Notification of a Proposal to issue a Certification Memorandum

Modelling & Simulation – CS-25 Structural Certification Specifications

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Log of issues

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1. Introduction

1.1. Purpose and scope

The purpose of this CM is to provide guidance on the main certification aspects to be considered when using Modelling & Simulation (M&S) techniques based on computational Finite (Element, Difference, Volume) Methods[1] to support the showing of compliance with structural certification specifications of CS-25. This CM is not intended to provide detailed guidance, nor to provide best practices, on how to actually use these M&S techniques for specific applications, but rather focuses on important certification aspects of M&S such as verification and validation, errors and uncertainties, extrapolation and similarity, experience and expertise, and documentation and record keeping.

The approach often called Certification (and Qualification) by Analysis[2], or C(Q)bA, a term used to indicate the drive towards increased reliance on M&S techniques often accompanied by a reduction in physical testing, is becoming more and more widespread throughout the aerospace industry. This trend requires more attention to the quality and validity of the application of these techniques to ensure the overall credibility of the M&S process, which is the main reason for publishing this CM.

This CM focuses on CS-25 (Large Aeroplanes) structural certification specifications, although many of the considerations contained in this CM would apply to other disciplines and other Certification Specifications as well.

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[1] Other techniques such as Multi-Body Simulations are not specifically addressed in this CM

[2] Other terms often used include Simulation Based Certification, Virtual Certification, Smarter Testing or Certification by Analysis Supported by Test

1.2. References

In addition to the CS-25 certification specifications and guidance material mentioned in this CM, it is intended that the following references be used in conjunction with this CM:

No.	Reference	Title	Issue	Date
1	ResearchGate	Numerical Solutions for Large Deformation Problems in Geotechnical Engineering, J. Konkol		2014
2	elib.dlr.de	Innovative SPH methods for aircraft ditching, P. Groenenboom et al.		2014
3	Cambridge	Verification and Validation in Scientific Computing, W. Oberkampf and C. Roy		2010
4	SAND2015-7455	V&V Framework, K. Salari and P. Knupp		2015
5	ASME V&V 10-2006	Guide for Verification and Validation in Computational Solid Mechanics		2007
6	AC 20-146	Methodology for Dynamic Seat Certification by Analysis for Use in Parts 23, 25, 27, and 29 Airplanes and Rotorcraft	A	2018
7	SAND2003-3769	Verification, Validation, and Predictive Capability in Computational Engineering and Physics, W. Oberkampf et al.		2003
8	(presentation)	Verification and Validation in Computational Simulation, W. Oberkampf		2004
9	SAND2000-1444	Code Verification by the Method of Manufactured Solutions, K. Salari and P. Knupp		2000
10	SAE ARP 5903	Droplet Impingement and Ice Accretion Computer Codes		2003
11	(presentation)	Verification and Validation of Models and Analyses: a must for the aeronautical industry, J-F Imbert		2012
12	International Journal for Numerical Methods in Engineering	A Spectral-Element Method for Modeling Cavitation in Transient Fluid-Structure Interaction, M. Sprague, and T. Geers		2004
13	(website)	https://community.sw.siemens.com/s/article/modal-assurance-criterion-mac		2019
14		FAA Generic IP on Finite Element Model Validation		(unknown)
15	(presentation)	Finite Element Modeling and Analysis Validation Requirements and Methods, P. Safarian		2017

No.	Reference	Title	Issue	Date
16	(presentation)	Uncertainty Quantification and Validation Assessment, B. Thacker		2016
17	Journal of Mechanical Design	Toward a Better Understanding of Model Validation Metrics, Y. Liu et al.		2011
18	AIAA-G-077-1998 (2002)	Guide for the Verification and Validation of Computational Fluid Dynamics Simulations		2002
19	ASME PTC 19.1-2005	Test Uncertainty		2005
20	ISO/IEC Guide 98-3:2008	Uncertainty of Measurement — Guide to the Expression of Uncertainty in Measurement (GUM)		2008
21	(website)	https://www.grc.nasa.gov/www/wind/valid/tutorial/errors.html		2008
22	Hermosa Publishers	Verification and Validation in Computational Science and Engineering, P. Roache		1998
23	EU Research: AeroGust	Uncertainty Quantification of Aeroelastic Systems with Structural or Aerodynamic Non-linearities		2018
24	Altair	Crash Analysis with RADIOSS – a Study Guide		2015

1.3. Abbreviations

AC	Advisory Circular
AIAA	American Institute of Aeronautics and Astronautics
ALE	Arbitrary Lagrangian-Eulerian
AMC	Acceptable Means of Compliance
ASME	American Society of Mechanical Engineers
CAD	Computer Aided Design
CEL	Coupled Eulerian-Lagrangian
CFD	Computational Fluid Dynamics
c.g.	Centre of Gravity
CM	Certification Memorandum
C(Q)bA	Certification (Qualification) by Analysis
CSD	Computational Structural Dynamics
CSM	Computational Structural (or Solid) Mechanics
CS	Certification Specification
DES	Detached Eddy Simulation
DIC	Digital Image Correlation
DNS	Direct Numerical Solution
DOA	Design Organisation Approval
EASA	European Union Aviation Safety Agency
EOS	Equation of State
F&DT	Fatigue & Damage Tolerance
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FEM	Finite Element Method

FM	Finite Method
FSI	Fluid-Structure Interaction
FVM	Finite Volume Method
GCI	Grid Convergence Index
HIC	Head Injury Criteria
IP	Issue Paper (FAA)
LES	Large Eddy Simulation
LoI	Level of Involvement
M&S	Modelling & Simulation
MES	Method of Exact Solutions
MMS	Method of Manufactured Solutions
NAV	Numerical Algorithm Verification
PDE	Partial Differential Equation
PIRT	Phenomena Identification and Ranking Technique
PCMM	Predictive Capability Maturity Model
RANS	Reynolds Averaged Navier-Stokes
ROM	Reduced Order Modelling
SDM	Simulation Data Management
SPH	Smoothed Particle Hydrodynamics
SQA	Software Quality Assurance
V&V	Verification & Validation
VOF	Volume of Fluid

1.4. Definitions

To provide a better understanding of this CM, several definitions are given in this paragraph. It is recognised that for some of these definitions no generally accepted description is available, and the following should therefore be read within the scope and context of this CM.

Verification
The process of determining that a computational model accurately represents the underlying mathematical model and its solution.

> Code Verification – establish confidence, through the collection of evidence that the mathematical model and solution algorithms are working correctly.
> Calculation Verification - establish confidence, through the collection of evidence, that the discrete solution of the mathematical model is accurate.

Validation
The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

Calibration
The process of adjusting physical modelling parameters in the computational model to improve agreement with experimental data.

Modelling & Simulation (M&S)
Modelling and Simulation (M&S) is the use of a (conceptual, mathematical or numerical) model as a basis for simulation by computational means of physical phenomena. Modelling is the act of constructing a model; simulation is the execution of a model to obtain analytical results.

Computational Mechanics
- Computational Solid or Structural Mechanics (CSM)
- Computational Structural Dynamics (CSD)
- Computational Fluid Dynamics (CFD)

The field of Computational Mechanics is concerned with solving problems on the basis of numerical approximation methods, involving discretization (see Finite Methods below) of the underlying equations in space and/or time.

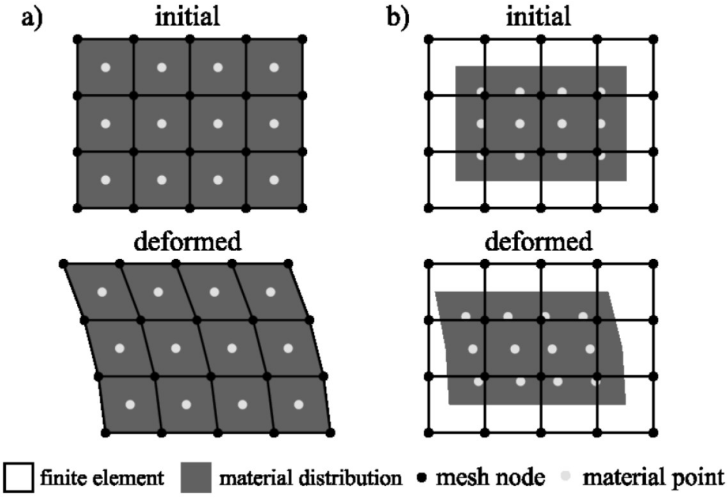
Computational Finite Methods
- Finite Element Method (FEM)
- Finite Difference Method (FDM)
- Finite Volume Method (FVM)

Partial Differential Equations (PDEs) can be used to describe a wide variety of phenomena such as impact dynamics, elasticity, fluid dynamics and heat transfer. These PDEs are derived from the laws of conservation, i.e. conservation of mass, momentum and energy. In order to be able to solve these PDEs numerically, some form of discretization is needed. Finite Methods can be used to perform this discretization.

The two most commonly classical Finite Methods used in aerospace applications are the Finite Element Method (FEM) and the Finite Volume Method (FVM). Both these methods use the integral form of the governing equations, as opposed to the Finite Difference Method (FDM) that uses the differential form. Once the PDEs have been discretized, numerical analysis techniques can be applied to solve the resulting equations.

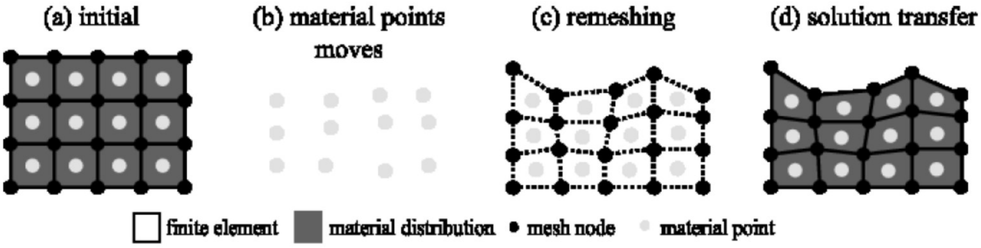
Spatial Discretization (Mesh Based versus Meshless Modelling)
In the traditional use of FEM the structure is broken down into finite number of regions or parts, called elements. The elements are connected to each other at grid points, called nodes. The assembly of elements interconnected at nodes, is called the finite element mesh (or grid). The attributes of the structural system (materials, physical properties, loads, constraints, etc.) are added to the finite element mesh to represent the engineering problem as closely to reality as possible.
In the FVM, similar techniques are used to break down the domain of interest (control volume) into a mesh or grid consisting of cells, which contain edges, faces and nodes (grid points). Definition of the boundaries of the domain, and within the domain, is also necessary.

Spatial discretization (definition of the mesh or grid) can be achieved in different ways, for example by applying a Lagrangian or an Eulerian approach. As illustrated below, from ref. 1, in the Lagrangian approach the material definition is “fixed” to the mesh/grid nodes, and both deform together, which may create computational issues in case of large deformations. In the Eulerian approach the mesh/grid remains fixed and the material may deform independently. When for example applying these two approaches to an impact scenario, the Lagrangian method may be used for the (fixed) target structure, whereas the Eulerian methods may be more suitable for modelling the (moving) projectile.

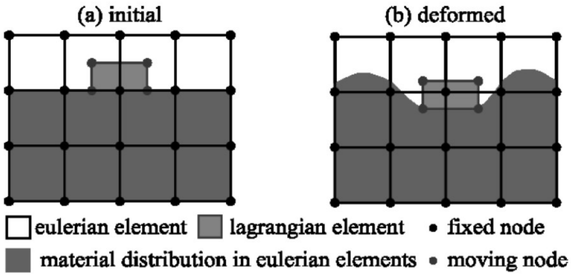


Lagrangian (a) and Eulerian (b) approach

To overcome some of the disadvantages of the Lagrangian and the Eulerian method, combinations of the two methods also exist: Arbitrary Lagrangian-Eulerian (ALE) and Combined Eulerian-Lagrangian (CEL). These two methods are illustrated below (ref. 1).

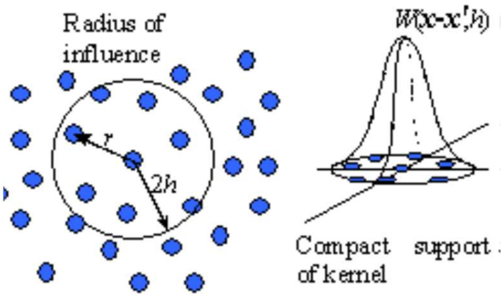


Arbitrary Lagrangian-Eulerian (ALE) approach



Combined Eulerian-Lagrangian (CEL) approach

In addition to the above mentioned mesh or grid based methods, meshless methods also exist. The Smoothed Particle Hydrodynamics (SPH) method is the most commonly used meshless method, where the fluid is replaced by a set of independent particles that interact with each other. A smoothing function (or interpolation kernel W) is defined that determines how the properties (such as density and velocity) are distributed over the particles, as well as the integration domain (defined by the smoothing length h) that defines which neighbouring particles are affecting each particle. The SPH methods is illustrated below (ref. 2).



Smoothed Particle Hydrodynamics (SPH) method

Temporal Discretization
In an explicit analysis (see below) the time step should be small enough to excite all frequencies in the mesh or grid to avoid that the solution becomes unstable. This requirement is known as the Courant-Friedrichs-Levy (or CFL) condition, and is often described as requiring that the time step Δt must be equal or less than the length l (the size of the smallest element) divided by c (the sound of speed in the material).

Implicit versus Explicit Analysis
In an implicit analysis, the solution of each step requires a series of iterations to establish equilibrium. An implicit analysis generally allows for larger time steps.
In an explicit analysis, iteration is not required as the nodal accelerations are solved directly. As a consequence smaller time steps are required to maintain stability and convergence.

Static versus Dynamic (Transient) Analysis
Static analysis is characterized by (very) slow application of the external loads, hence mass (inertia) or damping effects need not be considered.
For dynamic events where there is a rapid application of load, a dynamic (transient) analysis is more appropriate, that includes the effects of mass (inertia) and damping.

Linear versus Non-Linear Analysis
In a linear analysis, a linear relationship is assumed to exist between applied forces and displacements (i.e. the stiffness matrix K is constant). Deformations are small, loads remain unchanged throughout the duration of the analysis, both in magnitude and directionality, and the material remains in the elastic domain.
In a non-linear analysis, this linear relationship between applied forces and displacements does not exist (i.e. the stiffness matrix K is not constant), due to non-linearities caused by geometry (large displacements), material behaviour (elasto-plasticity, creep or rate dependent elasticity, visco-plasticity…) and/or contact.

Mass Scaling
The process of adding nonphysical mass to the structure to increase the time step, thereby reducing the run time.

Hourglass Effect
A non-physical, zero-energy mode of deformation which produces no strain and stress, but leads to excessive element distortions.

Shear locking
Shear locking is an error that occurs in finite element analysis due to the linear nature of quadrilateral elements. The linear elements do not accurately model the curvature present in the actual material under bending, and a shear stress is introduced, which makes the element appear to be stiffer than it actually is and gives bending displacements smaller than they should be.

Constitutive Equations
Mathematical expressions relating the stresses σ(ij) to the strains e(ij), describing how the material is constituted mechanically. The stress tensor can be expressed as the sum of a hydrostatic (dilatational) part and a distortional (deviatoric) part.

Equation of State (EOS)

An equation that describes the relationship between pressure, temperature and volume, and that can be used to describe (for example) the fluid-like behaviour of a bird when impacting a structure.

Reduced Order Modelling (ROM)

A technique for reducing the computational complexity of mathematical models in numerical simulations, by a reduction of the model's associated state space dimension or degrees of freedom.

Static and Dynamic condensation

Sub-structuring allows for the independent analysis of portions of the structure, but involves the reduction of nodal coordinates. The process of reducing the number of free displacements or degrees of freedom is known as static condensation. The same process can also be applied to dynamic problems and is then called dynamic condensation.

Heat Transfer / Thermal Analysis

- Conduction: the transfer of heat energy by direct contact.
- Convection: the movement of heat by actual motion of matter.
- Radiation: the transfer of energy by electromagnetic waves.
- Heat capacity or thermal capacity: a physical property, defined as the amount of heat to be supplied to a given mass of a material to produce a unit change in its temperature.
- Specific heat capacity of a substance: the heat or thermal capacity of a sample of the substance divided by its mass.
- Heat flux or thermal flux, sometimes also referred to as heat flux density: flow of energy per unit of area per unit of time.
- Heat flow rate: the amount of heat transferred per unit time in the material.

Computational Fluid Dynamics (CFD)

- Within the scope of this CM, the term CFD is meant to refer to “higher order” CFD methods, as mentioned below, i.e. more complex flow formulations than for example potential flow based methods such as the Vortex or the Doublet Lattice Method.
- “Higher order” CFD methods include Reynolds Averaged Navier-Stokes (RANS), Large Eddy Simulation (LES), Detached Eddy Simulation (DES) and Direct Numerical Solution (DNS). Distinction between these methods is mainly based on the formulation of the turbulent flow through turbulence models (except for DNS).
- Steady-state or transient (unsteady) flow: when the fluid properties do not change with time, it is called a steady-state flow; otherwise it is called a transient or unsteady flow.
- Viscous or inviscid flow: the viscosity of a fluid is a measure of its resistance to deformation. A fluid that has no resistance to shear stress is known as an ideal or inviscid fluid.
- Laminar or turbulent flow: in laminar flows, as opposed to turbulent flows, fluid layers slide in parallel, with no eddies, swirls or currents normal to the flow itself.
- Compressible or incompressible flow: in an incompressible flow, as opposed to a compressible flow, the fluid density is assumed to remain constant.
- Multi-phase modelling: a technique used to analyse the interaction between different matters (structure, water, oil,…) and/or different phases (solid, liquid, gas). Different techniques exist, such as Volume of Fluid (VOF), Lagrangian Multiphase (LMP), Discrete Element Method (DEM), etc.
- Chimera (overset): a mesh/grid system made up of blocks of overlapping meshes/grids, as different geometrical features may be better represented by different mesh/grid types.

Hardware and Software

- Hardware: the physical, tangible parts or components of a computer.
- Software: a collection of computer programs, libraries and related data.
- Computer program: a collection of instructions that performs a specific task when executed by a computer.
- Programming language: a formal language (such as Java, Python, Fortran and C++) that is used to write computer programs.
- Source code: any collection of computer code written using a programming language.
- Compiler: a computer program that translates code into another language, e.g. into machine code, to create an executable computer program.
- Algorithm: a finite sequence of instructions that can be implemented on a computer.
- Computer platform: a system that consists of a hardware device and an operating system that a computer program runs upon.
- Pre-processor: a computer program that processes its input data to produce output data, to be used as input for another computer program.
- Solver: a computer program that solves mathematical problems, such as a system of partial differential equations.
- Post-processor: a computer program that processes data after primary processing is done.
- Script, or script language: a programming language that automates the execution of tasks.

2. Background

In general, compliance with CS-25 structural certification specifications can be shown by test only, or by analysis supported by test. Compliance showing by test only is an option, but is often not considered as practical, for example due to the number of test articles that would be required to cover all critical design conditions. Therefore in most case the showing of compliance consists of a mix of analytical and test efforts. One of the keys to the acceptance of this approach for certification purposes is that it must be shown that the analysis leads to reliable and accurate (or conservative) results. Traditionally, this is shown by comparisons between test data and analytical results.

Defining and building test set-ups and test articles, as well as actually performing the tests can be expensive and time consuming. Also, testing has its limitations too, as not all design cases to be investigated can be easily reproduced.

For these and other reasons (like program risk mitigation) the use of analysis particularly in the form of Modelling & Simulation (M&S) techniques is becoming more and more widespread. This trend is further supported by the increase in computational capabilities as well as improved accuracy and user-friendliness ("democratization of simulations") of commercially available M&S software packages.

It should be noted that the term "analysis" actually has a very broad meaning. For example, the term could refer to classical hand analysis (as described in well-known references like Bruhn or Niu), or to sophisticated computational Finite Methods (as incorporated in commercially available software programs), or to company specific programs for example contained in Excel sheets. The focus of this CM is on M&S techniques based on computational Finite (Element, Difference, Volume) Methods, although many of the considerations in this CM would apply to other types of analysis too.

The balance between test and analysis efforts in the process of showing compliance with structural certification specifications is shifting towards the latter. Although comparisons between test data and analysis results still continue to play an important role in the validation of the analysis, with this shift a more careful consideration of all aspects related to M&S are becoming more important, which is the main reason for publishing this CM.

To ensure the credibility and acceptance of the analytical results from the M&S process, the application of a thorough Verification and Validation (V&V) process is required, as explained in more detail in paragraphs 4 and 5, as well as consideration of errors and uncertainties (paragraph 6). Other aspects of M&S are important as well, such as extrapolation and similarity (paragraph 7), experience and expertise (paragraph 8) and documentation and record keeping (paragraph 9).

It should be noted that M&S techniques can also be used by applicants in the design and development phase of the lifecycle of an aircraft, for example by investigating and optimizing manufacturing processes or improving material characteristics. Likewise, application of M&S techniques open the door to creating digital replicas (digital twins) of aircraft in service, to support the implementation of predictive maintenance and health monitoring systems. Virtual and enhanced reality techniques can also be used to assess the performance of maintenance tasks and flight crew training. However, as stated above, the focus of this CM is on M&S techniques based on computational Finite (Element, Difference, Volume) Methods to support the showing of compliance with structural certification specifications of CS-25.

The concept of increased reliance on analysis in the form of M&S techniques is often referred to as Certification (and Qualification) by Analysis[1], or C(Q)bA, a somewhat inaccurate and perhaps even slightly confusing term, as it implies testing would be no longer required at all, which would only be true if the analysis is properly verified and validated and applied with the limitations of its validity, as further explained in this CM. It is clear however that there is a strong drive within the aerospace industry to apply the C(Q)bA approach in many different subject areas, to improve the efficiency of the design and development process, to reduce program risk and to reduce the amount of physical testing required.

From a safety point of view, on the one hand the increased use of M&S techniques can be seen as beneficial. As stated before, tests have their limitations too, and with the proper analytical tools many more design conditions can be investigated, which ultimately could lead not only to a better, but also a safer product. On the other hand, modern M&S software tools are often deceivingly simple to use, and can easily lead to erroneous results, especially when not supported by the necessary experience and/or relevant test data.

Examples of CS-25 structural subject matters and their main associated certification specifications where M&S techniques in the form of computational Finite Method techniques are already used, include:

- Static strength (CS 25.307)
- Fatigue & damage tolerance (F&DT) (CS 25.571)
- Dynamic impact conditions
    - Emergency landing conditions
        - Crashworthiness (CS 25.561)
        - Ditching (CS 25.563)
    - Bird impact (CS 25.631, CS 25.775(b))
    - Dynamic emergency landing conditions (CS 25.562)
    - Uncontained engine failures (CS 25.903(d) and CS 25.963(e))
    - Wheel & tyre debris (CS 25.734)
    - Landing gear shock absorption (CS 25.723)
- Loads (CS 25.301)
- Aeroelasticity (CS 25.629) including Vibration & buffeting (CS 25.305(e))
- Heat transfer / Thermal analysis (CS 25.865, CS 25.603)
- Engine failure conditions (CS 25.362)

Note: this list is not meant to be exhaustive nor exclusive.

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[1] Other terms often used include Simulation Based Certification, Virtual Certification, Smarter Testing or Certification by Analysis Supported by Test

For the purpose of this CM and for convenience of structuring the discussion, distinction is made between the following categories of computational Finite Methods:

1. *Computational Structural (or Solid) Mechanics* (CSM)
   Relates to static strength, F&DT and heat transfer/thermal analyses.
2. *Computational Structural Dynamics* (CSD)
   Relates to analyses of dynamic impact conditions, as well as to the development of structural dynamic model(s) associated with the analysis of (dynamic) loads, aeroelastic stability and engine failure conditions.
3. *Computational Fluid Dynamics* (CFD)
   Relates to the aerodynamic model(s) associated with the analysis of loads and aeroelastic stability conditions.

Some of the structural subject matters mentioned above are associated with more than one computational Finite Method described in paragraph 1.4. For example, when investigating an emergency landing on water (ditching), a combination of FEM (behaviour of structural model) and FVM or SPH (behaviour of water) techniques may be used to address the problem of fluid-structure interaction (FSI). Similarly, in the event of a bird impact, the bird behaves similar to a fluid (which can be modelled using FVM or SPH), whereas the target structure could be modelled using FEM.

Many useful references on the subject of M&S exist, some of which are listed in paragraph 1.2. and in Appendix C. These and other references contain much more information and details than can be addressed in this CM and should be consulted for further details.

Also, due to the diversity of structural airworthiness subjects listed above, not all subjects are treated in equal depth in this CM, and often only selected examples are mentioned to illustrate the general concept. As such this CM provides a *framework* of main items to be considered from a certification point of view when performing M&S activities, and it is left to the applicant to apply this framework to a specific case or application in a more detailed and comprehensive manner, as necessary.

3. Modelling & Simulation – General

3.1. Modelling & Simulation Principles

Figures 1 and 2 below, taken from ref.'s 3 and 4 respectively, illustrate the basic principles to be considered and steps to be taken when performing M&S activities.

In Figure 1, as a first step, the reality (i.e. the real physical behaviour of a particular phenomenon) needs to be translated into a conceptual model. This conceptual model would contain all modelling assumptions and mathematical equations that describe the real behaviour, based on analysis and observations. An example would be describing the behaviour of fluids by the well-known Navier-Stokes (NS) equations.
In a second step this conceptual model needs to be translated into a computer model, by means of programming the software tool(s). For example, the partial differential NS equations need to be discretized by using the techniques described in paragraph 1.4. to make them suitable for numerical analysis.
In a third step, the computer model is used to perform the simulation(s), and the analytical results are compared again with reality (validation). Staying with the example of fluid dynamics, windtunnel and/or flight test data would be needed for this step.

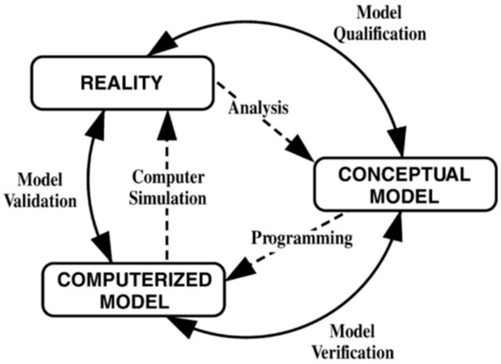


Figure 1. Basic Modelling and Simulation steps

The basic steps described above are further detailed in Figure 2. This figure shows that the programming or implementation step from mathematical model to computational model is associated with code verification, which is addressed in paragraph 4.2. The step from computational model to simulation results is associated with calculation (or solution) verification, addressed in paragraph 4.3. Validation, the comparison between simulation results and reality (experimental results), is covered in paragraph 5.1. through 5.3. If there is insufficient agreement between the simulation results and the reality, the analytical model may need further refinement, as discussed in paragraph 5.4.

Figure 2 also highlights that parallel to the mathematical modelling activities, several steps need to be taken to obtain and process the necessary experimental data to support the validation process. Errors and uncertainties exist for both analysis results and test data, and are addressed in paragraph 6.

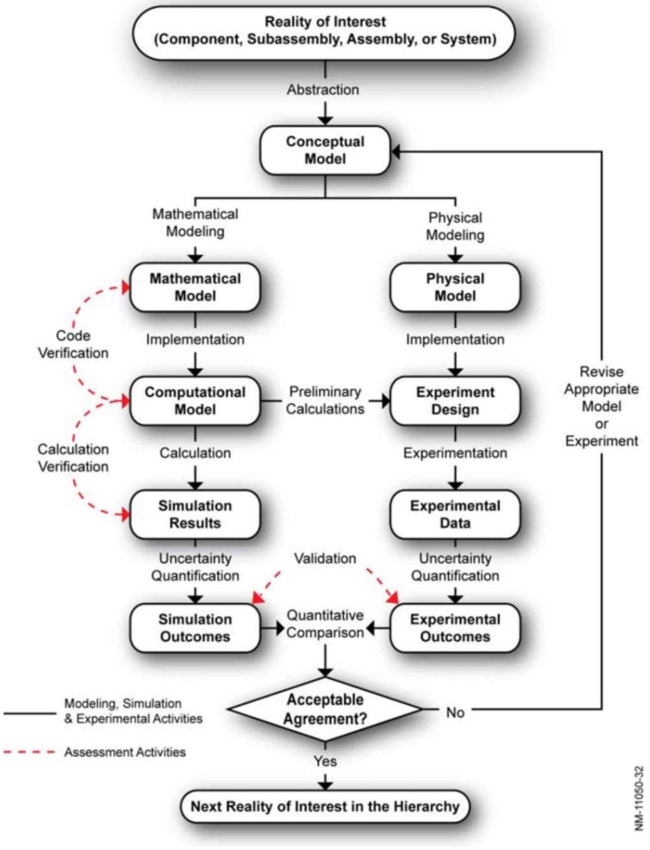


Figure 2. Modelling and Simulation steps

3.2. Modelling & Simulation Process Steps

When performing M&S activities using already available software programs (and hence omitting in this paragraph the programming step mentioned in paragraph 3.1.), the process usually start with defining the computational model, as shown in Figure 2. In that case, the following main process steps are typically performed:

1. Preparation
2. Pre-processing
3. Solution
4. Post-processing

Quite often these steps have to be repeated, for example because of modelling errors or unexpected results, or because an approach is applied in which the analysis is started with a relatively simple or coarse model which is refined step-by-step to obtain more accurate or detailed results.
In addition to the software program that contains the actual solver, performing these steps may require the use of separate programs that contain the pre-and/or post-processor.

3.2.1. Preparation

Before even starting M&S efforts, it is important to understand the physics of the problem and to determine the objectives of the analysis (including desired results and accuracy). It is desirable to have a first estimation of the results, for example based on hand analysis or known solutions from comparable cases. At this stage test data used for validation should not be made available to the analyst(s) for the reasons explained in paragraph 5.

This step also includes the identification of the need for and the source of the necessary data (geometry and dimensions, material characteristics, etc.) as well as determining the idealization and discretization strategy, the software tool(s) to be used and the verification and validation efforts required.

A gap analysis, for example based on the Phenomena Identification and Ranking Technique (PIRT) or on the Predictive Capability Maturity Model (PCMM) may be helpful to identify and to prioritize the phenomena that are important to be adequately captured by the analytical model, as well as any information or data where the level of confidence is deemed to be insufficient (see ref. 4 for more details on these two methods).

3.2.2. Pre-processing

This step includes both idealization (translation of the real world system into a simulation model and defining associated assumptions and simplifications) and discretization (such as breakdown of the simulation model into elements, defining loads and boundary conditions, etc.). Appendix A contains a number of suggested calculation (or solution) verification checks to be performed at this stage of the M&S process.

In the pre-processing steps also the output data of the analysis are defined and how they will be represented.

3.2.3. Obtaining Solution

In this step the mathematical problem formulated as discretized partial differential equations is solved by means of numerical analysis methods.

3.2.4. Post-Processing

In this last step the analysis results (such as strains, stresses, deformations, temperatures, heat flux, pressures and velocities) are tabulated and/or visualized and checked, first for overall plausibility and then in more detail. Appendix B contains a number of suggested checks to be performed at this stage of the M&S process.

It should be noted that in some cases filtering or defining certain sampling rates may influence the presentation of the analytical results and such techniques should therefore be applied with some care.

4. Verification

4.1. Introduction

In accordance with ref. 5, verification is defined as the process of determining that a computational model accurately represents the underlying mathematical model and its solution.

In many reference documents related to the subject of verification, further distinction is made between code verification on the one hand and calculation (or solution) verification on the other hand. These two terms are defined in ref. 5 as:

> Code Verification – establish confidence, through the collection of evidence that the mathematical model and solution algorithms are working correctly
>
> Calculation or Solution Verification - establish confidence, through the collection of evidence, that the discrete solution of the mathematical model is accurate

Both aspects, code verification and calculation or solution verification, are discussed in more detail in the next two paragraphs.

4.2. Code Verification

As stated in ref.’s 5 and 6, code verification is the process of determining that the numerical algorithms are correctly implemented in the computer code, and of identifying errors in the software. It helps to ensure that the mathematical model(s) and solution algorithms are working correctly, that is, the code solution predicts the (exact) analytical solution to a certain extent.

In ref.’s 5 and 7 the two components of code verification are identified, i.e. Numerical Algorithm Verification (NAV) and Software Quality Assurance (SQA), see Figure 3 below (from ref. 8). Numerical Algorithm Verification addresses the software reliability of the implementation of all of the numerical algorithms that affect the numerical accuracy and efficiency of the code. Software Quality Assurance emphasizes determining whether or not the code, as a software system, is reliable (implemented correctly) and produces repeatable results on specified computer hardware and a specified system with a specified software environment, including compilers, libraries, etc.

As described in ref. 3, SQA is considered to consist of three parts: static, dynamic and formal testing:

- Static testing is performed without running the code, and includes checking for compilation errors and consistency in the usage of the computer language;
- Dynamic testing is performed by running the code and checking for array indices that are out of bound, for memory leakage, coverage issues, etc.;
- Remaining errors (e.g. a line of code that calculates a quantity that is not used) are identified through formal testing.

For NAV, several methods are available (see ref. 3), and convergence testing and order-of-accuracy testing are among the most rigorous ones. A convergence test investigates the error between the analytical solution and the exact (or known) solution, to assess whether this error reduces as mesh/grid and time steps are refined. An order-of-accuracy test not only assesses the convergence, but also the order of accuracy.

As also explained in ref. 3, the approximate solution (of the discretized equations) is not the same as the exact solution (of the partial differential equations); the difference is called the discretization error. When the element or cell size or time step size decreases to zero, the discretization error should go to zero as well. The rate at which this convergence occurs is called the order of accuracy. Distinction can be made between the formal and the observed order of accuracy. The formal order-of-accuracy is the theoretical rate of convergence of the discrete solution to the exact solution, the observed order-of-accuracy is the actual rate of convergence as produced by the software program. The later one can be obtained by systematic grid/mesh refinement.

For successful code verification, the observed order-of-accuracy should be equal to, or exceed the theoretical order-of-accuracy, and the discretization error should be kept to a minimum within prescribed and defined limits.

Both methods (convergence and order-of-accuracy testing) require comparison with exact or known solutions, which may be difficult to obtain. As described in more detail in ref. 8, the Method of Manufactured Solutions (MMS) may be applied to address this problem.

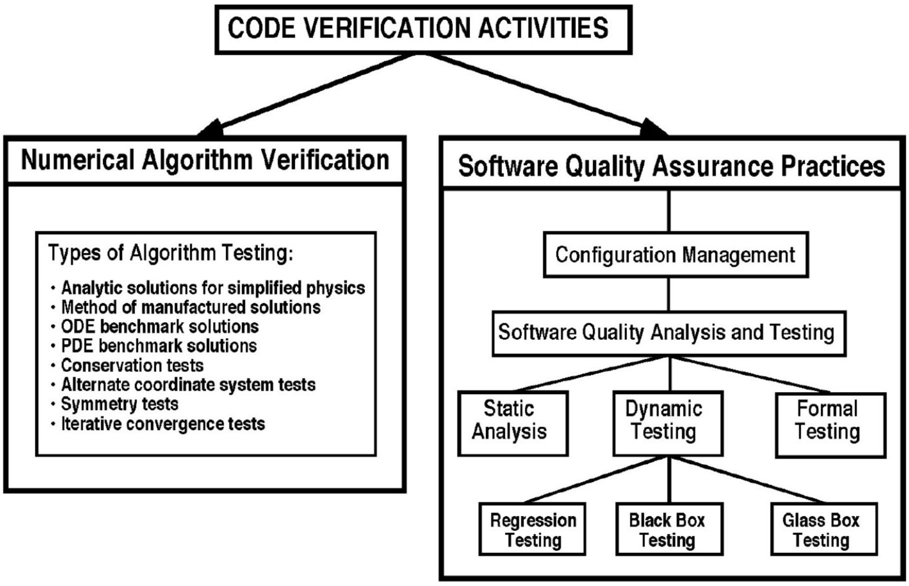


Figure 3. Overview of Code Verification Activities

It is important to note that:
- Code verification has to be performed only once (unless of course the code is modified), as opposed to calculation or solution verification (paragraph 4.3.) that has to be applied to every analysis performed;
- EASA does not approve software tools or programs, but only verifies the compliance data generated by these tools or programs (depending on the EASA level of involvement (LOI)).

Currently no specific certification specifications are defined for qualification of software tools that are used for M&S activities. Most applicants are using commercially available software packages that are widely used throughout the aerospace industry, in which case applicants normally would not get involved directly in the code verification process, which is more the domain of the software developer. It is expected however that the software developer has applied the appropriate SQA and NAV processes, including benchmark cases to verify the accuracy and consistency of the solutions. Evidence of these activities should be recorded and documented and be made available to the applicant and the Agency upon request.
In addition, theory manuals and user guides should be made available by the software developer, as well as customer support, training opportunities and a reporting system for errors and bugs.
See also ref. 10 for some further recommended practices for code developers, addressing issues like management, design, verification, validation and documentation of the software.

Even as an “end-user”, in addition to the items mentioned in paragraph 8, the applicant should verify that the software package is valid and suitable for its intended use, and should understand the underlying assumptions and limitations. Software configuration control is also necessary, and with subsequent versions/releases of the software program, a check is needed on the continuity of the previous results and solutions.

In some cases applicants may want to apply in-house developed software tools or programs. In such cases, the applicant itself is expected to perform the necessary code verification activities (SQA, NAV) as outlined above. The same would apply to any scripts written by the applicant to support the use of commercially available tools.

The above consideration would apply not only to any solver used in the M&S process but also to any pre- or post-processing software tool or program.

4.3. Calculation or Solution Verification

As stated before, calculation (or solution) verification is the process of determining the solution accuracy of a particular calculation or analysis. Ref.'s 3 and 8 identify three main aspects of calculation (or solution) verification:

(1) *Verification of analytical model (idealization & discretization) including input data*
Checks should be performed on how the analytical model(s) were defined (idealization and spatial and/or temporal discretization), as well as on the data used as input for the model(s). Appendix A of this CM contains some suggested items to be verified for different subject matters.

(2) *Numerical (analysis) error estimation of the solution*
Numerical errors may consist of:
   (a) Round-off errors;
   (b) Statistical sampling errors; and
   (c) Iterative convergence errors.
The main goal is to show that these numerical errors in the analysis results are (very) small compared to the error resulting from the discretization of the PDEs describing the physical behaviour.
For a more detailed discussion on numerical (analysis) errors and how to address them is referred to paragraph 6.3.

(3) *Verification of output data*
Checks should be performed on the output data (results) generated by the analytical model(s). Appendix B of this CM contains some suggested verification checks for different subject matters.

5. Validation

Validation is defined in ref. 5 as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.
In the following paragraphs a number of issues related to model validation are discussed.

5.1. Validation Principles

How well a model represents reality for the item(s) of interest is typically determined by comparing the numerical analysis or simulation results with experimental (physical test) data. For this comparison it is common practice to apply the building block approach, as illustrated in Figure 4 below from ref. 11.

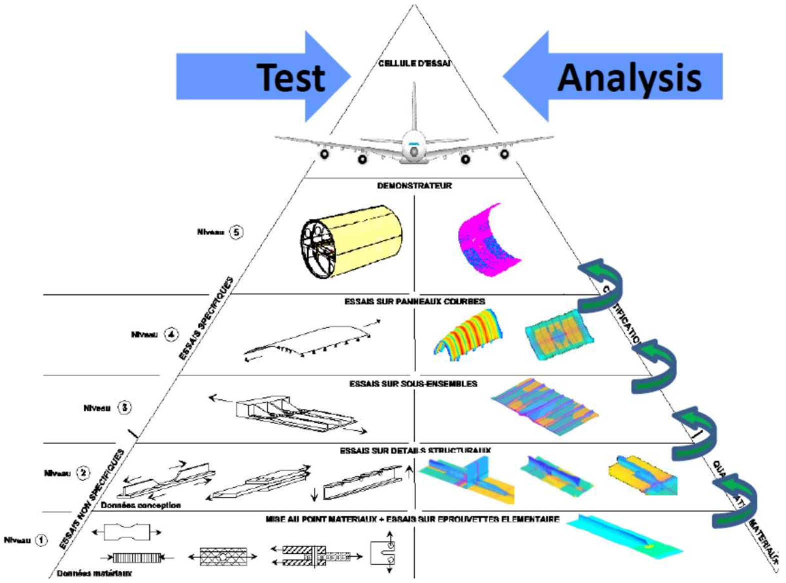


Figure 4. Building Block Approach ("Analysis and Test Pyramid")

In this approach, test data (on the left in Figure 4) and numerical analysis results (on the right) are compared with each other at every level of the "pyramid". These levels are often labelled as (from the bottom to the top): coupons - elements – details – subcomponents – components.
In the building block approach one typically moves level by level from the bottom to the top of the "pyramid", with increasing complexity of the structural details or behaviour being investigated and with decreasing number of specimens (aircraft components) being tested and analysed. This systematic step-by-step approach should ensure that the phenomena under investigation are well addressed and understood, both from a test and analysis point of view, and should help to isolate any unexpected or erroneous results.

Note that in Figure 4 the full-scale aircraft is at the top of the "pyramid", but this is not necessarily always the case. Also, the number of levels of the "pyramid" may vary, depending on the application. Likewise, the number of specimens and conditions required to be investigated and evaluated at each level will vary.

There are some issues to be considered when applying the building block approach to M&S activities:

- This approach requires the collection of high quality test data (e.g. high sampling rate, high accuracy) to be able to compare this data with numerical results in an acceptable manner, as discussed in the paragraph 5.2. In some references it is argued that the level of accuracy in the analysis need not be more stringent than the level of accuracy of the test data, but this would only be correct if it is ensured that the test data are of the highest possible quality.
- As many test data as possible should be collected, for example through the use of strain gauges, accelerometers, load cells and high speed cameras and/or techniques such as Digital Image Correlation (DIC).
- Inherent test variability should be considered and addressed as validation of a model based on an “outlier” data point may lead to erroneous results. Multiple tests are therefore typically required at different levels of the “pyramid” to address this issue.
- Numerical analysis results should be obtained before validation test results become available to the analysts, to avoid any undue tweaking of the simulation results and to increase the overall credibility and confidence in the M&S process.
- If M&S techniques are used to determine the critical components, locations or conditions to be tested, the test results should be used to validate the analysis to ensure the criticality assessment was performed in an appropriate manner.

5.2. Comparing Test Data with Analysis Results

Numerical analysis results can be compared with physical test data in a number of ways, both qualitatively and quantitatively. In this paragraph a number of techniques will be discussed, but other techniques exist which may be equally or more valid for a particular application. It would be the responsibility of the applicant to propose a suitable method of comparison and to substantiate why this would be an appropriate means.

Comparing numerical analysis results with physical test data can be done qualitatively, at least as a first step to get an impression of the adequacy of the simulation results. This could be done for example by examining photo or video material taken during a bird impact test and comparing the break-up of the projectile (bird) and the behaviour and response of the target (aircraft structure) with the simulation results. In some specific cases such a qualitative comparison may be sufficient, but in general some quantitative comparison is also required.

For scalar quantities of interest such as deformations or peak responses, a simple quantitative comparison method is the Relative (percentage) Error Criterion (REC), which is defined in ref. 6 as:

$$Error = \frac{\left|Peak_{test} - Peak_{sim}\right|}{\left|Peak_{test}\right|} * 100\%$$

For dynamic events, such as crashworthiness or dynamic seat testing, where not only the magnitude of the peak response but also the shape of the response curve is relevant, the Sprague & Geers method (ref.'s 6 and 12) is often preferred to evaluate the difference between two time histories. First the error in magnitude ($M_{S\&G}$) and phase ($P_{S\&G}$) is computed for the time histories, and the combined error ($C_{S\&G}$) is then used to provide an overall error measure between the two time histories:

$$C_{SG} = \sqrt{M_{SG}^2 + P_{SG}^2}$$

Another example of a quantitative comparison technique is the Modal Assurance Criteria (MAC), see for example ref. 13, used to compare analytical and experimental mode shapes, in support of showing compliance with aeroelastic stability and dynamic loads certification specifications, based on the equation:

$$MAC(\{\varphi_r\}, \{\varphi_s\}) = \frac{|\{\varphi_r\}^{*t}\{\varphi_s\}|^2}{(\{\varphi_r\}^{*t}\{\varphi_r\})(\{\varphi_s\}^{*t}\{\varphi_s\})}$$

This method is illustrated in Figure 5 from ref. 13.

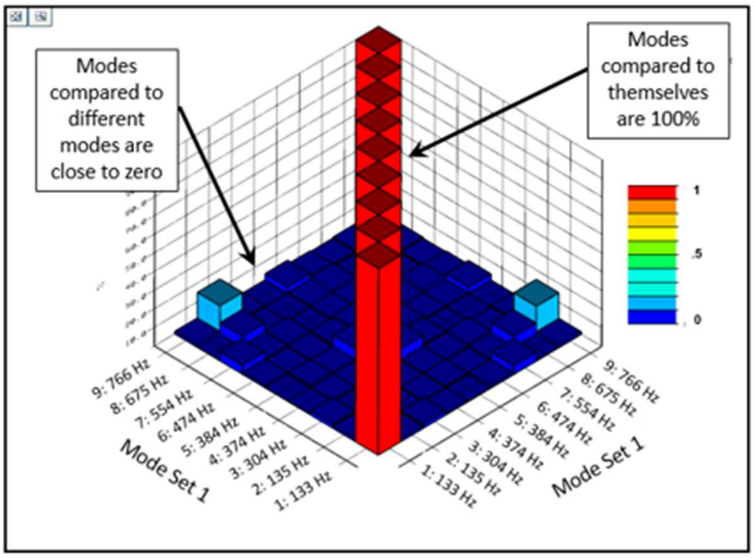


Figure 5. Model Assurance Criteria (MAC)

Further discussion on comparing test data with analysis results is contained in paragraph 6, where the effects of errors and uncertainties are discussed.

5.3. Validation Metrics

Having compared the test data with numerical analysis results, one needs to determine whether the difference between the two sets of data is acceptable or not, i.e. whether the simulation yields results with acceptable accuracy or not. These acceptability criteria are often called validation metrics. These criteria can be rather simple and straightforward, such as for example with deformations and stresses/strains obtained during the substantiation of the static strength of a component or full scale aircraft. It is commonly accepted (ref. 14) that deformations determined by numerical analysis should be within ± 5% of the corresponding test data. For stresses and strains, which are derived from the corresponding deformations, the commonly accepted value would be ± 10% as illustrated for strain levels in Figure 6 from ref. 15.

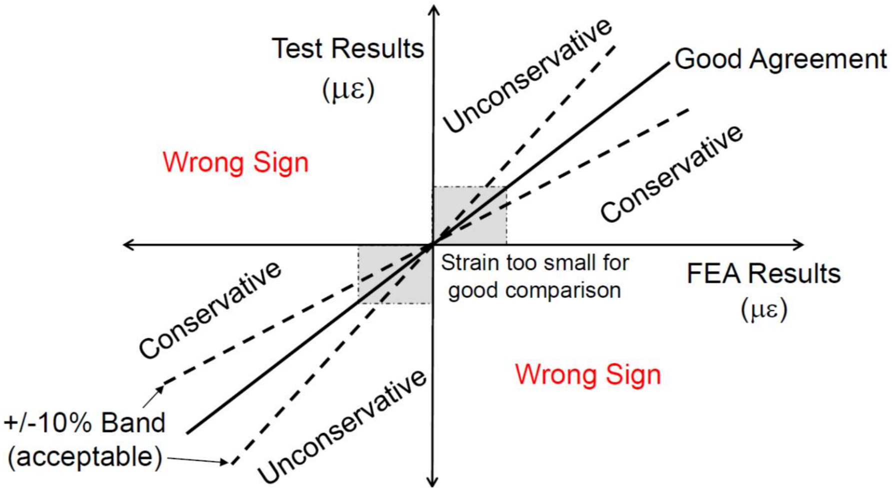


Figure 6. Validation Metrics for Strains

Another example is related to the showing of compliance with aeroelastic stability and dynamic loads certification specifications. Here, results from Ground Vibration Tests (GVT), when performed, need to be compared with the analytical structural dynamic model in terms of mode shapes and frequencies. This would result in a similar graph as shown in Figure 6, where a ± 10% difference between test data and analysis results could be acceptable.

When comparing analytical and experimental mode shapes using the MAC method as mentioned in chapter 5.2., often a value of 0.9 or 0.95 is used as a validation metric.

The last example of a validation metric is described in ref. 6 for compliance with the Head Injury Criteria (HIC). It is stated that the maximum analytical HIC value should correlate to within 100 HIC units of the maximum test derived HIC value.

Note: all values quoted above should not be taken as “hard” criteria, but rather as values that generally, but not necessarily in all cases, are considered to be acceptable. Comparison results that do not meet these criteria may still be valid, for example if related to non-critical conditions, however this would have to be assessed on a case by case basis.

More complicated and probabilistic based validation metrics also exist that take into account the uncertainty (see paragraph 6) that exist in numerical analysis results, such as frequentist's metric or area metric. Discussion of these methods is considered to be beyond the scope of this CM, but for example ref.'s 16 and 17 provide more details on such methods.

5.4. Model Calibration

Ref. 18 defines calibration as the process of adjusting numerical or physical modelling parameters in the computational model for the purpose of improving agreement with experimental data.
Often, when comparing numerical analysis results with test data, the agreement between the two is not satisfactory, for example because the validation metric is not met or there is a desire for improved accuracy. In such cases further improvement of the analytical model is needed, also known as model tuning or model updating.

A valid way to adjust modelling parameters would be by collecting additional experimental data, which helps to improve the understanding of the physical phenomenon and/or to reduce the variability in the supporting (input) data.

Calibration however should not result in adjusting parameters "randomly" in a blind attempt to improve the agreement between numerical analysis results and test data, as this could result in unrealistic values of such parameters. Also, the risk with such an approach would be that the analytical model is only "validated" against a given set of test data, which could render the model invalid when applying it to other conditions (see also paragraph 7). Applicants should therefore define and justify as part of the certification process their approach and methodology towards model calibration.

6. Errors and Uncertainties

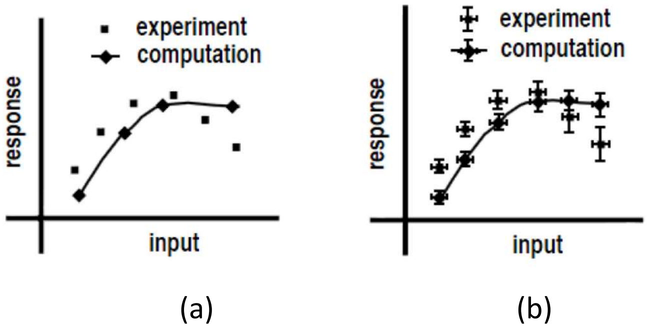
6.1. Introduction

The terms “error” and “uncertainty” are sometimes used in an interchangeable manner, but for the purpose of this CM the following definitions are used (ref. 18):

> Error: “A recognizable deficiency in any phase or activity of modelling and simulation that is not due to lack of knowledge”
>
> Uncertainty: "A potential deficiency in any phase or activity of the modelling process that is due to the lack of knowledge"

The key word in the definition of uncertainty is *potential*, which indicates that deficiencies may or may not exist. *Lack of knowledge* has primarily to do with lack of knowledge or understanding about the physical processes that is being modelled.
The definition for error implies that the deficiency is identifiable (*recognizable*) upon examination.

Errors and uncertainties exist in both test data and analysis results. To be able to make an informed assessment about the accuracy or credibility of the M&S process, these errors and uncertainties have to be identified and addressed, as described in the following paragraphs.
In Figure 7 this issue is further illustrated. In Figure 7(a) test data and analysis results are shown as discrete points with no indication of error or uncertainty. In Figure 7(b) error bands are included, providing a better insight in the correlation between test data and analysis results. Ideally these error bands should have the same level of confidence to enable a fair comparison.



(a) (b)

Figure 7. Comparison of Experimental and Computational Results

Figure 8 shows a particular combination of test data and analysis results. When there is a complete overlap of both associated error bands as shown in the figure on the left, one typically assumes that the correlation between test data and analysis results is satisfactory (although both could still be wrong). When there is a mismatch (no overlap) between the experimental and analytical data as shown in the figure on the right, there would be typically reason for concern about the correlation between the two data points. The other two cases in the figure lie in the middle and warrant some further (case by case) investigation to determine their acceptability.

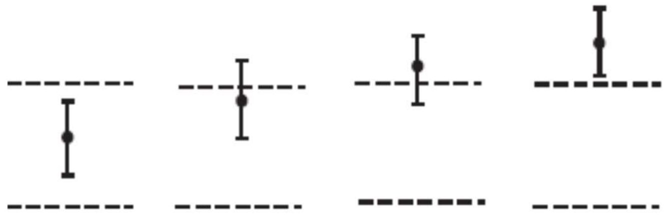


Figure 8. Comparison between Test and Analysis Data Points, with Error Bands

6.2. Test Errors and Uncertainties

As pointed out in ref.'s 19 and 20, every measurement has a certain amount of error associated with it, resulting in a difference between the measured value and the actual "true" value. This difference is defined as the total error that consists of a random error and a systematic error, as shown in Figure 9 (from ref. 19).

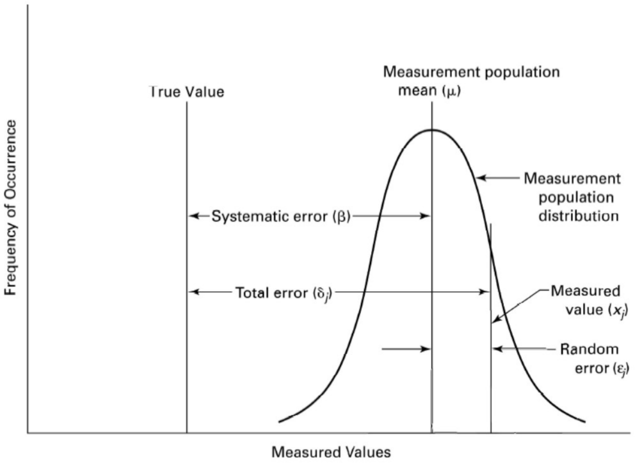


Figure 9. Total Error, Systematic Error and Random Error (ref. 19)

The random error varies randomly when performing measurements and may for example be due to uncontrolled test conditions (e.g. temperature changes) or due to certain data reduction techniques. This random error can be statistically assessed, for example by assuming a normal (Gaussian) distribution. The systematic error remains constant (i.e. resulting in a shift of the curve) and may for example be due to incorrect calibration techniques.

The total uncertainty in a measurement is defined as the combination of uncertainty due to random error and uncertainty due to systematic error. Applying the methods of ref's 19 and 20, one can define this (expanded) total uncertainty associated with a measured value as a function of the desired level of confidence. Confidence is defined here as the probability that the true value falls within the specified limits. For example, when measuring the length of an object one could state that the length is "X" (metres) and is expected to lie within "X" (metres) ± "y" (metres) with 95% confidence.

When presenting test data for certification purposes, most applicants do not follow the rigorous process as outlined above, probably for historical reasons and because of the amount of test data required. Applicants should however in any case assess errors and uncertainties associated with test data, especially when prone to variability, and at the very least indicate error bands when presenting test results. These error bands may be based on qualitative considerations and previous experience rather than a rigorous quantitative assessment as described above, but should anyway be presented.
In addition, systematic errors should be minimized, for example by proper calibration of test equipment.

6.3. Analysis Errors

For analysis errors, distinction can be made between acknowledged errors and unacknowledged errors, as for example per ref. 21:

> *Acknowledged errors* have procedures for identifying them and possibly removing them
>
> *Unacknowledged errors* have no set procedures for finding them and may continue within the code or simulation

When performing M&S activities, at least the following most common analysis errors should be considered and addressed appropriately.

(1) Acknowledged Errors
  (a) *Physical approximation errors* are those due to uncertainty in the formulation of the model and deliberate simplifications (e.g. geometry) of the model (called idealization in paragraph 4.3.). These errors should be addressed by careful evaluation of the underlying assumptions of the model and of the effects of any features (geometry) omitted or simplified.
  (b) *Computer round-off errors* develop with the representation of floating point numbers on the computer and the accuracy at which numbers are stored. These errors can be addressed by performing simulations at a higher (double) precision.
  (c) *Statistical sampling errors* may occur due to averaging of analysis results to obtain mean data. If this is the case, the simulation should be run long enough to minimize this error.
  (d) *Iterative (convergence) errors* exists because of the iterative method(s) used in solving the (often non-linear) equations governing the physical phenomena under investigation. Several methods exist to address these errors, see for example ref. 3.
  (e) *Discretization errors* (either *spatial* or *temporal*) are those errors that occur from the mathematical representation of the physical phenomena being modelled in a discrete domain of space and/or time. These errors can be addressed through mesh refinement (such as the Grid Convergence Index (GCI), see ref. 22) and/or smaller time steps, to improve accuracy and determine convergence of the solution.

(2) Unacknowledged Errors
   (a) *Computer programming errors* are "bugs" and mistakes made in programming or in writing the code. These errors should be removed or minimized by applying a proper code verification process, as described in paragraph 4.2.
   (b) *Usage errors* are due to the improper application of the code or incorrect input files. These errors should be removed or minimized through calculation (or solution) verification as described in paragraph 4.3. and Appendix A.

6.4. Analysis Uncertainty

In addition to the definition of uncertainty in paragraph 6.1., further distinction (ref. 3) can be made between *aleatory* and *epistemic* uncertainty.
Aleatory uncertainty (sometimes called variability) is due to the inherent variation associated with the physical system or environment. For example, the dimensions of an aircraft component, or the Young's modulus of the material used, will vary from component to component due to variation within the manufacturing process controls and tolerances.
Epistemic uncertainty on the other hand has primarily to do with lack of knowledge or understanding about the physical processes that is being modelled. For example, the turbulence models currently used in a CFD analysis are only an approximation of the real turbulence characteristics of a fluid, simply because a full and comprehensive understanding of this phenomena has not yet been achieved.
As mentioned in ref. 3, some uncertainties are a mixture of aleatory and epistemic uncertainty.

Epistemic uncertainty can be reduced (or even eliminated) when additional knowledge or understanding of the physical phenomena is acquired, for example by performing additional experiments. Aleatory uncertainty on the contrary is inherent to the system or environment, and in the example of aircraft components mentioned above, could be reduced by changing the manufacturing process controls.

Aleatory uncertainty can be addressed in a probabilistic (stochastic) manner. In this approach, sources of uncertainty are identified and characterized, for example via probability or cumulative density functions. These uncertainties are then propagated through the model, for example using sampling methods like the Monte Carlo approach, to obtain multiple outputs (results) of the simulation which can then be assessed via a stochastic analysis. This process is illustrated in Figure 10 from ref. 16.

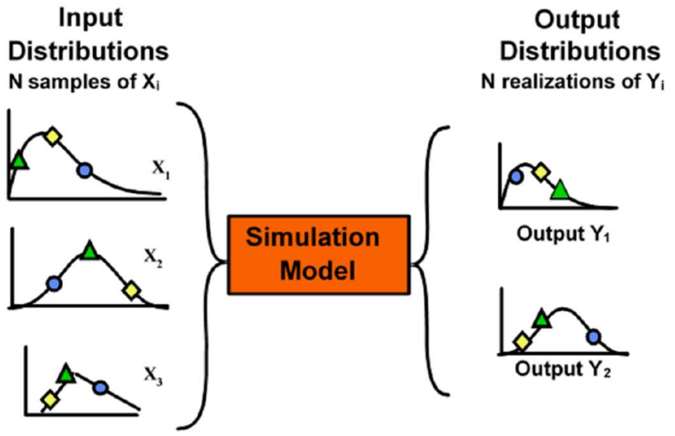


Figure 10. Stochastic Analysis Process of Uncertainties

However, this probabilistic approach requires careful identification of the nature and characteristics of the uncertainties involved, as well as running multiple simulations. Although some attempts have been made to implement this approach (see for example ref. 23), these applications mostly remain in the research domain and are currently not used at an industrial scale to support the showing of compliance to certification specifications.

A much more common deterministic approach is to address analytical uncertainties through the use of a safety factor, such as for example defined in CS 25.303 (factor of safety between limit load and ultimate load) and CS 25.621 (casting factor). These safety factors are typically not derived from probabilistic considerations but are rather based on experience, and generally serve to increase the severity of the design condition in order to minimize the probability of structural failure during in-service operation.

A mix of a probabilistic and a deterministic approach is also possible, as for example contained in ref. 6 for lumbar loads and HIC. Based on the variability observed in experimental data, a safety (or knockdown) factor is applied to the regulatory limits for lumbar loads and HIC. It is stipulated that only test data below these limits may be used for validation of the analytical mode, and likewise analytical results should not be above these limits.

In general, the use of safety factors, often in combination with the use of conservative data, assumptions and analysis techniques, and the application of parametric variation of the key parameters (see paragraph 6.5.) that govern the physical phenomenon and the simulation process, is considered a practical and acceptable way of addressing analytical uncertainties. However, this may result in a design that is not fully optimized, and for example applicants seeking to remove some of these conservatisms and/or to reduce the amount of supporting test data used to validate the analysis should pay more attention to identify and address uncertainties in the M&S process.

6.5. Sensitivity Analysis

An important tool to identify and to address uncertainties is the performance of a sensitivity analysis. A sensitivity analysis identifies those parameters that are most important in describing the physical phenomena being investigated. Efforts should be directed towards quantifying these important parameters and minimizing their variability as much as reasonably possible, because they have the largest effect on the results of the simulation. Lesser important parameters may require less effort and attention.

As mentioned in paragraph 6.4. for analysis uncertainty, also a sensitivity analysis can be performed in a probabilistic or deterministic way. In the probabilistic approach input parameters are propagated through the model and their contribution to the simulation result can be made visible for example via a Pareto analysis. See ref. 16 for an example of this technique.

A more deterministic approach is described in AMC 25.629, where variation of critical parameters, such as mass, stiffness and control system characteristic, from nominal values for aeroelastic stability analyses is addressed. In this reference it is stated that such investigations to account for uncertainties in the values of parameters and expected variations due to in-service wear or failure conditions. Also, if aeroelastic stability margins are found to be sensitive to these parameters, then additional verification in the form of model or flight tests may be required.

7. Extrapolation and Similarity

Once all the necessary verification and validation steps have been satisfactorily performed, and errors and uncertainties have been identified and addressed, the computational model can be considered as sufficiently credible ("validated") to be used to support the showing of compliance. It is however equally important to establish the limits of validity of the computational model, to ensure the model is applied within these limits defined by the assumptions, conditions and underlying data used to develop the model.

In Figure 11 (from ref. 8) several scenarios are illustrated.

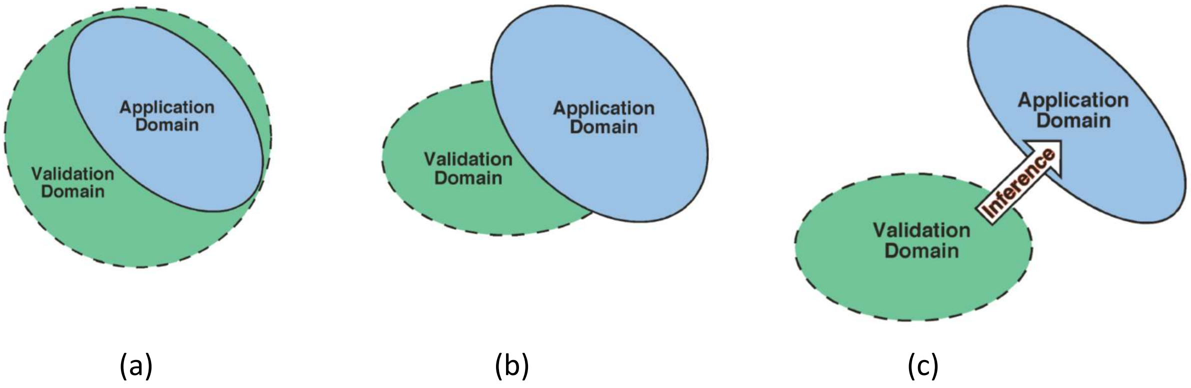


Figure 11. Different Extrapolation Scenarios

In the first scenario (sub (a)) the application domain lies within the validation domain. This means no extrapolation beyond the validation domain is required when applying the computational model. This would be the case for example when M&S techniques are used to determine the critical cases that are going to be tested, and the test data are used to perform the necessary validation steps, as outlined in paragraph 6. Taking the example of a newly developed aircraft, typically the static strength substantiation is based on a series of limit and ultimate load tests that envelop as much as practically feasible the critical design load cases. The remaining less critical load cases are substantiated by analysis, based on the computational model(s) validated by the test program.

In the second scenario (sub (c)) the application domain lies outside the validation domain. Here, significant extrapolation is needed beyond the substantiated limits of validity of the model. It will be obvious that the model cannot be used without additional validation, typically in the form of additional test data. This would for example be the case when the design to be approved deviates significantly from the previous one, as in the case of bird impact on a composite design instead of on a metallic design. In this example it is likely that the structural model itself also needs adjustment (such as the definition of damage initiation and propagation of the composite material), which would require additional verification to be performed, and re-assessment of errors and uncertainties.
Another example of this scenario would be when applying a different aerodynamic theory, such as applying a higher order CFD method instead of the Doublet Lattice Method.

The third scenario (sub (b)) is the most challenging one to address. Here, there is a certain amount of overlap between the application domain and the validation domain, i.e. a part of the application domain lies outside the validation domain. Using again the example of static strength substantiation, this situation may occur when the design weights of an already approved aircraft are increased, and the effect of the increase in loads is substantiated by analysis only, using the previously validated computational model(s). In this scenario the change(s) to the previous design are not as significant as in the second scenario, and are such that the computational model (updated as necessary) is still valid and can be used, although in some cases it may be necessary to perform some limited additional testing to obtain data for specific design features.

The key issue and main challenge for the second and third scenario is often to establish whether the new design to be approved deviates significantly from a previously approved design, i.e. whether the amount of similarity between the two designs (in terms of design features, behaviour, design conditions, methods and assumptions, etc.) is sufficient to warrant continued application of previously validated analysis techniques.

For some subject matters guidance is available on how to determine whether the use of (validated) analysis only could be acceptable, or whether additional test data are required, for example:

- AMC 25.307 provides means of compliance on this topic in relation to static strength substantiation, distinguishing between New Structure, Similar/New Structure and Derivative Structure, basically addressing the three scenarios (a), (b) and (c) mentioned above;
- In ref. 6 guidance is provided on which design changes to seats could be substantiated by (validated) analysis, and which design changes would require testing;
- CS 25.629(e) states that flight flutter testing is necessary unless the design change(s) have been shown to have an insignificant effect on the aeroelastic stability;
- AMC No. 2 to CS 25.301(b) provides means of compliance on the need to perform a flight load measurement campaign to support the validation of analytically derived flight loads intensities and distributions;
- CS 25.723(c) allows minor changes in design to be substantiated by analyses without additional shock absorption tests, and AMC 25.723 provides examples of such minor design changes.

Another approach to this issue would be to establish a specific threshold on the analysis results, for example 80% of the maximum allowable strain. If this threshold is exceeded the decision could be made to perform additional testing to provide increased confidence in the analysis.

Important to note is that if an accumulation of a number of minor changes occurs, the cumulative effect should be investigated and additional validation may need to be undertaken.

The discussion above already highlights the fact that determining whether an analytical model is still valid and can continued to be used to show compliance, or that additional data are necessary to support the M&S process, is subject to engineering judgement and can result in significant discussions between the applicant and the Agency. Give the importance of identifying any required additional efforts, considering for example the cost involved and time needed to prepare and execute tests, applicants are encouraged to discuss this aspect with the Agency as early as possible in a certification project in order to obtain agreement on the proposed means of compliance.

8. Experience and Expertise

The terms experience and expertise are used in this CM to indicate the professional knowledge (understanding of the subject matter) present within the company and with its staff performing M&S activities. Other items are included in this terms such as:

- Qualification (education, e.g. engineering degree);
- Skills & competences (understanding of processes, procedures, roles and responsibilities);
- Training (initial and recurrent).

When performing M&S activities, experience and expertise play an important role, especially in relation to more complex simulations. It is relatively easy for inexperienced analysts to use modern M&S software programs and to generate seemingly correct results, but it requires training and experience to come to credible results that can withstand the required level of scrutiny.
In a general sense, the need for experienced staff is recognized in Part 21.A.245, that states that the design organisation shall demonstrate that the staff in all technical departments are of sufficient numbers and experience. By extension this also applies to any M&S activities performed by the applicant, or by its partners or subcontractors, as part of the compliance demonstration.

Experience and expertise can be defined at the level of the company or organisation, and at the level of the staff involved in M&S activities.

At an organisational level, applicants are expected to have processes, procedures and standards in place to identify, obtain, maintain and retain the necessary level of skills, knowledge and experience to be able to perform M&S activities in a sufficiently credible manner. These procedures should include identification of the roles and responsibilities, and the necessary qualifications, competences and skill levels for staff performing specific tasks as part of the M&S process. This may depend on factors such as the criticality of the application in terms of consequences of failure as well as the company “environment” (for example, presence and support of senior staff members with considerable experience in M&S activities).
In addition, company procedures should be in place to address subjects such as sharing and documenting lessons learned and “best practices” within the organisation, for example via design standards or quality manuals, when and how to perform peer reviews, and requirements for initial and recurrent training.
If applicable, these processes and procedures should be part of the applicant’s Design Assurance System under the Part 21 Subpart J Design Organisation Approval (DOA) (see also paragraph 9).

At the level of the individual staff member, establishing the required qualifications, competences, experience and skill level of the persons performing specific tasks as part of the M&S process should be based on several criteria, such as the education received, the number of years of experience (both with M&S techniques in general and in relation to specific applications), the number and complexity of projects and applications involved in, the level of involvement and responsibilities in these projects, etc.

In the end, should an applicant not be fully confident or unable to convince the Agency of the ability to perform certain M&S activities, it may be necessary to seek assistance of, or even subcontract these activities to, other more established and experienced organisations and companies.

9. Documentation and Record Keeping

9.1. Documentation

Applicants are expected to properly document all relevant aspects of the M&S activities, including the pre-processing, solution and post-processing phases that are part of the showing of compliance to the applicable certification specifications. This should not only include the applicant's own activities, but also those of partners or subcontractors.

Properly documenting all relevant information is necessary to enable the Agency to understand the steps and decisions taken in the M&S process, as outlined in the previous paragraphs of this CM, to understand the underlying assumptions and limitations, and to assess the validity of the analytical results. In addition, providing sufficient details of the M&S activities helps to establish the overall credibility of the M&S process applied. Proper and sufficiently detailed documentation also benefits the applicant, as it ensures traceability of the M&S process as well as the ability to reproduce results, or develop new results, later on if needed.

Documentation should not only focus on the steps taken during the M&S process for a particular application, such as description of the analytical model(s), input data and results, but should also address the processes and tools necessary to support the M&S activities. Examples would include a description of the configuration management process (for example, record keeping and version control of the model(s) used) and procedures related to the required knowledge and experience level of the staff performing certain tasks (see paragraph 8). A software and hardware overview should also be included in the documentation, identifying items such as the version (release, issue) of the M&S software, the operating system, and the computer hardware platform used, as well as addressing any hardware and/or software changes that may have occurred relative to previous applications.

Many applicants have developed and are maintaining a "best practices" document that contains guidance on the different step in the M&S process (for example, the use of recommended elements for certain applications) that draws upon lessons learned and further supports the consistency and credibility of the tasks performed. The creation of such a handbook or design standards is strongly encouraged by the Agency.

The manner in which the relevant processes and procedures, and information and data is documented and shown/submitted to the Agency is not prescribed in any detail in this CM, but should normally be in line with the general practices already established by the applicant. If applicable, the necessary processes and procedures to support the M&S activities should be part of the Design Assurance System under the Part 21 Subpart J (DOA) approval.

To document the information and data associated with the M&S process, it may be beneficial to define one (or more) specific compliance document(s) to describe the various M&S activities in sufficient detail. In ref. 6 the content of such a report (in this reference called Validation and Analysis Report (VAR)) is described in more detail in relation to dynamic emergency landing conditions for seats. This is only one example, but the intent is to make sure the required information is properly documented and easy to access, read and understand.

Conclusions (for example, on the adequacy of the model validation when comparing test data with analysis results) and any limitations or conditions associated with the numerical analysis should also be clearly identified and documented.

The compliance documents described above would be in addition to the data package typically supporting an application to the Agency, such as a Certification Program and a Compliance Checklist. In cases where tests are performed to support the M&S activities, test plans and test result reports should also be defined.

9.2. Record Keeping

Part 21.A.55 requires applicants to hold all relevant information and data at the disposal of the Agency and to retain it in order to provide the information necessary to ensure the continued airworthiness of the product. Although not explicitly stated, the general expectation is that information and data are kept and retained until the particular design is no longer in service, which could mean for many years to come.

The most straightforward way to comply with this requirement would be to store all relevant information and data gathered and generated during the M&S process. Assuming this information and data is properly stored and remains accessible this would ensure the necessary retention.

However, the amount of information and data to be stored can become excessive, especially when an applicant performs a large number of complex M&S activities over a longer period. The alternative to storing all information and data is to make a careful selection of what will be stored, for example the definition of the (final) analytical model and the input data, in a way that it is possible to fully reproduce the analysis results. Of course, the previous analysis results still need to be sufficiently available to make a comparison with the reproduced data, but these previous results could be stored in a manner less burdensome for the applicant.

A third option would be to recreate the analytical model when the need arises to reproduce previous analysis results, and although some applicants in the past have been forced to do so, this would not be the preferred option due to the increased risk of a larger mismatch between the previous and the recreated data sets.

An issue may occur when the hardware and software required to access the stored information and data is no longer available, maintained or operating. This also applies to attempting to re-run a previous simulation to reproduce earlier results. To circumvent this problem it may therefore be necessary to store specific hardware and software in order to be able to use these in the future.

All of the above consideration have driven in the recent years the development of Simulation Data Management (SDM) systems and processes that not only help to properly store the relevant data in a structured way, but also make the data accessible, searchable and traceable. Applicants involved in numerous and/or complex M&S activities are strongly encouraged to implement such an SDM system.

10. EASA Certification Policy

10.1. General

The use of Modelling & Simulation (M&S) techniques such as those based on computational Finite Methods, to support the showing of compliance with CS-25 structural certification specifications is becoming more and more widespread in the aerospace industry. In some cases these analytical techniques are proposed to replace (some of) the physical testing that otherwise would have taken place to support the showing of compliance.

These M&S techniques have become more versatile and powerful in the last decade and have been accompanied by a significant increase in computational capabilities, to the extent that these techniques are now basically available to all applicants, to be applied to a range of physical phenomena at an affordable cost and effort.

This development necessitates the establishment of a set of criteria that need to be addressed by applicants who want to use M&S techniques as part of the proposed means of compliance with CS-25 structural certification specifications, to ensure the credibility and validity of these analyses. Therefore, applicants are requested to address the items mentioned in paragraph 10.2. and to seek early agreement from the Agency on the acceptability of the proposed means of compliance.

It is not the intention of this CM to prohibit or change certification practices that have long been established by the aerospace industry and have been accepted by the Agency. It is already common practice to support the showing of compliance with CS-25 structural certification specifications by a mix of analysis (including M&S techniques) and test data, and this practice is allowed to continue, although it is recognized that some applicants may be more advanced in their use of analysis than others. However, in certain instances an increased attention should be paid to the use of these M&S techniques, for example when an applicant wishes to increase the previous reliance on M&S techniques and/or decrease the amount of testing that historically or otherwise would have taken place, or wants to extrapolate the analysis results beyond what has currently been accepted. Other example cases where this policy is relevant would include applicants with less experience in using certain M&S techniques, or those who want to apply such techniques to subject matters new to their company or organisation.
Other considerations would include the sensitivity, complexity and the criticality of the analyses performed, again weighed against factors such as the amount of supporting test data, the conservativeness of the assumptions made, the safety factors or margins applied, the extent of extrapolation and the experience of the applicant. The diversity and complexity of the M&S applications necessitates a “case by case” approach.

10.2. Items to be Addressed

With reference to the much more detailed discussion contained in the previous paragraphs and the Appendices to this CM, it is recommended that applicants adequately address and document the following items in their substantiation when using M&S techniques to support the showing of compliance with CS-25 structural certification specifications. Decisions and choices made related to the M&S process should be properly justified and documented as well.

(1) Verification (paragraph 4)

  (a) Code Verification

  An assessment of the software tools in terms of the suitability for its intended purpose should be provided by the applicant, as well as evidence of adequate code verification (both Software Quality Assurance and Numerical Algorithm Verification) for the software tools used in the M&S process, including pre- and post-processors, solvers and scripts.

  (b) Calculation (or Solution) Verification

  Items mentioned in paragraph 4.3. and Appendix A and B (related to idealization and discretization, input data, numerical errors and output data) should be addressed.

(2) Validation (paragraph 5)

A validation strategy should be defined and documented, and presented to and agreed by the Agency preferably in the early stages of a certification project, detailing the test data available and/or to be collected, as well as the comparison means (including validation metrics and calibration process) between analysis results and test data.

(3) Errors and Uncertainties (paragraph 6)

Different types of errors and uncertainties in test data and analysis results as described in paragraph 6 should be identified and documented, and it should be determined how they are mitigated and accounted for in the M&S process.

(4) Extrapolation and Similarity (paragraph 7)

The applicant should establish the validation domain of the numerical analyses performed, and substantiate any extrapolation beyond this domain.

(5) Experience and Expertise (paragraph 8)

  (a) Organisation

  The applicant should have processes, procedures and standards in place to identify, obtain, maintain and retain the necessary level of skills, knowledge, expertise and experience to perform M&S activities.

  (b) *Staff*

  It should be demonstrated that the personnel involved in M&S activities is sufficiently knowledgeable, experienced, trained and qualified to use the analysis tool(s) and interpret the results.

(6) Documentation and Record Keeping (paragraph 9)

(a) Documentation

All information relevant to the M&S process should be properly documented and made available to the Agency upon request, including the definition of analytical models used, input data and analysis results, as well as procedures, processes and software tools used.

(b) Record Keeping

A record keeping and data management system should be implemented by the applicant that ensures all relevant data can be retrieved and/or recreated.

11. Remarks

1. This EASA Proposed Certification Memorandum will be closed for public consultation on the 4th August 2020. Comments received after the indicated closing date for consultation might not be taken into account.
2. Suggestions for amendment(s) to this EASA Certification Memorandum should be referred to the Certification Policy and Planning Department, Certification Directorate, EASA. E-mail: CMs@easa.europa.eu
3. For any question concerning the technical content of this EASA Certification Memorandum, please contact:

Name: Wim DOELAND
Function: Senior Structures Expert, Large Aeroplanes
Phone: +49 (0)221 89990 4041
E-mail: willem.doeland@easa.europa.eu

Appendix A: Idealization & Discretization

A.1 Introduction

This Appendix describes the main items to consider in the pre-processing phase (see paragraph 3.2.2. - idealization and spatial and/or temporal discretization of the model) for a number of structural subject matters. Applicants are requested to document how these items have been addressed including justification of the choices made. The overview is not claimed to be exhaustive, and additional considerations may apply.

A.2 Computational Structural Mechanics

A.2.1. Static strength

(with a focus on implicit type of Finite Element Analysis)

(i) Type of Finite Element Analysis

- Linear or non-linear analysis
- General FEM (definition of "global" internal loads) or Detailed FEM (definition of "local" strains and stresses)
- Use of Reduced Order Modelling and/or static condensation

(ii) Physical properties (dimensions and geometry)

- Transformation (e.g. from CAD models or drawings) to analytical model (simplification, approximation or removal of certain design features).
- The idealization should represent the stiffness and load path of the real structure. Particular attention should be paid to the modelling of joints and splices, e.g. mechanically fastened or bonded.
- Full model or sub-model (use of symmetry or anti-symmetry)

(iii) Materials and material characteristics (for metallic, composites or hybrid materials)

- Linear or non-linear (elasto-plastic) behaviour
- (Quasi) isotropic or anisotropic behaviour
- Material properties & allowables
    - A- or B-basis allowables
    - Use of true-stresses and true-strains
- Consideration of environmental considerations (humidity, temperature)
- Use of layered (composite) material versus smeared/consolidated properties

(iv) Units

- Use of consistent units

(v) Elements

- Dimension (0-D, 1-D, 2-D, 3-D)
- Type (bar or rod, beam, shell, solid, spring,…)
- Shape (quadrilateral, triangular, hexahedron, tetrahedron, …)
- Number of nodes
- Number of integration points (full or reduced)
- Order (linear, quadratic, or higher order)
- Properties (e.g. assigned/omitted stiffness, fixed/released degrees of freedom at nodes, etc.)

(vi) Mesh

- Use of automatic meshing and/or manual meshing
- Structured or unstructured mesh
- Number of elements - fine or coarse mesh depending on stress/strain gradients

(vii) Boundary conditions

- Supports and constraints (fixed, simply supported)

(viii) Definition of contacts (master/slave surfaces)

(ix) External loads application

- Introduction of concentrated loads, pressure loads, weight,…

A.2.2. Heat Transfer / Thermal Analysis

(with a focus on uncoupled heat transfer analyses, where temperatures, heat flux, etc. are determined but stresses/deformations are initially not considered)

(i) Type of analysis

- Consideration of conduction, (forced or natural) convection and/or radiation
- 2-dimensional or 3-dimensional analysis
- Steady-state or transient analysis
- Linear or non-linear analysis (material properties, boundary conditions)

(ii) Dimensions and geometry

- Transformation (e.g. from CAD models or drawings) to analytical model(s) (simplification, approximation or removal of certain design features).
- Use of symmetry or anti-symmetry

(iii) Materials and material characteristics (for metallic, composites or hybrid materials)

- Thermal conductivity coefficient(s)
- Convection coefficient(s)
- Specific heat
- Coefficient(s) of thermal expansion
- Surface emission/absorption coefficient(s)
- Mass density

(iv) Units

- Use of consistent units

(v) Elements

- Dimension (1D, 2-D, 3-D)
- Type (rod/bar, shell, solid, …)
- Shape (quadrilateral, triangular, hexahedron, tetrahedron,…)
- Number of nodes
- Number of integration points (full or reduced)
- Order (linear, quadratic, or higher order)

(vi) Mesh

- Use of automatic meshing and/or manual meshing
- Structured or unstructured mesh
- Number of elements - fine or coarse mesh depending on temperature gradients

(vii) Time steps/no. of increments (transient analysis)

(viii) Boundary conditions

- Temperatures

(ix) Initial conditions (temperature)

(x) Definition of contact areas / interfaces

(ix) Thermal loads

- Heat fluxes, radiation conditions, convective conditions,…

A.3. Computational Structural Dynamics

(with a focus on explicit type of analysis of dynamic impact conditions)

Note: many of these considerations apply to both projectile and target, as applicable.

(i) Type of analysis

- Lagrangian, Eulerian, Arbitrary Lagrangian-Eulerian (ALE), Combined Eulerian-Lagrangian (CEL), Smoothed Particle Hydrodynamics (SPH)
- “Soft” body impact or “rigid” body impact
- Use of Reduced Order Modelling and/or dynamic condensation

(ii) Dimensions and geometry

- Transformation (e.g. from CAD models or drawings) to analytical model (simplification, approximation or removal of certain design features). Particular attention should be paid to the modelling of joints and splices, e.g. mechanically fastened or bonded
- Use of symmetry or anti-symmetry

(iii) Materials and material characteristics (for metallic, composites or hybrid materials)

- Linear or non-linear behaviour
- Elastic or elasto-plastic behaviour (or visco-elastic or visco-plastic)
- (Quasi) isotropic or anisotropic behaviour
- Equation(s) of state
- Material properties & allowables
  - A- or B-basis allowables
  - (Quasi) static or strain rate dependent behaviour
  - Use of true-stresses and true-strains
- Consideration of environmental considerations (humidity, temperature)
- Use of layered (composite) material versus smeared/consolidated properties
- Damage initiation and propagation models/assumptions
- Definition of failure models
- Specific energy absorption (function of geometry)

(iv) Units

- Use of consistent units

(v) Elements

- Dimension (1-D, 2-D, 3-D)
- Type (bar or rod, beam, shell, solid, spring,…)
- Shape (quadrilateral, triangular, hexahedron, tetrahedron,…)
- Number of nodes
- Number of integration points (full or reduced)
- Order (linear, quadratic, or higher order)
- (For SPH) Definition of particles (number, type, kernel function, smoothing length, spacing and distribution)

(vi) Mesh

- Use of automatic meshing and/or manual meshing
- Structured or unstructured mesh
- Number of elements - fine or coarse mesh

(vii) Boundary conditions

- Supports and constraints (fixed, simply supported)

(viii) Initial conditions (e.g. initial velocity)
(ix) External loads application
- Introduction of concentrated loads, pressure loads, weight,…

(x) Damping values/factors
(xi) Static and dynamic (kinetic) friction coefficients
(xii) Definition of contacts (master and slave surfaces)
- Kinematic constraint method, distributed parameter method or penalty method
- Contacts automatically defined or manually selected
- Point to point, point to surface, surface to surface, self-contact,…

(xiii) Analysis time duration and time step
(xiv) Mass scaling
(xv) Element deletion (during impact / penetration)

A.4. Computational Fluid Dynamics

(with a focus on “higher-order” methods (beyond potential flow methods) and on the Finite Volume Method)

(i) Type of CFD analysis
- Reynolds Averaged Navier-Stokes (RANS), Large Eddy Simulation (LES) , Detached Eddy Simulation (DES), Direct Numerical Solution (DNS),…
- Mach range (subsonic, transonic, supersonic)
- 2-dimensional or 3-dimensional flow
- Steady-state or transient (unsteady) flow
- Viscous or inviscid flow
- Laminar or turbulent flow
- Compressible or incompressible flow
- Internal or external flow
- Multi-phase modelling

(ii) Solution characteristics
- Solution order of accuracy (first, second,…)
- Time marching or space marching solution
- Cell-centered or vertex-centered approach
- Approximation for cell face values (schemes)
    - First or second order upwind, power law, central differencing,…
- Pressure-based or density-based solution
- Use of Reduced Order Modelling and/or dynamic condensation

(iii) Definition of analysis domain (control volume)
(iv) Dimensions and geometry
- Transformation (e.g. from CAD models or drawings) to analytical model (simplification, approximation or removal of certain design features). Particular attention should be paid to the modelling of joints and splices, either mechanically fastened and/or bonded
- Use of symmetry or anti-symmetry

(v) Boundary conditions
- At flow inlet and outlet, far-field region, physical walls
- Pressure, velocity, temperature, turbulence variables, gravity
- Symmetry conditions

(vi) Loads
- Body forces (e.g. due to rotation)
- Gravity

(vii) Grid / mesh
- Number of elements - fine or coarse mesh
- Structured, unstructured or hybrid (single-block or multi-block)
- Overset (chimera)
- Mesh/grid adaptation (refinement or coarsening of mesh/grid during solution)
- Definition of boundary layer
- Fixed versus moving/deforming

(viii) Elements / cells
- Dimension (2-D, 3-D)
- Shape (quadrilateral, triangular, hexahedron, tetrahedron,…)

(ix) Turbulence and transition model(s)
- One-equation models (Spalart-Allmaras,…).
- Two-equation models (k-omega, Shear Stress Transport (SST), k-epsilon, …)
- Three- (or more) equation models
- Reynolds Stress Model (RSM)

(x) Initial conditions
- Velocity, density, temperature, turbulence variables

(xi) Reference (or operating) pressure, temperature and density

(xii) Material (fluid) properties
- Density, viscosity, temperature

Appendix B: Calculation (or Solution) Verification

B.1. Introduction

As part of the process steps described in paragraph 3.2., calculation (or solution) verification requires checks to be performed on the idealization and discretization of the model (see Appendix A) as well as on the output data (results) of the numerical analysis. The depth and scope of this verification is mostly determined by the complexity and criticality of the analysis, whereas the nature of the verification is dependent on the type of M&S that is performed.

In the following subparagraphs a number of calculation (or solution) verification checks are listed on idealization and discretization of the model and on output data for different structural subject matters. These lists are not meant to be exhaustive and engineering judgement should always be applied to determine the adequacy of such checks.

Many software programs already routinely perform, or have the option to perform, such checks and this possibility should be exploited as much as possible.

B.2. Computational Structural or Solid Mechanics

B.2.1. Static strength

(a) General checks on Finite Element model:

- All items mentioned in Appendix A should be checked for correctness and consistency
- Proper element use (right element for the right purpose)
- Coordinate systems (when using multiple input and/or output coordinate systems)
- Differences in stiffness (should be avoided or very carefully modelled)
- Parametric variation (to identify effects of model input parameters on response)
- Unit enforced displacement and rotation (the model should move as a rigid body when it is translated one unit or rotated one radian)
- Unit gravity loading (to verify that the model will provide reasonable displacements and reactions forces under gravity loading, e.g. no large deformations)

(b) Discretization checks:

- Connections and connectivity (to check nodes/elements are connected correctly, e.g. no free edges)
- Coincident nodes check (to identify erroneous coincident nodes)
- Coincident elements check (to identify coincident elements)
- Mesh convergence (change mesh density to check convergence of solution)
- Bar/beam orientation (to check correct orientation of elements)
- Mesh quality (to check for aspect ratio, internal angles (skewness) and warping of elements, mesh anisotropy or directionality)
- Plate/shell element normal direction (to check normal direction of elements)
- Mass and c.g. location (check for mass and c.g. location)

(c) Checks on output (results):

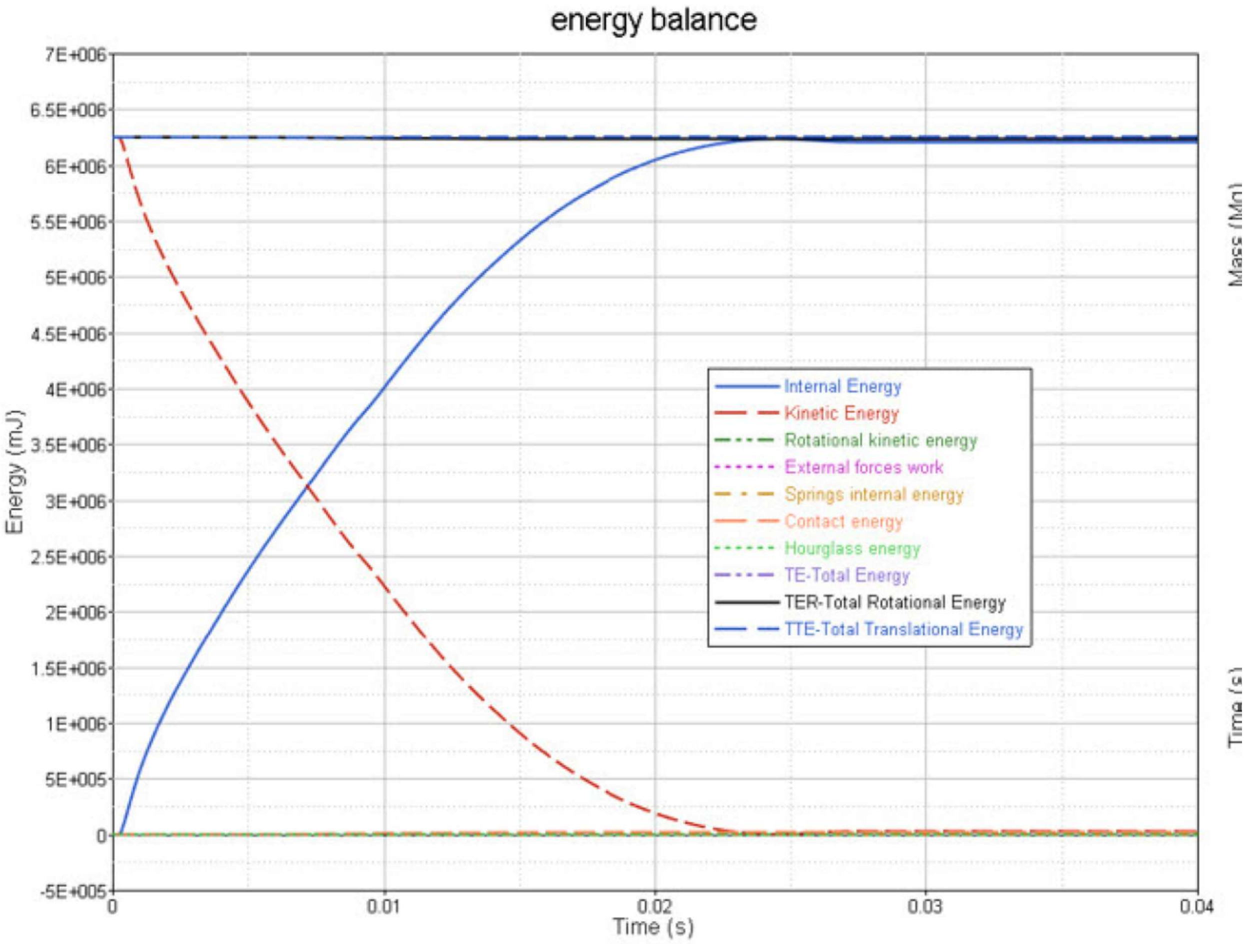
- Program errors and warnings (should be assessed and if necessary addressed)
- Overall deformations (should be reasonable and as expected)
- Reaction forces (should be reasonable and as expected)
- Comparison of averaged and non-averaged results (for example, compare averaged von Mises stresses with non-averaged element stresses)
- Areas with rapid changes in stress or deformations (should be assessed and if necessary addressed)
- Stress singularities (check for locations where the stress value is unbounded)
- Unconstrained equilibrium check (the residual forces at the unconstrained nodes should be zero or small compared to the residual forces or reaction forces on the constrained degrees of freedom)
- Maximum and minimum node responses (should be reasonable and as expected)
- Check for hourglass effects and shear locking (should not occur)

B.2.2. Heat transfer / Thermal analysis

- All items mentioned in Appendix A should be checked for correctness and consistency
- Many of the checks mentioned in paragraph B.2.1. would apply as well
- Check analysis results for reasonableness:
  - Temperature distribution
  - Heat flux distribution (magnitude contours, vectors)
  - Temperature contours should be perpendicular to insulated boundaries
  - Near surfaces with specified temperatures, the temperature contours should be nearly parallel to the surfaces
  - Heat flux vectors should be parallel to insulated surfaces
  - Heat flux vectors should be nearly perpendicular to surfaces with a specified constant temperature
  - Temperature gradient should be discontinuous at an interface between different materials

B.3. Computational Structural Dynamics

- All items mentioned in Appendix A should be checked for correctness and consistency
- Many of the checks mentioned in paragraph B.2.1. would apply as well
- Review of energy balance (internal energy, kinetic energy, hourglass energy, contact energy,…) – see figure on the next page
  - Total energy should remain (approximately) constant
  - Hourglass energy should be small (e.g. less than 10% of total energy)
  - Contact energy should be small (e.g. less than 5% of total energy)
  - Impact (kinetic) energy should match internal energy



Energy balance diagram (ref. 24)

B.4. Computational Fluid Dynamics

- All items mentioned in Appendix A should be checked for correctness and consistency;
- Examination of iterative convergence of the solution of the flow equations, by monitoring the residuals and the relative changes of integral quantities (such as lift and drag), and check if the prescribed tolerance is attained;
- Examination of mesh/grid resolution, including:
    - Acceptable height of first grid cell on no-slip wall;
    - Sufficient number of cells in boundary layer and in areas with geometric “non-smooth” features and/or large flow gradients
    - Spatial (grid) convergence, by changing the number of grid points and check for convergence - for example by determining the grid convergence index (ref. 22);
- Examination of mesh quality:
    - Minimum number of required mesh points in regions of large flow gradients;
    - Acceptable amount of cell distortion, cell stretching and cell type transition (skewness, smoothness, aspect ratio);
- Examination of solution consistency, by checking if the relevant applicable conservation principles (mass, momentum, energy) are satisfied;
- Examination of temporal convergence, by changing the time step and check for convergence;
- Comparison of results obtained with other CFD programs.

Appendix C: Additional References for Some Subject Matters

This Appendix contains a small selection of references (in addition to the ones already identified in paragraph 1.2.) that are related to M&S techniques for some subject matters, and that have been used in preparing this CM. Use of the methods and data contained in these references should be further discussed with and agreed by the Agency.

(1) Verification and Validation

Reference	Title	Issue	Date
NASA-STD-7009	Standard for Models and Simulations	A	2016
MIL-STD-3022	Documentation of Verification, Validation and Accreditation (VV&A) for Models and Simulations	Ch. 1	2012
LA-14167-MS	Concepts of Model Verification and Validation	-	2004

(2) Static strength *(CS 25.307)*

Reference	Title	Issue	Date
-	FEA Best Practices, International Journal of Recent Developments in Engineering and Technology	-	2014
-	NAFEMS V&V Master Class	-	2017
-	FEMCI On-line FEM Book – Validity Checks (www.femci.gsfc.nasa.gov/)	-	2006
-	Building Better Products with Finite Element Analysis, V. Adams and A. Askenazi	First	1999

(3) Dynamic impact conditions

(a) Emergency landing conditions

(i) Crashworthiness *(CS 25.561)*

(ii) Ditching *(CS 25.563)*

Reference	Title	Issue	Date
-	Transport Aircraft Crashworthiness and Ditching Working Group (TACDWG) Report to FAA	B	2018
CRI C-01	A350 Special Condition "Crash Survivability for CFRP Fuselage"	Final	2011
DOT/FAA/AR-10/04	Development of Computational Models for Simulating Full-Scale Crash Tests of Aircraft Fuselage and Components	Final	2012
NASA/TM-2002-211944	Best Practices for Crash Modeling and Simulation, K. Jackson	-	2002
-	EU Research Programs SMAES & SARAH (www.cordis.europa.eu)	-	2011-2014, 2016-2020
-	Aerospace Structural Impact Dynamics International Conference (ASIDIC) (www.asidiconference.org)	-	2012, 2015, 2017, 2019

(b) Bird impact *(CS 25.631, CS 25.775(b))*

Reference	Title	Issue	Date
-	Bird Strike, an Experimental, Theoretical and Numerical Investigation, R. Hedayati and M. Sadighi	-	2016

(c) Dynamic emergency landing conditions *(CS 25.562)*

Reference	Title	Issue	Date
SAE ARP 5765	Analytical Methods for Aircraft Seat Design and Evaluation	A	2015

(d) Uncontained engine failures *(CS 25.903(d) and CS 25.963(e))*

Reference	Title	Issue	Date
DOT/FAA/AR-03/57	Failure Modeling of Titanium 6Al-4V and Aluminum 2024-T3 with the Johnson-Cook Material Model	-	2003
DOT/FAA/AR-08/36	Explicit Finite Element Analysis of 2024-T3/T351 Aluminum Material Under Impact Loading for Airplane Engine Containment and Fragment Shielding	-	2008
DOT/FAA/AR-08/37	Explicit Finite Element Modeling of Multilayer Composite Fabric for Gas Turbine Engine Containment Systems, (several Parts)	-	2009

(e) Wheel & tyre debris *(CS 25.734)*

Reference	Title	Issue	Date
-	Impact of aircraft rubber tyre fragments on aluminum alloy plates: II – Numerical simulation using LS-DYNA. International Journal of Impact Engineering, 34(4), 647-667, D. Karagioza	-	2007

(f) Landing gear shock absorption *(CS 25.723)*

Reference	Title	Issue	Date
SAE 5644	Landing Gear Shock Absorption Testing of Civil Aircraft	A	2019

(4) Computational Fluid Dynamics

(a) Loads *(CS 25.301)*

(b) Aeroelasticity *(CS 25.629)* including Vibration & buffeting *(CS 25.305(e))*

Reference	Title	Issue	Date
SAND2002-0529	Verification and Validation in Computational Fluid Dynamics	-	2002
AIAA 2016-3811	Development and Use of Engineering Standards for Computational Fluid Dynamics for Complex Aerospace Systems	-	2016
ASME V&V 20 – 2016	Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer	-	2016
AIAA R-100A-2001	Recommended Practices When Flight Modelling is Used to Reduce Flight Testing Supporting Aircraft Certification	V12.2	2020

(5) Engine failure conditions *(CS 25.362)*

Reference	**Title**	**Issue**	**Date**
AMC 25.362	Engine Failure Loads	-	2009
AMC 25-24	Sustained Engine Imbalance	-	2009