown that each specific FEM should be sufficiently verified and validated to ensure that the results obtained from it are within acceptable accuracy for use in showings of compliance.

5.3 Before using a FEM to support a showing of compliance with CAA regulations, complete the verification checks in Section 6 and the validation checks in Section 7.

6. Verification

6.1 Perform verification checks before using a FEM to support a showing of compliance with CAA regulations. The verification process outlined in 6.2 – 6.4 serves as a baseline for a linear static solution and should be adjusted, as applicable, depending on the type and complexity of the FEM and its intended use.

6.2 *Document Verification Checks*—Document verification checks in the applicable compliance document(s). Include verification checks for any variations of the FEM (including variations to match validation testing). Include the following information and/or other applicable information:

6.2.1 Listing of type design data (including materials) to which the FEM conforms along with discussion of simplifications or other deviations of the FEM from the type design data;

6.2.2 Listing of material data sources used in the FEM [*Materials Properties Development and Standardization (MMPDS) Handbook-10*,[4] company tests, and so forth];

6.2.3 Figure(s) of overall FEM;

6.2.4 Figure(s) of loads and constraints, including rigid elements, with descriptions;

6.2.5 Listing(s) of materials and properties;

6.2.6 Figure(s) of fastened joint representations;

6.2.7 Figure(s) of overall deformation for critical load conditions;

6.2.8 Figure(s) of buckling mode shapes for critical load conditions;

6.2.9 Figure(s) of post-buckling deformation for critical load conditions;

6.2.10 Figure(s) of stresses, strains, deformations, and/or internal loads for critical load conditions; and

6.2.11 Checklist(s) of pre- and post-processing checks listed in 6.3 and 6.4.

6.3 *Preprocessing Checks*—Complete the following checks and/or other applicable checks before running a FEM.

6.3.1 All nodes are correctly located.

6.3.2 No nodes are free.

6.3.3 No nodes are coincident with other nodes (unless intentional).

6.3.4 All elements are connected to correct nodes.

6.3.5 All elements are of acceptable sizes, types, and quality.

6.3.6 All elements have correct offsets.

6.3.7 All elements have correct and consistent normals, or orientations, or both.

6.3.8 All elements have correct first-edge directions.

6.3.9 All elements have correct material directions.

6.3.10 All elements have correct properties (matching as-tested values or design values as appropriate).

6.3.11 No elements are coincident with other elements (unless intentional).

6.3.12 All multipoint constraints (rigid elements) have correct degrees of freedom.

6.3.13 No multipoint constraints (rigid elements) are the sole connection to a node unless it is a load application node.

6.3.14 All properties have correct materials.

6.3.15 All properties have correct material directions.

6.3.16 All properties have correct dimensions (thickness, I1, I2, and so forth).

6.3.17 All laminate properties have correct materials, stacking sequence, orientations, thicknesses, and interlaminar values or have correct layups (if used).

[4] *Metallic Materials Properties Development and Standardization (MMPDS) Handbook-10*, available from SAE International, https://www.sae.org/publications/books/content/b-980/.

6.3.18 All layups (if used) have correct materials, stacking sequence, orientations, thicknesses, and interlaminar values.

6.3.19 All materials have correct stiffness values.

6.3.20 All part connections (such as fasteners) are correctly modeled (with proper transverse, axial, and bending stiffnesses, and continuities across layers, as applicable).

6.3.21 All load locations, values, and directions (including pressure loads, thermal loads, and so forth) are correct. Test cases used for validation match test loads.

6.3.22 Thermal reference temperatures are correct.

6.3.23 Summations of applied loads are correct. Pressure loads sum to zero or near zero for enclosed volumes. Flight loads sum to zero or near zero for statically balanced conditions.

6.3.24 All constraint locations and degrees of freedom are correct. Design cases are constrained in a way that does not have an appreciable effect on results in areas of interest. Test cases used for validation match test constraints.

6.3.25 Solver settings are appropriate to the solution desired and troubleshooting settings such as BAILOUT or AUTOSPC are properly accounted for or are not used.

6.4 *Post-Processing Checks*—Complete the following checks and/or other applicable checks after running a FEM for each critical load case.

6.4.1 No fatal run errors and any run warning messages are acceptable.

6.4.2 Total applied load matches intended input load.

6.4.3 Total constraint force is equal and opposite to the total applied load.

6.4.4 No loaded free nodes.

6.4.5 Displacements and connectivity are as expected.

6.4.6 Modal results are as expected.

6.4.7 Buckling results, including mode shapes, are as expected.

6.4.8 Internal loads, stresses, and strains are as expected.

7. Validation

7.1 Perform validation checks before using a FEM to support a showing of compliance with CAA regulations. The validation process in 7.2 – 7.5 serves as a baseline for a linear static solution and should be adjusted, as applicable, depending on the type and complexity of the FEM and its intended use. Where classical analysis methods can accurately predict deflections, buckling eigenvalues and modes, and internal loads (which is sometimes the case for less complex models), they may be used in place of testing for validation. When testing is used for validation, new or historic test data or both may be used.

7.2 *Document Validation Checks*—Document validation checks in the applicable compliance document(s). Include the following information and/or other applicable information:

7.2.1 Reference to verification checks (see Section 6),

7.2.2 Listing of test article deviations from type design data,

7.2.3 Discussion addressing errors and uncertainties (see 7.4),

7.2.4 Picture(s) of overall deformation,

7.2.5 Picture(s) of areas of interest from the testing,

7.2.6 Figure(s) and table(s) of strain and deformation results and correlation,

7.2.7 Figure(s) and table(s) of buckling load results and correlation, and

7.2.8 Justifications for correlation exceedances that are deemed acceptable (see 7.5).

7.3 *Locating Gauges:*

7.3.1 During test planning, select an appropriate number of strain or deflection locations or both to measure. The quantity required varies with the size and purpose of the FEM.

NOTE 1—Individual gauges are discussed in 7.3.2 – 7.3.5. However, alternative methods (such as digital image correlation (DIC), and so forth) are acceptable if they provide measurements of acceptable accuracy in areas of interest.

7.3.2 Place deflection gauges at high-stiffness fittings to measure rigid body motion for tests that are not rigidly constrained. For tests that are rigidly constrained, ensure that the "zero displacement" location is not displacing (or measure it if it is). If deflection curvatures of surfaces are sought, include at least four deflection gauges approximately evenly spaced along the span on each structural member for which deflection curvature information is desired.

7.3.3 Locate strain gauges in areas of high strain with low-strain gradients, that is, away from holes, cutouts, and so forth. Locate strain gauges in areas of constant structural sizing. Avoid steps, joggles, ply drop-offs, tapers, and so forth. Do not locate strain gauges near load application points. For post-buckled structure, locate gauges both on predicted unbuckled areas (such as on skin over stiffener centerlines) and locations of maximum predicted bending. In areas of local bending, use back-to-back strain gauges so as to be able to separate the axial and bending portions of the total strains. Orient gauges as desired (often aligned with geometry, direction of maximum principal strain, fiber direction, etc.).

7.3.4 Locate sufficient strain gauges across the structure to ensure the ability to determine the load distribution. For instance, for a stiffened wing skin panel, at a given spanwise station, locate strain gauges on each stiffener centerline, one on the skin and one on the stiffener cap.

7.3.5 In addition to gauges used for general correlation, strain gauges can be placed in peak strain locations (door cutout corners, window cutout corners, and so forth) of interest. Do not use these gauges for general correlation.

7.4 *Address Errors and Uncertainties:*

7.4.1 Address errors and uncertainties in test article physical properties and test measurements. This should include proper calibration of test equipment, test article and test setup conformities, evaluation of measurement tolerances, and so forth.

7.4.2 Practical and acceptable ways of addressing analytical uncertainties include:

7.4.2.1 The use of safety factors such as those defined in CAA regulations for ultimate loads, casting factors, fitting factors, and so forth.

7.4.2.2 Parametric variation of key parameters that govern the physical phenomenon and the simulation process.