DOT/FAA/AM-25/06
Office of Aerospace Medicine
Washington, D.C. 20591

Expanded Use of Modeling and Simulation in Ditching Applications

Author: Delta G Design Inc.

Joseph A Pellettiere
FAA Chief Scientific and Technical
Advisor for Crash Dynamics
Washington, DC 20024

Civil Aerospace Medical Institute (CAMI)
Federal Aviation Administration
Oklahoma City, OK 73169

February 2025

NOTICE

This publication and all Office of Aerospace Medicine technical reports are available in full text from the Civil Aerospace Medical Institute's publications website and at the National Transportation Library's Repository & Open Science Access Portal.

Technical Report Documentation

1. Report No. DOT/FAA/AM-25/06	
2. Title & Subtitle Expanded Use of Modeling and Simulation in Ditching Applications	**3. Report Date** February 2025 **4. Performing Organization Code** AAM-632
5. Author(s) Delta G Design Inc.	**6. Performing Org Report Number** DOT/FAA/AM-25/06
7. Performing Organization Name & Address FAA Civil Aerospace Medical Institute P.O. Box 25082 Oklahoma City, OK 73125	**8. Contract or Grant Number** N/A
9. Sponsoring Agency Name & Address Aircraft Certification Service (AIR) Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591	**10. Type of Report & Period Covered** Technical Report

11. Supplementary Notes
The Federal Aviation Administration (FAA) funded this through the Research, Engineering, and Development (RE&D) program budget.
This report underwent peer review: William Carroll, David Moorcroft, and Joseph Pellettiere
Technical report DOI: https://doi.org/10.21949/1529674
The authors have no conflicts of interest to disclose.

12. Abstract
Applicants seeking Federal Aviation Administration (FAA) certification for an aircraft are required to provide substantiation of the aircraft's ability to successfully execute a controlled emergency landing on a body of water per 14CFR Part 25.801 , also known as a ditching maneuver. FAA certification for ditching requires that the passengers and crew can survive, with minimal risk of injury, and successfully evacuate the aircraft prior to it sinking. The post-evacuation state of the aircraft is not a consideration.

Traditionally, ditching certification applicants have had two approaches available to them: establishing similarity to an already certified aircraft sufficient to satisfy the FAA or performing physical testing using scale models and/or a full airframe. While these two approaches are still acceptable today, advances in computational computer tools have created a third approach that may be appropriate for a ditching certification applicant. This document discusses best practices for model development and simulation of each phase in a ditching maneuver (approach, impact, landing, floatation, and evacuation). This report also recommends requirements for applicants simulating an aircraft's ditching performance, and questions regulators can ask to evaluate an applicant's simulation.

13. Key Word Aviation, Certification, Ditching, Modeling, Simulation	**14. Distribution Statement** Document is available to the public through the National Transportation Library: https://rosap.ntl.bts.gov

15. Security Classification (of this report)	**16. Security Classification (of this page)**	**17. No. of Pages**	**18. Price**
Unclassified	Unclassified	39	N/A

Table of Contents

List of Figures

List of Tables

List of Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
AFM	Aircraft Flight Manual
AIAA	American Institute of Aeronautics and Astronautics
AIR	Aircraft Certification Service
Aref	reference area, typically the aircraft wing area
ASME	American Society of Mechanical Engineers
CAMI	Civil Aerospace Medical Institute
CD	drag coefficient
CEL	Coupled Eulerian–Lagrangian
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
CG	center of gravity
CL	lift coefficient
Cp	surface pressure
deg	Degrees
DMIG	Direct Matrix Input at a Grid
DOI	Digital Object Identifier
DOT	Department of Transportation
EID	Element Identification Number
etc.	et cetera
FAA	Federal Aviation Administration
FEA	finite element analysis
FEM	finite element method
ft	Feet
ft^2	feet squared
Fx	force in the X degree of freedom (aircraft drag)
Fy	force in the Y degree of freedom (aircraft lateral)
Fz	force in the Z degree of freedom (aircraft vertical)
HW	hot wet
i.e.	"that is"
KCAS	knots calibrated airspeed
lb	Pound
lbs	Pounds
mm	Millimeters
My	pitch moment
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NS	Navier–Stokes
OEM	Original Equipment Manufacturer
psi	pounds per square inch
q	dynamic pressure
RTD	room temperature dry
SA	Spalart–Allmaras
sec	seconds
SPH	Smoothed Particle Hydrodynamics
SST	Menter Shear Stress Transport

V&V	Verification and validation
vs.	versus
W	weight
X	fuselage station coordinate
y+	dimensionless wall distance

Abstract

Applicants seeking Federal Aviation Administration (FAA) certification for an aircraft are required to provide substantiation of the aircraft's ability to successfully execute a controlled emergency landing on a body of water per 14CFR Part 25.801, also known as a ditching maneuver. FAA certification for ditching requires that the passengers and crew can survive, with minimal risk of injury, and successfully evacuate the aircraft prior to it sinking. The post-evacuation state of the aircraft is not a consideration.

Traditionally, ditching certification applicants have had two approaches available to them: establishing similarity to an already certified aircraft sufficient to satisfy the FAA or performing physical testing using scale models and/or a full airframe. While these two approaches are still acceptable today, advances in computational computer tools have created a third approach that may be appropriate for a ditching certification applicant. This document discusses best practices for model development and simulation of each phase in a ditching maneuver (approach, impact, landing, floatation, and evacuation). This report also recommends requirements for applicants simulating an aircraft's ditching performance, and questions regulators can ask to evaluate an applicant's simulation.

Motivation

The Federal Aviation Administration (FAA) Policy and Standards Division (AIR-600) needs to address limitations in existing policy and guidance so FAA and industry can more efficiently certify aircraft components.

Based on this research report, AIR-600 will address the limitations in existing FAA policy and guidance to help FAA and industry certify aircraft components more efficiently by fiscal year 2030 (FY30). This research will support FAA and industry in making informed aircraft certification decisions for ditching applications when they submit modeling and simulation data. This research report will support the development of an FAA framework that allows analysis to be directly used in certifying new products.

This research report discusses best practices for developing models and simulating each phase of a ditching maneuver (approach, impact, landing, flotation, and evacuation). This research report recommends requirements for applicants simulating an aircraft's ditching performance and poses questions regulators can ask to evaluate an applicant's simulation.

Introduction

The ditching maneuver is typically divided into five phases: Approach, Impact, Landing, Flotation, and Evacuation. Compliance with the FAA regulations is shown through design, analysis (including simulations), testing, or a combination of these.

The Approach Phase encompasses the beginning of the ditching maneuver, from the determination by the crew that a ditching maneuver is necessary through the airframe's final approach to the body of water. Certification analysis for this phase is focused both on identifying acceptable aircraft flight parameters for approach and on defining the aerodynamic initial conditions at the point of water contact.

The Impact Phase encompasses the initial airframe contact with the water. This phase produces the greatest impact forces on the airframe. It is during this phase that airframe damage is typically initiated.

The Landing Phase of a ditching maneuver encompasses the portion of the maneuver initiated immediately after initial contact with the water through the final settling of the aircraft.

FAA certification analysis for the Impact and Landing Phases is often combined, as these data are typically generated by a single physical test or computer simulation that encompasses both phases. The separation of analysis data for the Impact and Landing Phases is not required for FAA certification, though it is often performed during the design and internal testing stages of aircraft development.

The Flotation Phase of a ditching maneuver encompasses the portion of the maneuver initiated immediately after the aircraft has lost all forward velocity and has come to rest on the water's surface. FAA certification for ditching requires that the aircraft remain sufficiently buoyant during the Flotation Phase to allow all passengers and crew to successfully exit the aircraft and enter available life rafts.

The Evacuation Phase of a ditching maneuver encompasses the portion of the maneuver initiated when crew and passengers begin their egress from the aircraft through to the release of the life rafts from the aircraft. In effect, the Evacuation Phase is a subphase of the Flotation Phase, as the Evacuation Phase occurs within the Flotation Phase. The Evacuation Phase requires separate analysis, however, as the Evacuation Phase is primarily concerned with the equipment and procedures necessary to safely evacuate all aircraft occupants, not with the aircraft's ability to maintain sufficient buoyancy throughout the entire evacuation of the aircraft.

Materials and Methods

APPROACH PHASE

The Approach Phase of a ditching maneuver is the only phase in which the flight crew is primarily responsible for the aircraft's responses. Once the aircraft contacts the water, the dynamic forces caused by this contact will become the primary driver of the aircraft's responses.

How the aircraft enters the water will have a significant impact on the resulting airframe responses in a ditching maneuver. One of the primary goals in Approach Phase analysis is, therefore, the determination of the flight condition(s) (altitude, airspeed/Mach, and attitude) that must be achieved by the flight crew prior to water contact in order for the aircraft to successfully execute the entire ditching maneuver. In addition to the aircraft design parameters, the determination of an acceptable flight condition for the ditching approach requires the determination of the aerodynamic loads experienced by the aircraft up to and including the point of initial impact with the water. These aerodynamic loads must be included in the aircraft loading experienced during the initiation of the Impact Phase analysis.

Modeling and simulation have been accepted by the FAA for findings of compliance with specific regulations using validated geometric surface models and accepted numerical simulation methodologies. This section will discuss the use of one acceptable method, computational fluid dynamics (CFD), to develop the aerodynamic loads on a transport aircraft in support of showing compliance to 14 CFR Part 25.801 (Reference 1).

The technical report “Transport Water Impact and Ditching Performance” (Reference 2) defines ditching as “a planned emergency landing in water” with a descent rate no greater than 5 ft/sec and vertical and longitudinal loads within the aircraft design parameters. CFD can be used to determine the aerodynamic loads acting on the aircraft at the moment of impact with the water for the Approach Phase of the analysis. These aerodynamic loads, along with inertia loads, are then mapped to a finite element model that can be used to evaluate the aircraft’s structural responses during the Impact and Landing Phases of the ditching maneuver.

CFD analysis has been successfully used to predict external aerodynamic loads (forces and moments) acting on the total aircraft and on individual components of the aircraft (fuselage, wings, horizontal, vertical, antennas, and radomes) for a given flight condition (altitude, airspeed/Mach, and attitude). Successful use of CFD in generating accurate loads, however, depends on three things:

- the accuracy of the external surface model geometry
- the model mesh/gridding methodology
- the flow solver

Surface Model Development

Surface model geometry can be developed from aircraft loft line drawings or, more typically, using high-accuracy 3D laser scanning. The resulting point cloud is used to develop the surface model and dimensionally verified against all major dimensions, control surface dimensions, positions, deflection angles, and surface smoothness. Scans would include all flap/slat positions and stabilizer trim travel. It is important to know how the surface model was developed and, if scanning was used, the accuracy of the scanning tool used to generate the data. Scan accuracies up to 0.1 inches (2.5mm) are typically acceptable for producing surface models. Surface discontinuities such as skin lap joints do not need to be modeled for the fuselage unless in critical locations, such as flow stagnation or slope transition points, where a more precise solution is required. Wing and flight control trailing edge thicknesses of 0.25 inches or greater should be modeled.

Model Grid Development

Grid generation, or meshing, plays a critical role in the quality and accuracy of the CFD solution. Coarse or poor-quality grids can lead to highly inaccurate results. The meshing technique used by the aerodynamic engineer/modeler is a key contributor to the accuracy of the CFD results. The engineer must define initial grid spacing based on the desired y+ (dimensionless wall distance) to characterize the boundary layer of the surface model. The engineer must also verify that areas of known flow concern (leading edges, trailing edges, surface intersections, radomes, etc.) have adequate cells to accurately capture the local flow effects. Meshes can be structured (regular-shaped, usually four-sided, easy to define and assemble) or unstructured (flexible, varying shape, complex geometries). Figure 1 shows an example of an unstructured surface and far-field mesh.

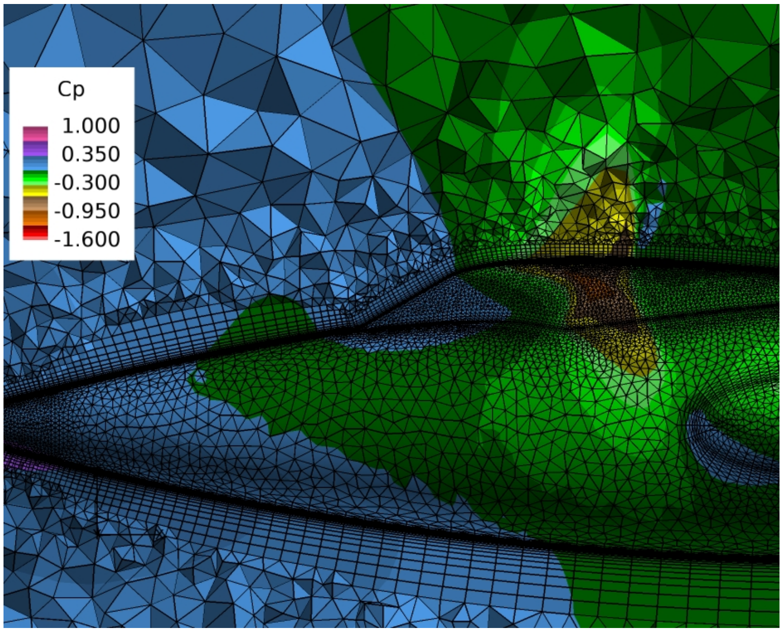

Figure 1 – Example of Surface and Far-Field Grid

One of the key aspects of an accurate CFD solution is to develop a grid/mesh that minimizes the uncertainty and error in the simulation results. A coarse grid will tend to be less accurate and have a greater error than a fine (denser) grid. A grid convergence study can be performed to determine how the refinement of the grid improves the solution. This is accomplished by running a flow solution test case using a nominal grid density. The model is then modified to a finer grid, and the test case is repeated. The refinement and run are again repeated for a finer grid. The solutions (example: total and/or component Fx, Fy, Fz) for each are then compared to see the change in values for each grid refinement and to evaluate the potential error. A detailed discussion on grid convergence studies can be found in the following NASA hyperlink:

https://www.grc.nasa.gov/www/wind/valid/tutorial/spatconv.html

A coarse mesh will take less computational time than a fine mesh. Depending on the application of the CFD analysis, there may be diminishing returns to a highly refined grid model. A grid model that requires three times the computational time compared to a more coarse model but only produces a 1% increase in accuracy is not an efficient use of computational resources, especially if multiple conditions are required to be run. For CFD analysis of transport aircraft, the grid modeling methods for accurate solutions tend to be repeatable from one transport aircraft to another. In other words, the gridding method used on a B757 will be the same as that used on a B737 or an Airbus A320 or an Embraer 195. See Reference 3 for guidance on grid/mesh densities used in CFD. The total grid count may vary, but the method for determining the grid spacing will be the same. This is why a CFD background and CFD experience are needed to minimize uncertainty and errors in the simulation.

Flow Solver

In the past twenty years, significant improvements in computational technology have made it more time- and cost-efficient to solve the Navier–Stokes (NS) equations. The NS equations are used to solve viscous fluid motion. Fluid (gas or liquid) flow produces boundary layer motion that is laminar (steady, no turbulence) or turbulent (unsteady, chaotic) flow, as shown in Figure 2.

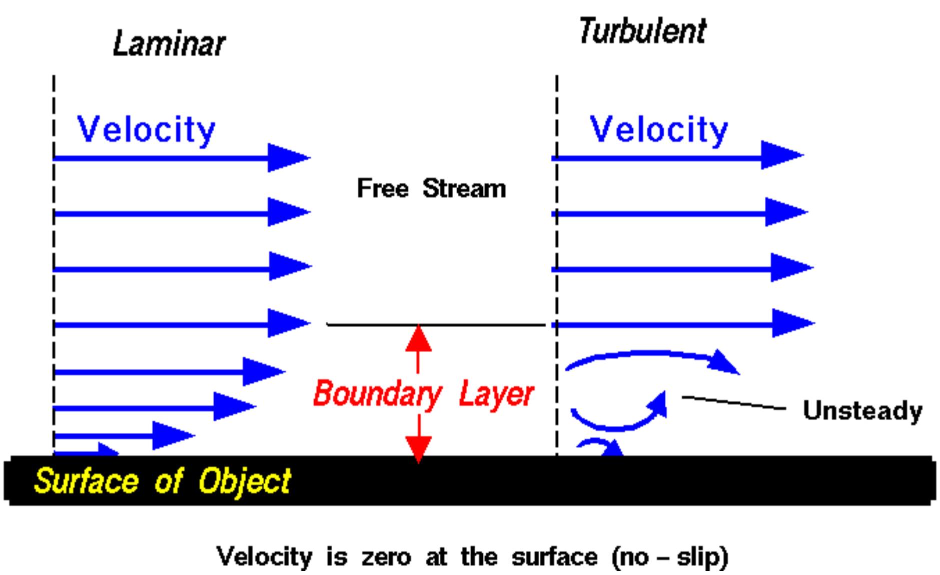

Figure 2 – Laminar vs. Turbulent Boundary Layer Motion

Boundary layer flow analyzed for aircraft loads is predominantly turbulent. There are various turbulent models that can be selected for use in the NS flow solver. Turbulence models are used within NS to model the average turbulent flow effects. Two of the widely used turbulence models for subsonic flow are the Spalart–Allmaras (SA) model and the Menter Shear Stress Transport (SST) model.

There are multiple commercial and government-developed NS flow solver tools available for use. Examples are Ansys' Fluent, Siemens' STAR -CCM+, and NASA's FUN3D. The commercial solvers typically integrate pre- and post-processing software into the software package to allow for grid development, a flow solver, post-analysis, and presentation. The stand-alone solvers typically require separate tools to develop the surface grid and far-field grid (Figure 1), as well as a post-processing solution for data analysis. Examples of post-process results are shown in Figure 3.

The selection and use of the flow solver is also part of this methodology. The engineer/modeler needs to know the capabilities and limitations a specific solver might have. The FAA has previously accepted a methodology if it could be validated against known flight test data. An example of this is modeling the X-15 research aircraft using surface geometry obtained from NASA and comparing it to in-flight surface pressure data documented in the NASA flight test report (Reference 4).

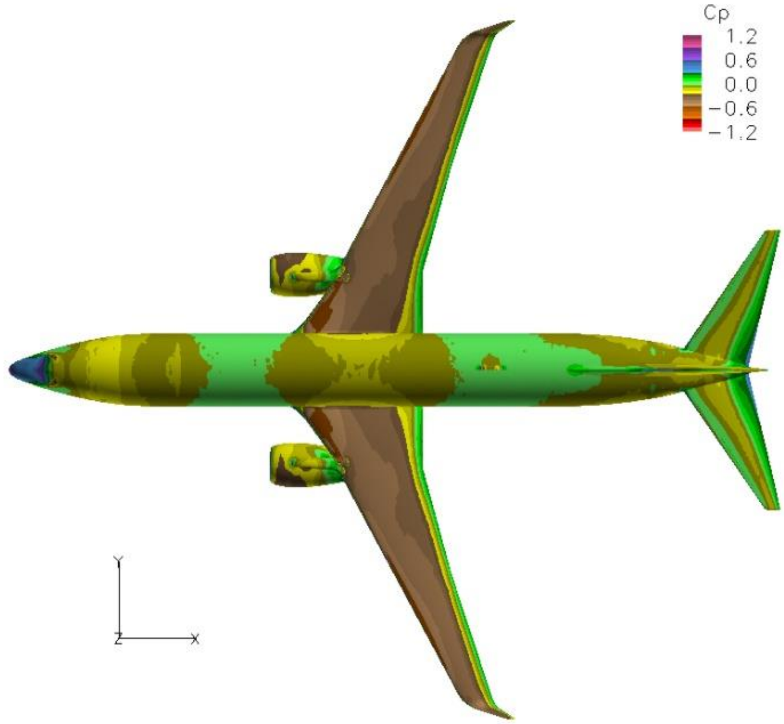

Figure 3 – Example of Surface Pressure (Cp) Results from NS Flow Solver

Methods of Model Validation

For a ditching maneuver, the airspeed range of interest is limited to below Mach 0.3, which is less than 200 knots calibrated airspeed (KCAS) conditions. The CFD model and methodology can be validated by two methods, as follows:

a. Use either flight test data from 1 g stall testing in the landing configuration or the published landing configuration stall speeds from the Aircraft Flight Manual (AFM) for comparison to the CFD maximum lift coefficient (CL) values for the same configuration and airspeed conditions. CL is a function of the weight and airspeed (q) for a specific configuration where CL = W/(q * Aref).
   Where:
   CL = Coefficient of lift (non-dimensional)
   W = Weight of the aircraft – pounds
   q = Dynamic pressure ($\frac{1}{2} \rho V^2$) – lb/ft^2
   Aref = Wing reference area – ft^2

   Comparative results should be within ± 5%. A minimum of three points should be used. Method to calculate the $\%\Delta = ((CL_{CFD} - CL_{AFM}) / CL_{AFM}) * 100$ *(see Figure 4).*

Published AFM DATA

Landing Wt (lb)	Stall Speed* KCAS	q (lb/ft)	C_L
55,000	95.3	30.7477	1.743
60,000	99.4	33.4502	1.748
65,000	104.4	36.9001	1.717

CFD Results

Altitude	q (lb/ft)	Max CL	ΔCL	%Δ
S. L.	30.74	1.72	-0.023	-1.33
S. L.	33.45	1.69	-0.058	-3.32
S. L.	36.9	1.73	0.013	0.77

* for landing configuration

Aref = 1026.1 ft^2

Figure 4 – Example of Maximum Lift Comparison

b. Compare CFD lift and drag coefficient (CL & CD) results to wind tunnel results for the same configuration and run conditions. Verify that the CFD model produces results within ±5% of wind tunnel results. This is done on a point-to-point basis. Some technical discretion should be used for a point that falls outside of the range. See Figure 5.

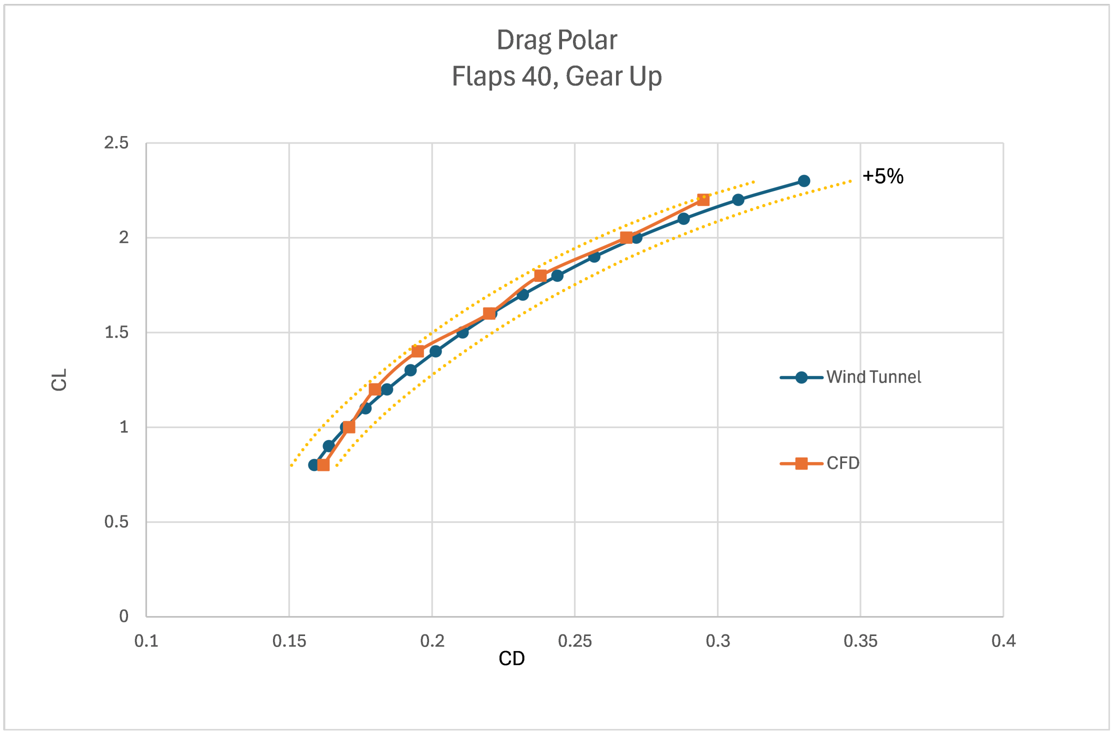

Figure 5 – Example Drag Polar

Using CFD for the Approach to Ditching

For ditching maneuver analysis, the aerodynamic loads acting on the aircraft prior to water impact will need to be determined. Multiple variables will determine these external loads, including flap configuration, airspeed, and angle-of-attack. The airspeed and angle-of-attack will be a function of aircraft weight and center of gravity (CG) for the configuration.

Configuration

Section 2.1 of Reference 2 provides a recommended procedure and configuration for the ditching maneuver. To minimize the energy at impact with the water and improve survivability, the aircraft should be flown at the lowest speed and minimal descent rate at which control of the aircraft is maintained. Transport aircraft typically have multiple flap/slat configurations available. The use of flaps/slats increases lift and reduces stall speed for a given weight. The available configurations at heavy and light weights should be analyzed to determine the acceptable ditching configurations. Additionally, to maximize pilot controllability and minimize deceleration at touchdown, the gear should be retracted. To summarize, the aircraft configuration should:

- minimize weight if possible (dump fuel if time permits)
- have flaps/slats deployed (landing or approach to minimize speed)
- be geared up/stowed (to minimize deceleration and structural damage)

Airspeed

The airspeed to be flown for the Approach Phase will be based on the flap configuration and aircraft weight. With large transport aircraft, approach speeds can vary greatly with changes in weight due to fuel and payload. The analysis should cover the lowest and highest stall speeds for the weight and flap configuration. The airspeed at impact should be at or just above stall warning (typically at the start of aerodynamic buffet or, if so equipped, the stick shaker) to minimize descent rate and forward velocity while maintaining aircraft control. The airspeed used for the analysis is based on knots calibrated airspeed or KCAS. Calibrated airspeed is the indicated airspeed the pilot reads off the aircraft airspeed indicator corrected for position (location of the static port) and instrument errors. The airspeed correction is usually found in the performance section of the Aircraft Flight Manual (AFM). A knot is defined as the speed to move 1 nautical mile (6080 ft) in one (1) hour.

Aircraft Attitude

At impact, the aircraft should have a pitch attitude of 10° to 14° degrees nose up (Reference 2), allowing the aircraft to slow and contact the water tail down. The nose should be held up as long as possible after water contact. The aircraft should be maintained directionally straight with wings level. Pitch is defined as the angle between the aircraft's longitudinal axis and the horizon. Angle-of-attack is defined as the angle between the aircraft longitudinal axis and the flight path of the aircraft.

- Nose up 10° to 14° (Figure 6)
- Directionally straight (no yawing, Figure 7)
- Wings level (no roll, Figure 8)

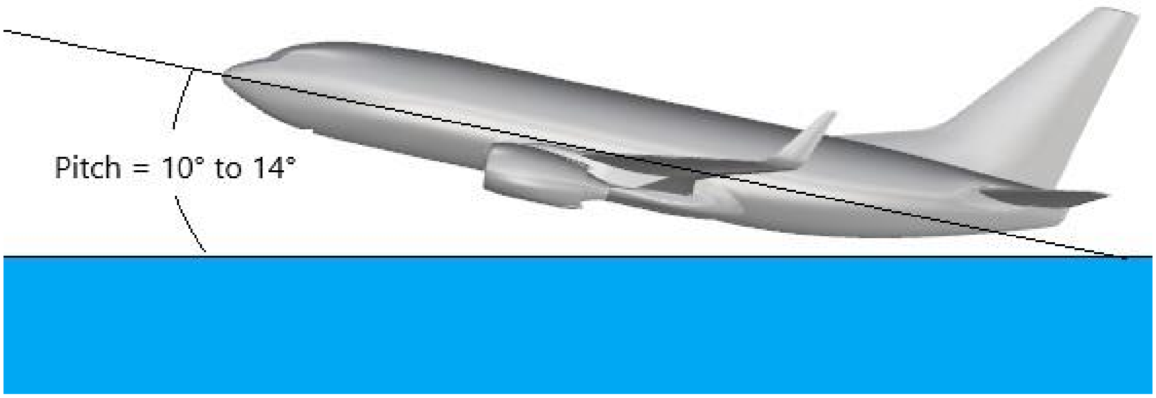

Figure 6 – Pitch Attitude

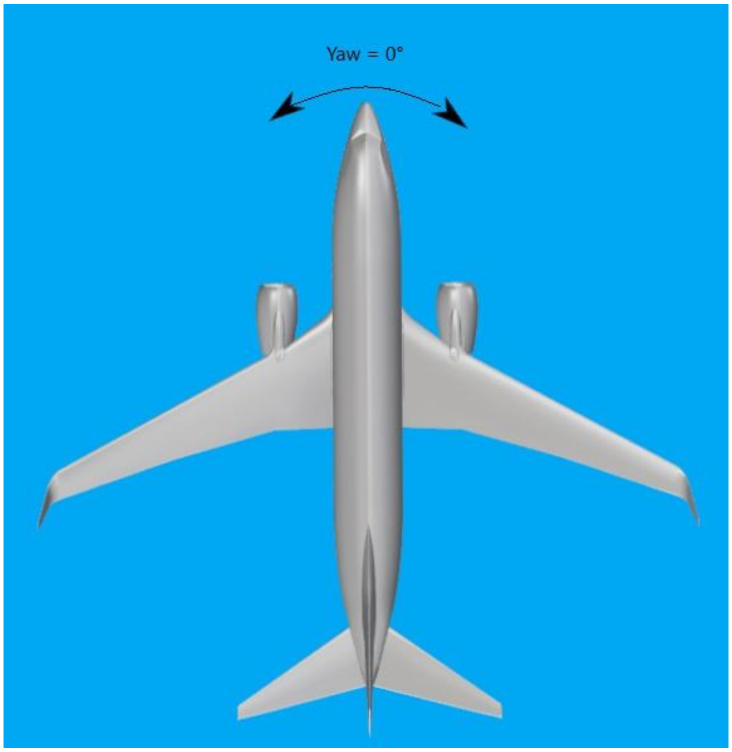

Figure 7 – Yaw Attitude

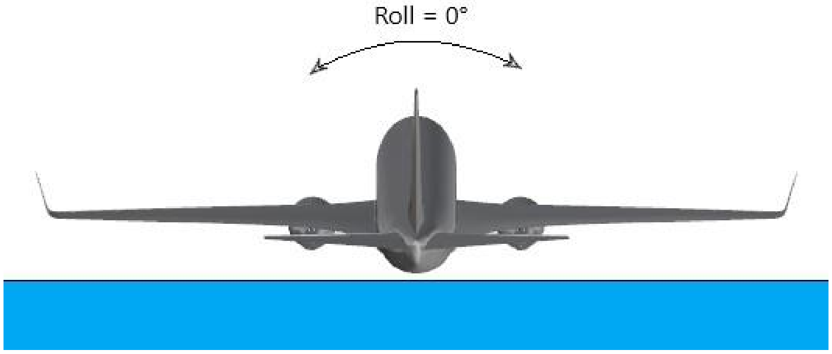

Figure 8 – Roll Attitude

Load Conditions

Based on the configurations, airspeeds, weight, and CG discussed above, a matrix of ditching conditions will be run. Heavy aircraft will have a higher impact speed than light aircraft. The CG position will also influence stall speed for conventional aircraft. A forward CG will increase stall speed as compared to the same weight at an aft CG. An example set of load conditions is shown in Table 1.

CASE ID	SPEED (MACH)	VELOCITY (KCAS)	Altitude (ft)	q (lb/ft^2)	Alpha (deg)	Beta (deg)	Flaps	W (lb)	CG
1	0.2116	141	0	0.46	8	0	Full	145000	Aft
2	0.2116	141	0	0.46	14	0	Full	145000	Fwd
3	0.136	102	0	0.19	8	0	Full	80000	Aft
4	0.136	102	0	0.19	14	0	Full	80000	Fwd
5	0.222	147	0	0.508	8	0	Approach	145000	Aft
6	0.222	147	0	0.508	14	0	Approach	145000	Fwd
7	0.1663	110	0	0.2845	8	0	Approach	80000	Aft
8	0.1663	110	0	0.2845	14	0	Approach	80000	Fwd

Table 1 – Example of CFD Approach to Ditching Conditions

	Load Set	EID	P1	P2	P3	P4
PLOAD4	1	1	-0.141	-0.127	-0.127	
PLOAD4	1	2	0.045	-0.037	-0.031	0.024
PLOAD4	1	3	0.024	-0.031	-0.032	0.014
PLOAD4	1	4	0.014	-0.032	-0.028	0.003
PLOAD4	1	6	-0.014	-0.006	-0.033	-0.034
PLOAD4	1	7	-0.004	-0.032	-0.033	-0.006
PLOAD4	1	8	-0.004	0.003	-0.028	-0.032
PLOAD4	1	9	0.053	-0.045	-0.037	0.045
PLOAD4	1	10	0.067	-0.053	-0.045	0.053
PLOAD4	1	11	0.060	-0.057	-0.053	0.067
PLOAD4	1	12	0.079	-0.040	-0.057	0.060
PLOAD4	1	13	0.112	-0.013	-0.040	0.079
PLOAD4	1	14	0.152	0.027	-0.013	0.112
PLOAD4	1	15	0.190	0.072	0.027	0.152
PLOAD4	1	16	0.243	0.134	0.072	0.190

Figure 9 – Example of Mapped CFD Pressure Load on Surface

Results from the CFD analysis of each run will produce surface pressures distributed on the surface of the aircraft. As shown in Figure 9, these resulting pressures can then be mapped to the structural FEM surface nodes to provide aerodynamic normal forces acting on the aircraft at the initiation of the Impact Phase of the ditching maneuver. Figure 9 is an example of a NASTRAN PLOAD4 card set that is used to load the FEM element identification number (EID) nodes with unit load normal to the surface of the element (P1, P2, P3, P4). The "Load Set" provides an option to record the run set used to generate the unit load for each line. An example of an EID quad element with mapped pressures is shown in Figure 10. Other methods besides NASTRAN may also be available.

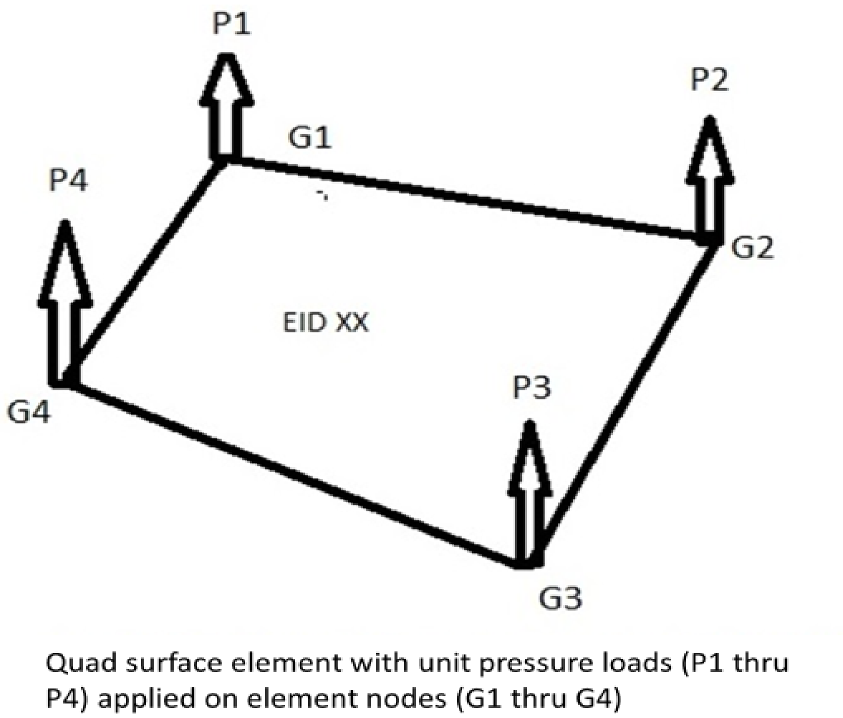

Figure 10 – Example of FEM Element with Pressure Loads

IMPACT AND LANDING PHASES

Unlike the other three phases of a ditching maneuver, the Impact and Landing Phases produce kinetic energy transfer between the airframe and water. As such, it is during these two phases that most or all airframe damage will occur.

Because the Impact and Landing Phases are a single dynamic event within the ditching maneuver, a single analysis can be provided to show FAA compliance.

Historically, scale-model physical tests were employed to validate FAA ditching compliance. This approach requires a physical model to be designed and fabricated that is then subjected to physical testing, which may be destructive. The potential degradation of a physical model from physical testing may require additional models to be built before testing can be resumed.

The development of finite element analysis (FEA) has made it possible to create virtual models with which computer simulations of ditching maneuvers can be performed. Unlike physical models for physical testing, FEA models of the airframe and water can be subjected to repeated ditching simulations without suffering degradation.

Many aircraft companies employ FEA models and simulations for the development of their aircraft. FEA models and simulation results created during the development of an aircraft can be used to show compliance with certification requirements. For ditching maneuver simulations, both an airframe structural model and a hydrodynamic sea model are developed. Note that there will need to be a hydrodynamic sea model for each sea state being analyzed.

A simulation composed of the airframe structural model and one hydrodynamic sea state model is used to show results for both the Impact and Landing Phases. Numerous simulations, each composed of various Approach Phase parameters combined with various sea state models, may be required to show compliance with 14CFR Part 25.801 (Reference 1). This section discusses considerations and best practices for creating these FEA models and simulations.

Impact Phase-Specific Considerations

Although both phases are run as a single simulation, the Impact Phase is distinct from the Landing Phase in several ways. The Impact Phase produces the greatest forces on the airframe; it is during this phase that airframe damage is typically initiated; and this phase is directly affected by the results of the Approach Phase, as discussed below.

Impact Phase Parameters

Unlike an uncontrolled crash, a ditching maneuver allows the flight crew to configure the aircraft and its flight path to predetermined parameters. These flight parameters can directly affect the airframe’s responses during the Impact Phase of a ditching maneuver. Determining preimpact flight parameters that will minimize unacceptable damage to the airframe during a ditching maneuver is a necessary component of a successful application for ditching certification.

Flight parameters are largely determined by aircraft characteristics, such as stall speed, and as such, are typically determined during the analysis of the Approach Phase. These parameters include but are not limited to the definition of the flight path with respect to the sea state, impact and landing velocities, impact angle of attack, impact and landing airframe weight, and mass distribution. The Impact Phase of a ditching maneuver evaluates the effects of the Approach

Phase parameters on the airframe during initial contact with the water. Note that during airframe design development, it may be necessary to reassess the Approach Phase if the Impact Phase analysis reveals unacceptable airframe failures.

As stated previously, analysis of the Approach Phase of a ditching maneuver should produce the flight parameters required to properly initiate an FEA simulation of the Impact Phase. Airframe parameters determined by the airframe's design are also required to properly create an FEA airframe model for use in this simulation. Table 2 contains a non-exhaustive list of parameters required for performing Impact Phase analysis.

Ditching Maneuver Impact Phase Parameter	Defined By
Center of Gravity	Airframe Design
Contour of Lower Belly	Airframe Design
Engines Arrangement	Airframe Design
Gear Arrangement	Airframe Design
Wing Arrangement	Airframe Design
Mass	Airframe Design
Structural Arrangements Between Nose and Fwd Fuselage	Airframe Design
Structural Arrangement Between Wing and Tail	Airframe Design
Accelerations	Approach Phase Analysis
Attitude	Approach Phase Analysis
Flap Configuration	Approach Phase Analysis
Flight Path	Approach Phase Analysis
Gear Positions	Approach Phase Analysis
Velocity	Approach Phase Analysis
Airframe Applied Pressure and Distribution Due to Seas	Approach Phase Analysis
Sea State	Approach Phase Analysis
Aircraft's Relative Approach to Sea State (Parallel, Normal, Etc.)	Approach Phase Analysis

Table 2 – Primary Ditching Impact Phase Parameters

Landing Phase-Specific Considerations

Landing Phase Parameters

Unlike the Impact Phase, which begins with initial conditions that can be determined independently, i.e., without FEA simulation results, the Landing Phase's "initial conditions" are dependent on the airframe and hydrodynamic sea models' responses to the Impact Phase. For a single simulation, the parameters defining the transition from Impact to Landing Phase can be identified by the FEA solver directly.

The highest loads generated between the hydrodynamic water model and airframe model during the Landing Phase will occur in the nose region of the airframe. Following the Impact Phase, the airframe will rotate in a pitch-down fashion until the nose impacts the water. At this point in the simulation, the shockwave forces will now include a dependency on the airframe's angular acceleration. Note that the impact forces imposed on the airframe during the Landing Phase are directly proportional to the airframe's mass, linear accelerations, and angular accelerations. This is why the airframe model must include the correct mass and center of gravity, as discussed earlier.

FEA Simulation Considerations

The analysis performed for the Impact and Landing Phases of a ditching maneuver is used to identify the airframe responses during these phases. As stated, most or all airframe damage incurred during a ditching maneuver will occur during these two phases. The airframe responses from these two phases, including incurred damage, are then examined to determine whether conformity with FAA ditching requirements is achievable for the Flotation and Evacuation Phases. Note that it is likely that the Impact Phase of ditching will introduce airframe damage that must be accounted for during the Landing Phase. For example, during the Impact Phase, the metallic airframe structure could exceed yield or rupture prior to the Landing Phase, while the airframe composite structure could accumulate damage or fail.

FEA Simulations vs. Physical Test Simulations

As stated previously, a single FEA simulation is typically performed to analyze both the Impact and Landing Phases. Compared to scale-model and destructive airframe testing, the use of FEA tools can significantly reduce the cycle time for evaluation of Approach Phase parameter variations, such as sea state variations, as well as any design concepts that may need to be introduced in order to conform to FAA ditching certification requirements. Once FEA models have been constructed that accurately represent the airframe and the water, simulations using the flight parameters defined in the Approach Phase can be performed that capture the progressive airframe responses from the initiations of the Impact Phase through the final settling of the Landing Phase.

Airframe/Water Impact Loading Considerations

A ditching maneuver will result in a high-speed water impact on the airframe, which introduces airframe loadings that are unique from all other airframe design conditions. These loadings include airframe responses (shockwaves) that are dynamic in nature and involve the interaction between a hydrodynamic body and a metallic and/or composite airframe.

Because an airframe's design is not uniform across its long axis, the airframe's response to these shockwaves will vary depending on the water's impact zone on the airframe. It is common to set aircraft parameters during the Approach Phase of ditching that will limit the airframe impact zone to an area of the airframe that can sustain the highest fuselage belly loads with minimized damage. For example, areas between the wing and tail that include bulkheads are commonly selected as primary impact zones rather than areas that only include simple framing structures. Note that the selection of the initial impact zone during the Approach Phase has a direct effect on the airframe's response during the Impact Phase and a significant, if indirect, effect on the airframe's response during the Landing Phase.

Analysis Requirement Considerations

If an applicant is unable to substantiate a sufficient similarity to an airframe that has already been granted FAA certification for ditching, an applicant will need to provide airframe analysis for the Impact and Landing Phases before ditching certification can be granted.

In some instances, the airframe being submitted for FAA ditching certification is similar to an existing certified airframe. If these airframes are sufficiently similar, the granting of FAA ditching certification for the uncertified airframe may not require comprehensive ditching maneuver analysis or any additional ditching analysis at all. If additional analysis is determined to be necessary, a full comprehensive ditching maneuver analysis may still not be required. For example, the analysis required to show compliance with FAA ditching criteria for a new non-derivative airframe would be greater than that required for a new derivative airframe, and that would be greater than that required for the addition of a fairing to the belly of an existing certified airframe. Determining whether ditching maneuver analysis must be performed in these instances will be a point of discussion between the FAA and the applicant.

Regardless of the extent of the analysis required, analysis of an airframe's response to the Impact and Landing Phases of a ditching maneuver must be performed in a manner acceptable to the FAA in order for certification to be granted. This section will offer guidance for producing an acceptable analysis of these two phases using FEA simulations.

FEA Methodology Considerations

Determining Appropriateness of FEA Simulation Approach

FEA models and simulations of ditching maneuvers can be appropriately used to substantiate an airframe's compliance with FAA ditching requirements in most instances. The appropriateness of an FEA simulation approach for a given applicant, however, depends on the abilities of the FEA solver the applicant chooses to employ and the applicant's level of adherence to acceptable FEA guidelines.

FEA solver requirements and FEA guidelines for producing a ditching maneuver analysis acceptable for FAA ditching maneuver certification are discussed below. If an applicant is unable to meet these requirements and/or adhere to these guidelines, a non-FEA approach to performing this analysis should be employed by the applicant. A detailed discussion of non-FEA approaches to FAA ditching maneuver certification is beyond the scope of this document.

FEA Design Considerations

Accurate FEA model development for the Impact and Landing Phases of a ditching simulation requires properly addressing several FEA design considerations. FEA design considerations addressed in this document are:

- FEA Solver Selection
- FEA Model Design Guidelines
  - Element Formulations
  - Complex Parts
  - Boundary / Initial Conditions
  - Attachment Configurations
  - Airframe Mass
  - Material Curves Up to and Including Rupture
  - Interaction Between a Hydrodynamic Sea and Metallic / Composite Airframe Structure
- FEA Simulation Verification
- FEA Simulation Validation

Guidance for each FEA design consideration is provided below.

FEA Solver Selection

There are several FEA solvers available on the market that are used in the airframe industry. Not all solvers, however, have the capabilities necessary to accurately perform ditching analysis. The FEA solver employed by the certification applicant to produce acceptable certification ditching analysis must include the ability to:

- simulate hydrodynamics
- simulate the interaction between hydrodynamic entities and metal and/or composite entities (i.e., airframe structure)
- include element/part contact formulations that include friction properties
- accommodate element formulations that include material response curves beyond yield, up to and including the point of rupture, for relevant airframe materials — isotropic material response curves for metallic structure, anisotropic material elastic properties with failure allowables for composite structure
- accommodate element formulations that include accumulated damage and complete element failure
- correctly idealize fastener stiffness
- remove a fastener from the simulation based on deflections and/or mechanical fastener allowables
- automatically vary step size (commonly referred to as a “variable step size” feature) by reducing step size when interactions become complex in nature (node-to-surface contacts), an element’s damage has accumulated to near rupture, a fastener’s load or displacement is approaching a defined failure allowable, or a node is reaching a high acceleration state with respect to adjacent nodes

FEA Model Design Guidance

Element Formulations

Impacts that include a high energy transfer into the airframe structure can cause high deformations in the airframe at the point of impact. These high deformations limit the type of elements that can be used in these simulations.

For example, solid elements cannot be used to idealize impact surfaces. This is because solid elements that undergo high deformations during nonlinear FEA solver steps can cause the simulation to fail. This failure occurs when an element collapses, resulting in the solver attempting to generate a local stiffness matrix for a near-zero or zero element volume.

The preferred element type for impact surfaces is plate elements that include derivations supporting tractions, shear, and bending. It is important that the idealized structure matches the airframe’s stiffness and inertia as closely as possible to ensure that the responses in the simulation accurately reflect those of the aircraft structure.

Note that if the desired structural idealization for a thin part excludes bending stiffness, it is still recommended that bending stiffness be included in the part’s elements’ formulations. For thin parts, a bending load of any significance will not be generated. What is important is that each node in the model includes some amount of rotational stiffness in the global stiffness matrix. The lack of any rotational stiffness at a node can either introduce undesirable restraint forces into the part or result in abnormally high rotational accelerations that will cause the simulation to fail. This is especially true for nonlinear solutions such as those required in ditching maneuver simulations.

As stated in the FEA Solver Selection section, the plate element's derivation must include the ability to generate differential stiffness matrices that can be updated to include the effects of stress, strain, damage, and failure. This is necessary because element deformations (i.e., shape changes) can occur during a dynamic simulation that will affect the element's stiffness. If the element's stiffness matrix is not updated during each nonlinear step, the model simulation will fail to incorporate property changes (beyond yield), progressive damage, failures, and deformations correctly. A dynamic nonlinear analysis must include the ability to update an element's stiffness for each nonlinear step due to these deformations, as well as the ability to update accumulated element damage. Note that in high-impact regions of the model, an element's properties will change from step to step after the element has exceeded its yield strength. This is why, as stated previously, it is an FEA solver requirement to be able to include full material curves up to and including rupture for ditching simulations.

Fastener element derivations must include the ability to define stiffness in at least the axial and shear planes, and a fastener coordinate system. If the fastener uses the global aircraft coordinate system and the fastener is not parallel to that system, the axial and shear stiffnesses will be applied incorrectly to the model's global stiffness matrix. Note that this would also affect the ability of the solver to properly accumulate damage and failure because the axial and shear planes would be incorrectly assigned.

Complex Parts

In general, the FEA solver employed to perform ditching maneuver analysis must be able to correctly idealize the affected airframe structure. In some instances, however, complex parts that cannot be excluded from the airframe model are overly difficult to correctly idealize using 2D plate elements.

Certain complex components, like the seats, are designed to avoid introducing extra load paths that could affect the stiffness of the airframe structure, thus avoiding additional airframe bypass loads. A non-load path complex part is typically represented in the airframe model as a mass item at the part's CG. These non-load path mass items are typically attached to the airframe model using load distribution elements that do not add stiffness to the airframe model's global stiffness matrix.

Complex parts that introduce load paths into the airframe can be represented in the airframe model by including their correct stiffness and matrix coupling terms in the model. The correct stiffness values for the complex part can be calculated by building a detailed static model of the part that represents the part's shape, volume, and elastic material properties. For meshing efficiency, it is acceptable to use 3D solid elements in this detailed static model, as opposed to 2D plate elements. Using a static solver, the detailed part can be restrained at attach points on one end and unit loaded (i.e., 1,000 lbs) at attach points on the opposite end. The resulting displacements on the loaded part can be used in conjunction with the known unit load to calculate the part's stiffness in particular degrees of freedom. Once these stiffness values have been calculated, 1D elements (i.e., springs) with those stiffness values can be added to the airframe dynamic model, thus including the correct stiffness for complex parts in the airframe model. The dynamic solver can then add the appropriate coupling terms necessary to fully idealize the complex part's load path.

If a complex part introduces a load path into the airframe but has insignificant mass, the addition of the part's stiffness into the dynamic airframe model is sufficient to represent the complex part in the airframe model. If, however, the complex part's mass is significant, a mass item must be included in addition to the part's stiffness. As with non-load path complex parts, this mass item is included in the airframe model at the part's CG.

Note that while this inclusion is usually sufficient to properly represent the complex item's effect on the simulation's overall airframe responses, it may be necessary to perform additional component testing, i.e., physical testing, of the complex item and its attachments. This testing is necessary if the complex item could cause unacceptable damage if it separated from its attachments during the Impact and/or Landing Phases.

Boundary / Initial Conditions

The boundary conditions for the FEA simulation are essentially the initial conditions for the Impact Phase of ditching. As such, they must be derived during Approach Phase analysis prior to initiating an FEA simulation intended to analyze the airframe responses to the Impact and Landing Phases of ditching. These conditions include velocity vectors, airframe attitudes, structural arrangements, mass, mass distributions, and sea states.

FEA simulations used to evaluate the Impact and Landing Phases of ditching must include two separate models: one of the hydrodynamic sea and one of the airframe structure. The hydrodynamic sea model's initial condition includes a static state (no velocities or accelerations). At the initiation of the Impact Phase of the FEA simulation, the airframe model's initial conditions will include the velocity vectors defined by the Approach Phase analysis. Since the airframe model will move towards and impact the hydrodynamic sea model, the hydrodynamic sea model's initial conditions do not include additional velocity vectors.

Unlike the Impact Phase, boundary conditions for the Landing Phase cannot be derived prior to initiating an FEA simulation designed to analyze airframe responses during both the Impact and Landing Phases. In effect, the boundary conditions for the Landing Phase of an FEA simulation are generated by the simulation itself during the Impact Phase of that simulation.

Note that the boundary conditions for the Landing Phase must include not only velocity vectors, accelerations, airframe attitudes, structural arrangements, mass, and mass distributions resulting from the Impact Phase but also damage that the airframe experiences during the Impact Phase. This damage must be incorporated into the airframe model geometry prior to restarting the simulation at the point of initiation of the Landing Phase. Airframe responses due to dynamic impacts include shockwaves and accumulated damage. This is discussed in greater detail in the sections on Material Curves Up to and Including Rupture, and Interaction Between a Hydrodynamic Sea and Metallic / Composite Airframe Structure.

Carveout Models

In some cases, such as a modification to an existing airframe that has already been certified for ditching, the entire airframe may not need to be represented in an FEA simulation being used for ditching certification. For example, if a modification has been made to the fuselage belly aft of the wing in a pressurized area, a ditching simulation analysis model does not need to include the tail, wings, or forward fuselage. Assuming a coarse-resolution full-airframe FEA model already exists, a carveout model may be the most suitable approach.

A carveout model is essentially a subsection of a full-airframe model that has been removed or "carved out" from the full-airframe coarse model and remodeled at a higher resolution and with more structural details. Figure 11 is an example of a detailed carveout model.

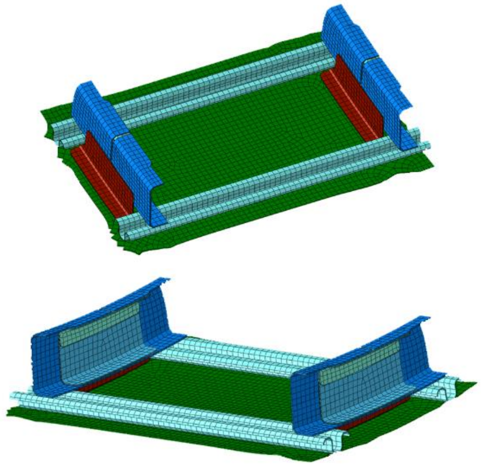

Figure 11 – Carveout Model of a Fuselage Section

As Figure 11 shows, a carveout model does not include much of the airframe structure. The stiffness, mass contributions, and inertia properties of the excluded airframe structure, however, must be included. This is accomplished by adding these properties as boundary conditions. If the carveout model's boundary stiffness and mass are incorrect, the simulation will not represent the correct airframe response to dynamic impact forces, which are directly proportional to the airframe's total mass.

In general, stiffness matrices are accumulative. The stiffness of each node in a model is essentially a summation of the stiffness of each element that attaches to that node, along with the appropriate coupling terms. A carveout model will include nodes at its cut boundary, but those boundary nodes will be missing accumulated stiffness and mass values from the airframe structure that was excluded from the carveout model. It is possible to add these missing contributions to the boundary nodes by including them during the solver's global matrix assembly stage.

A common format for including these missing terms in the solver's assembly stage is a Direct Matrix Input at a Grid (DMIG). A DMIG is fundamentally a vector list of node IDs, their degrees of freedom, and their stiffness and mass values. This list is generated by removing the carveout area from an existing full-airframe model (static or dynamic) and requesting the solver supply stiffness and mass values for the nodes at the carveout area cut boundary (a DMIG). Figure 12 shows these boundary nodes for the carveout model example in Figure 11.

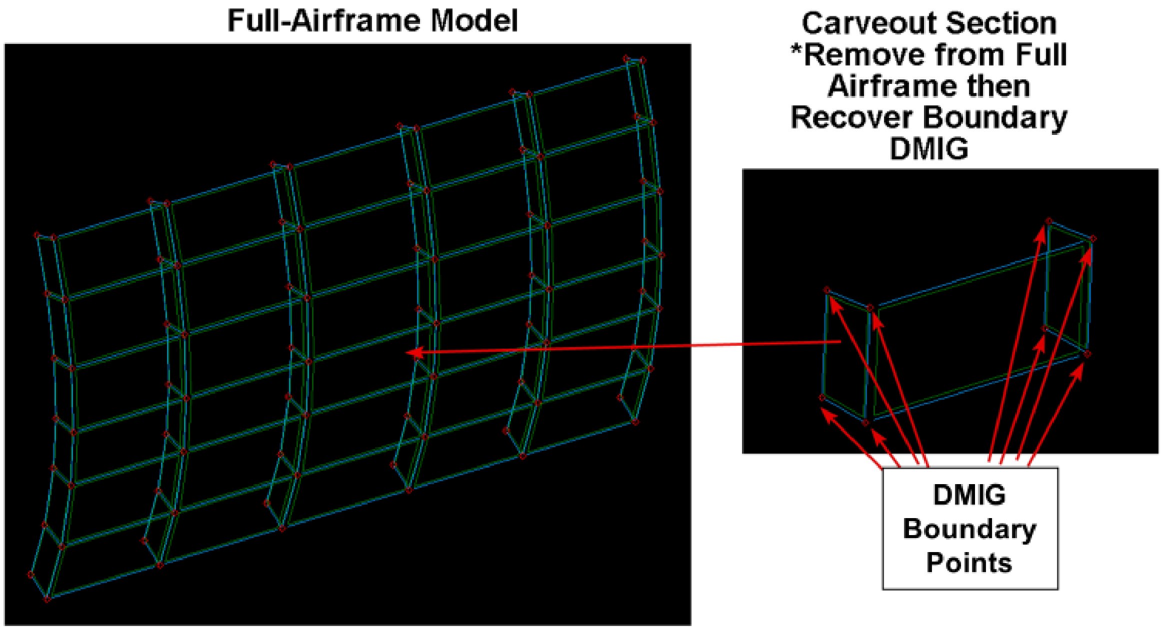

Figure 12 – Boundary Conditions for Fuselage Section Carveout Model

If the stiffness and mass are correctly extracted from the remaining full-airframe model (excluding the carveout section) and correctly applied to the carveout model boundary, the carveout model's total stiffness and mass will match that of the full-airframe model. This should be verified during certification analysis evaluation.

Attachment Configurations

A common structural attachment modeling method uses surface ties. Although this is a simpler approach, it should be avoided in ditching FEA simulations because it does not provide the ability to simulate the unzipping of fastener lines during high-energy impacts. In some cases, these tie elements can add additional fictitious stiffness and coupling terms to the global stiffness matrix. This approach also makes it more difficult to use classical stress analysis to evaluate fastener loads with respect to their allowables and stresses due to bearing contacts.

A more suitable attachment configuration includes individual fasteners modeled as line elements. As stated in the FEA Solver Selection section, a solver that supports stiffness values with coordinate systems and failure load values must be employed. Although it is possible to model these attachments where the line elements directly attach to a part node, this requires adjustment of the endpoints of each node to match the fastener location.

A more suitable approach is to use a load distribution element that does not alter the stiffness matrix of the structure adjacent to the fastener attachment. Load distribution elements like these will require at least three nodal attachments on each end. These nodes must not be in a line, which would introduce a mechanism into the model's stiffness matrix. Note that it is not common to include rotational stiffness in these elements unless the intent is to evaluate the effects of pin bending.

Airframe Mass

Because mass is a significant component of impact forces, generating the correct energy transfer between the hydrodynamic sea and the airframe structure requires that the airframe model include the correct mass. In the Impact and Landing Phases of ditching maneuver simulations, the model’s total mass will include the mass of airframe structure, the mass of nonstructural items, and, if a carveout model approach is used, the mass of the airframe excluded from the carveout model.

The mass of the airframe structure can be correctly added to the FEA model by using plate elements with the correct thickness and material density. Nonstructural mass items can be added at discrete points as long as their distribution attachment elements are connected to the correct structural locations and those distribution attachment elements do not introduce additional coupling terms into the model’s global stiffness matrix. See Figure 13.

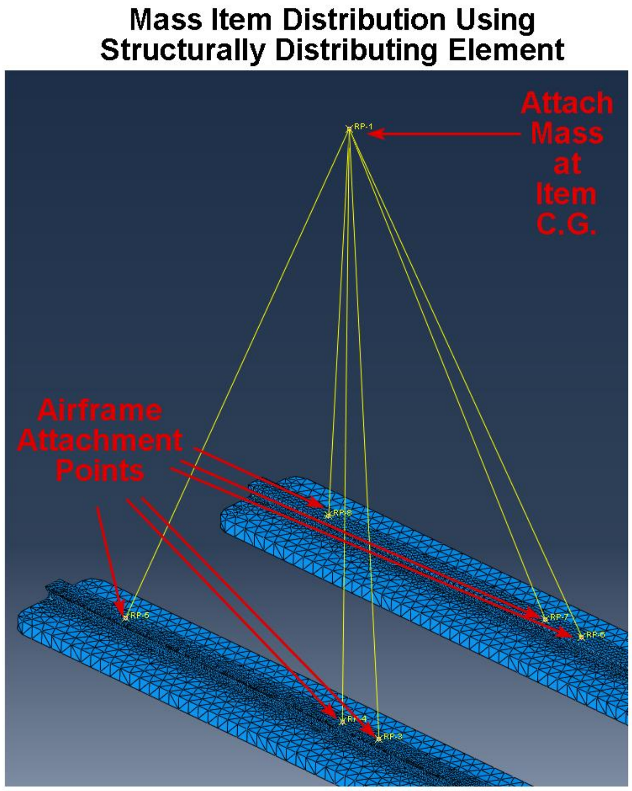

Figure 13 – Mass Item Distribution Using Structurally Distributing Element

Note that if a carveout model approach is used, the mass vectors for the removed structure should be included in one of the DMIG’s vectors, as discussed in the Carveout Models section. Otherwise, the airframe mass outside of the carveout model must be added to the model manually.

Carveout models are verified with the same methods used to verify full-airframe models. These verification methods are discussed in the FEA Simulation Verification section.

Material Curves Up To and Including Rupture

High-energy impacts often cause large deformations in a very short time span. These large deformations strain the airframe structure to the point at which it is common for the structure to exceed its yield point. Material definitions for these simulations must include the full material curve up to and including rupture, as shown in Figure 14.

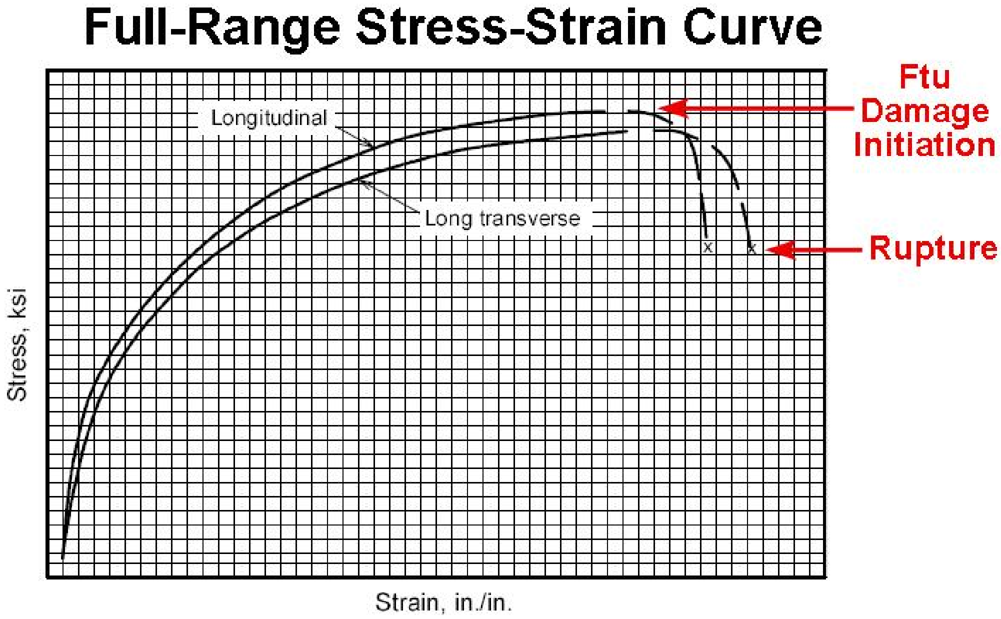

Figure 14 – Stress–Strain Curve Showing Nonlinear Region with Rupture

Impacts generate shockwaves that traverse the airframe structure. These shockwaves can be seen by reviewing time histories of the airframe's deformations. The material definitions for the airframe elements must include the necessary data for the solver to accumulate damage and degradation caused by these shockwaves into each element's differential stiffness matrix.

It is possible for an element near the point of impact to initially exceed yield, causing damage and degradation, but not rupture, then relax as the shockwave moves on. However, secondary shockwaves near that same point of impact may then cause the damaged element to reach the final point of rupture. If damage due to the initial shockwave has not been accumulated correctly (hysteresis, permanent deformation), the element's response to the secondary shockwaves will not be accurate and will lead to unconservative results.

Interaction Between a Hydrodynamic Sea and Metallic / Composite Airframe Structure

Although there are several different methods that can be used to model the interaction between a hydrodynamic object and an airframe, the most common and reliable are the Coupled Eulerian–Lagrangian (CEL) method and the Smoothed Particle Hydrodynamics (SPH) method. The selection of the appropriate interaction method, CEL or SPH, is described below.

The Impact and Landing Phases of ditching will introduce shockwaves into the hydrodynamic object (the sea). The ability to simulate these shockwaves and reflected shockwaves will more accurately represent the dynamic impact forces between the water and the modeled airframe structure. Note that while initial impact shockwave forces are greater than reflected shockwave forces, reflected shockwaves can combine, increasing in force as they return to the airframe structure. These dynamic forces cause a high-impact load on the airframe during the Impact Phase of ditching. They also contribute to the airframe's dynamic response during the Landing Phase of ditching. This is due to the airframe's continued acceleration, both linear and angular, as the nose of the aircraft pitches down during the Landing Phase, introducing secondary interactions between the water and airframe. These secondary interactions will introduce additional shockwaves into the airframe.

The CEL method employs a model of the hydrodynamic object. This model includes the use of solid elements. These solid elements must include the properties of the water, along with the Hugoniot equation terms, including the speed of sound in water. The introduction of the Hugoniot equation terms into the properties of the hydrodynamic object allows accurate simulation of shockwave reflections within the hydrodynamic object, making it possible for this method to correctly simulate a high-energy single-surface impact.

The SPH method includes a volume filled with water particles and a path for the water particles to traverse. The path that the water particles take can include reflections and angles, depending on the shape of the airframe at the point of impact. Due to the particles' ability to dynamically reflect and maintain mass, this method correctly simulates a high-energy single-surface impact, along with secondary impacts depending on the particles' dynamic reflection.

Because the SPH method includes particle-tracking algorithms, the number of computations the solver must perform increases directly with the size of the SPH interaction volume. Additionally, any interactions that should take place outside of this volume will not be included in the simulation. Both factors must be considered when selecting the interaction volume size.

An efficient analysis path can include both methods. The CEL hydrodynamic model can be used for both the Impact Phase and the Landing Phase of a ditching maneuver. This analysis set will computationally take less time than the SPH hydrodynamic model and provide good results with respect to the total impact energy and its transfer into the airframe. If damage occurs that requires a more detailed analysis, the introduction of a sub-model (carveout), along with a correct SPH interaction volume, can provide a more detailed simulation of damage and failures within the carveout structure. This is due to the fact that the SPH water particles will be smaller and more detailed than the CEL coarse solid elements. However, the SPH will require more analysis time for the additional computations.

FEA Simulation Verification

The AIAA (Reference 5) defines computational simulation verification as “the process of determining if a computational simulation accurately represents the conceptual model, but no claim is made of the relationship of the simulation to the real world.” The ASME defines verification as “the process of determining that a computational model accurately represents the underlying mathematical model and its solution.” (Reference 6)

Note that these definitions do not include determination of the computational simulation’s accuracy in representing real-world results. The ASME defines “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” as validation (Reference 6). The validation process is discussed separately in the FEA Simulation Validation section below.

Because simulation verification does not include comparisons to real-world results, it is not reliant on physical test data comparisons. Instead, verification is achieved by reviewing an FEA model’s design and the FEA simulation’s definition within the FEA solver. An applicant seeking certification via FEA simulation results should have some form of verification process established. ASME V&V 10 (Reference 6) provides a detailed discussion of considerations for establishing such a process, as well as for establishing a validation process.

In addition to general FEA model and simulation verification processes, verification of an FEA ditching maneuver simulation requires several specific review steps:

- Review of the FEA model’s design process to ensure acceptable FEA design methods were employed during model development. This review is typically performed by someone other than the individual(s) whose design process is being reviewed.
- Review of the FEA model’s material definitions to identify and correct any errors. These errors can take the form of incorrect material selection, incorrect material definition selection (i.e., composite RTD vs. HW), or simple typographical errors in an otherwise properly defined material.
- Review of the FEA model’s geometry to identify and correct any errors. This review should include:
    - ensuring none of the model’s elements have shapes that would cause issues with the FEA solver’s interpretation of those elements
    - ensuring no model parts penetrate other model parts
    - ensuring the model’s geometry matches that of the conceptual model.

<u>*Verifying Material Failures*</u>

Dynamic ditching simulations require FEA solvers that include the ability to model isotropic materials that include their elastic, nonlinear, and rupture properties. If the dynamic response time is short enough (i.e., 1.0 e^{-3} seconds), it may be necessary to include the material’s stress triaxiality states with respect to strain rates.

These material properties must be entered into the FEA model’s material definitions. As with all predefined model and simulation parameters, these entries must be verified for accuracy. In addition to visual inspection for typos and transcription errors in the model’s code, the accuracy of the material properties defined in the model should be verified after it has been used in a simulation.

Post-simulation verification of model material properties is accomplished by confirming that model elements failed at expected stress levels. A review of the simulation's stress time histories can identify areas and timings of material failures. This review is usually done by examining an animation of the simulation. Figure 15 shows two time steps from a simulation in which element rupture can be seen.

Simulated Element Rupture Example

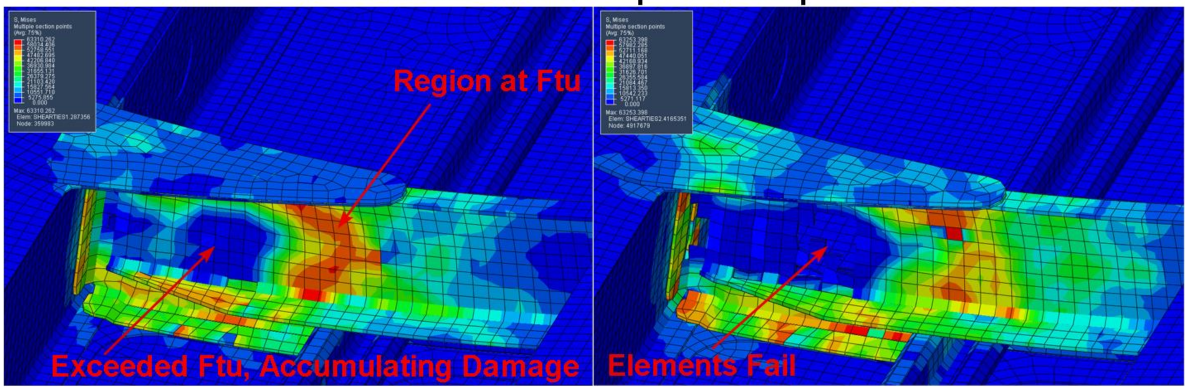

Figure 15 – Example of an Element at Rupture Level

Once these failure areas are identified, the model elements failing in these areas are identified, and their stress state immediately prior to failure is compared to the expected ultimate tension and compression for the model element's material. If the element's stress state prior to failure is less than or greater than the expected ultimate stress allowable, the material model must be reviewed and corrected. Also, as mentioned above, make sure the gravitational constant has been correctly accounted for in the material model's density.

Verifying Element Geometry

Finite element solvers incorporate algorithms that calculate element stiffness based primarily on the element's mechanical properties. The stiffness algorithms for four-node plate elements typically include a variable strain formulation. Although these variable strain formulations do take element edge lengths (geometry) into consideration when determining the element's stiffness contribution to its attachment nodes, it is common for the solver's stiffness algorithms to assume right angles (90^o) at each corner of the element. It is, however, nearly impossible to mesh a part such that all of its four-node elements include only right angles (90^o). When four-node elements include interior angles that are not 90^o, the element has deviated from its original intended formulation. Most finite element solvers include element geometry checks where acceptable interior angles can vary between 30^o and 150^o.

Three-node plate elements typically include a constant strain formulation. This formulation assumes each interior angle is 60^o. Three-node plate elements' stiffness calculations are more sensitive to interior angles other than 60^o. When two of the three element edge lengths are significantly larger than that of the third (resulting in a small interior angle), the stiffness contributions at each of the element's attachment nodes will be inaccurate. This is due to the constant strain formulation that results in stiffness values that are equal at all three nodes, regardless of the element's actual shape. Due to this formulation limitation, all slender three-node plate elements must be reshaped to avoid these stiffness inaccuracies.

Finite element solvers typically include a summary of poorly shaped elements in the solver's analysis output section. This section, if it exists, should be reviewed, and all elements identified as deviating from the solver's stiffness formulation must be corrected prior to the ditching simulation's final analysis.

Removing Part Penetrations

As stated in the FEA Solver Selection section, element and part contact needs to be included in a dynamic ditching simulation. Contact formulations prevent parts from penetrating each other in an unrealistic manner during the simulation. Contact formulations also allow the dynamic solver to correctly idealize the heel–toe effects as parts bend and fastener lines are loaded. If the model includes parts that are penetrating into other parts, the contacts between those parts cannot be correctly established by the solver prior to the initial simulation step. In some cases, the solver will add initial displacements to these parts, shifting them in order to remove these penetrations. These displacement shifts cause the elements being moved to include strains prior to the initial simulation step, which, in most cases, are undesirable.

Displacement shifts can be identified by plotting the model's deformed shape at the beginning of the initial simulation step. These displacement shifts should be used to identify which parts in the airframe model need to be adjusted manually to remove these penetrations and avoid initial strains that are unrealistic.

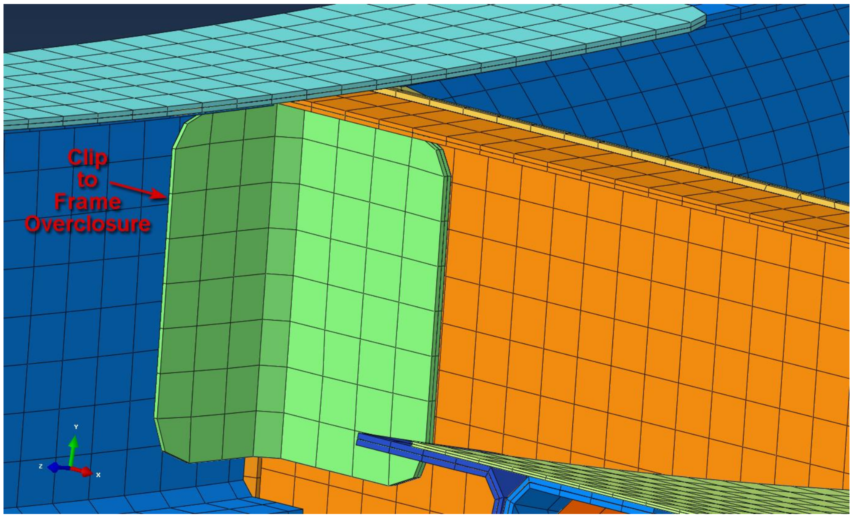

Figure 16 – Example of Part Overclosure, Clip Embedded in Frame

Note that the clip in Figure 16 appears thinner on its left edge than on the right. This is because the clip is penetrating the blue frame, as indicated.

Verifying Airframe Model Mass and CG

Some Explicit Dynamic Impact Solvers include the gravitational constant (i.e., add the gravitational constant to model masses and material densities) when a simulation is run. SIMULA's Explicit Solver is a widely accepted commercially available example. The inclusion or exclusion of the gravitational constant by the applicant's employed solver must be determined prior to entering mass items and material densities into the model definition(s) to ensure proper representation of mass items and material densities in the simulation.

If the FEA solver being employed does include the gravitational constant, and if the values for mass items and material densities being used by the applicant already account for the gravitational constant, then the gravitational constant must be removed from the mass items and material densities prior to their entry. This is typically accomplished by dividing mass items and material densities by 386.4 (if using English units). If the gravitational constant is not removed from these items for a solver that includes it by default, the simulation will incorrectly represent their mass/density by duplicating the effects of the gravitational constant.

Conversely, if the solver being employed by the applicant does not include the gravitational constant, and if the values for the mass items and material densities being used by the applicant do not account for the gravitational constant, the simulation will not correctly represent their mass/density by failing to include the gravitational constant.

A common practice to ensure the airframe's total mass and CG are modeled correctly is to review the solver's output summary to ensure its total mass and CG match those of the actual airframe. If the solver's output summary does not list the model's CG, it is possible to calculate the model's CG by using the solver's output that sums both forces and moments (typically summed about the origin). In this case, the CG can be calculated by dividing the appropriate moment by the appropriate force. As an example, the model's X (fuselage station) CG can be calculated by dividing the total My (pitch moment) by the total Fz (vertical shear).

FEA Simulation Validation

Validation is the process of determining if an FEA simulation accurately represents the real world. Validation, therefore, requires that real-world data, i.e., physical test data, be compared to the simulation's results. Numerous approaches can be used to show validation. As with verification, the applicant should have a defined validation process. Detailed discussions of general validation approaches can be found in publications such as the AIAA Guide to Verification and Validation (Reference 5), ASME V&V 10-2006 (Reference 6), and Verification and Validation in Scientific Computing by Oberkampf and Roy (Reference 7).

Validation by Physical Testing

Physical testing for validation of FEA simulations can be conducted using component testing, scale-model testing, and/or full-airframe testing. Each of these is briefly discussed below.

Strain gauge results and physical damage/failures are compared to the FEA simulation's results. If acceptable correlation is achieved between the FEA simulation results and physical test results, this correlation can be used to validate the FEA ditching simulation. Broadly speaking, a deviation of more than 15% is considered unacceptable. The level of deviation considered acceptable can vary and should be determined by agreement between the FAA evaluator and the applicant.

Component Testing

Component testing is the physical testing of a single part or simple structure. The FAA may require a ditching certification applicant to validate that their employed FEA solver is capable of accurately simulating water impacts. This validation can be achieved through physical component testing.

This component testing often takes the form of a simple water impact test. A simple water impact test is typically performed by mounting a stiffened panel at the bottom of a water chute. The top of the water chute contains a known mass of water suspended at the top of the chute by a drop door. When the drop door is opened, the known mass of water is dropped from a known height onto the test panel. It is usually necessary that the test fixture design allows for variations in the water's mass so that component damage can be adjusted. Figure 17 illustrates the basic configuration of a water impact test.

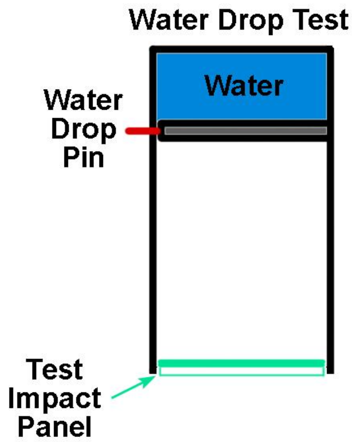

Figure 17 – Simple Water Impact Test Configuration

An FEA simulation of this water impact test must be created using the FEA solver being validated. Results from the water impact test are compared to the results from this FEA simulation's strains, failed fasteners, and other related impact damage, such as deformation.

Note that the test panel needs to be sized such that the test water mass and drop height will cause visible damage to the test panel. If the water test does not damage the panel, the FEA simulation can only be used to correlate to element strains where the strain gauges were placed on the test panel. Damage correlation can only be performed if the test panel is visibly damaged after the test. This is why the test fixture is usually designed to allow water mass to be varied.

The stiffened panel must also be designed using materials with known full-range stress–strain curves and fasteners with known axial and shear failure allowables. This provides confidence that the interaction between the water traveling at a known velocity and impacting the test panel can be accurately simulated. This test will also provide confidence that the material curves and fastener failures can be accurately simulated.

Scale-Model Testing

Scale-model testing is typically conducted in a controlled water test setting with a scale model that has been designed and built in such a way that it accurately represents the responses of the full airframe during the ditching maneuver. The water test setting must include control systems that can establish the desired velocity, accelerations, attitude, and height above the water prior to dropping the model into the water. Figure 18 illustrates the basic configuration of a water tank test (Reference 9, pg.3).

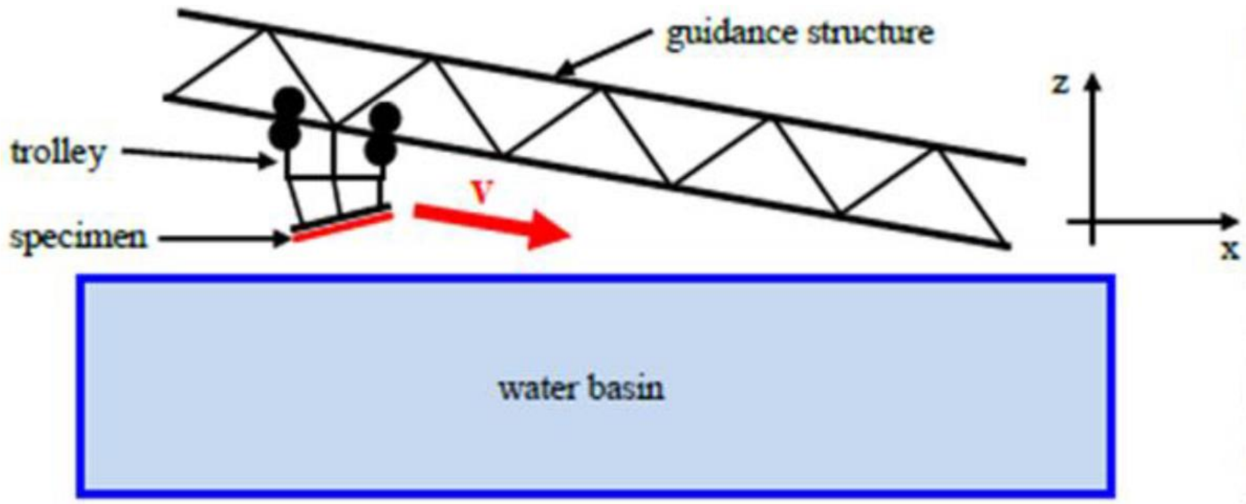

Figure 18 – Scale-Model Tank Test Configuration
**Reference 9, pg.3*

Testing the scale model will require placing pressure transducers on the model's belly in the region that will impact the water, as well as linear and angular accelerometers at the nose, tail, and model center of gravity. The data taken from the pressure transducers are the primary data used to validate the FEA airframe ditching model.

The scale model's transducer data can be scaled up to the full airframe by using the methods described in Reference 8. Once these test data are scaled up, the contact pressure between the FEA airframe structural model and the hydrodynamic water model can be recovered from the FEA simulation and compared to the scaled-up physical model test data.

Full-Airframe Testing

Performing a full-scale airframe test on an aircraft for which ditching certification is being sought may be sufficient to show ditching compliance for that aircraft. While this test may not be sufficient to show compliance if certification is sought for a variation of the full-scale tested aircraft, the data from this test can be used to validate an FEA model of the variant aircraft and an FEA ditching simulation.

Validation in such an instance would involve creating an FEA model of the tested aircraft and an FEA simulation of the full-scale airframe test. If an acceptable correlation is found, the FEA solver, airframe model, and ditching simulation are validated. The FEA model of the aircraft can then be modified to represent the variant aircraft.

Note that the FEA model is validated before being modified. Applicants who have access to full-airframe test results, as described above, typically perform this validation prior to beginning FEA ditching simulation analysis for the variant aircraft.

Use of Data from Actual Aircraft Ditching Event

Simulation validation by comparison to full-airframe damage resulting from actual ditching events is problematic. The damaged airframe would have to have the same structural arrangements as the simulation, i.e., wing, engine, frame, and bulkhead locations, the same gross weight and CG, and have ditched using the same approach parameters. Even if the damaged airframe met these requirements, the applicant would have to accurately separate ditching event damage from post-ditching damage, such as that which occurred during recovery of the airframe.

FLOTATION PHASE

The Flotation Phase of a ditching maneuver encompasses the portion of the maneuver initiated immediately after the aircraft has lost all forward velocity and comes to rest on the water's surface through the end of the evacuation process. FAA certification for ditching requires that the aircraft remain sufficiently buoyant during the Flotation Phase to allow all passengers and crew to successfully exit the aircraft and enter available life rafts.

At the beginning of Flotation Phase analysis, the buoyant force equation is in equilibrium with the mass of the airframe. This linear equation includes the density of the water, the gravitational constant, the mass of the airframe, and the volume of the water displaced by the airframe. This initial condition can be used to calculate the waterline of the airframe after the Landing Phase has completed. Including moment balancing terms and the airframe's center of gravity in this linear equation allows for the calculation of the airframe's initial attitude at the beginning of the Flotation Phase. Note that all water displaced by the aircraft and the remaining airframe air-filled volumes above the waterline will have been tabulated at this point.

After the buoyant force equation in equilibrium with the airframe mass has been defined, all openings in the airframe that could allow water ingress must be identified. These openings must include both those caused by damage resulting from the Impact and Landing Phases, as well as all emergency exists that may be opened (depending on the aircraft's post-Landing Phase attitude and the aircraft's buoyancy waterline). Note that the areas of these openings can be dynamic in nature depending on where the buoyancy waterline of the airframe is positioned relative to these open areas. For example, if an emergency exit is partially submerged, its water ingress area increases as the airframe's buoyancy waterline rises.

Once the airframe's equilibrium balance and water ingress areas have been defined, an exact balanced differential equation can be written. This balanced differential equation starts with the static buoyancy force equilibrium equation. Next, the areas of water ingress are added to this equation, and known air-filled volumes above the current airframe buoyancy waterline are subtracted simultaneously. These areas in the balanced differential equation can now be entered into the time domain. Note that these areas may include nonlinear features, such as openings that vary in size as the airframe's buoyancy waterline rises. This balanced differential equation is similar in nature to common balanced mass flow rate equations where boundaries are defined that allow the transfer of liquids and/or gases from one volume to another. (Typically, one of those volumes is the atmosphere.)

It is also possible to include the sloshing effects of various sea states (waves) in this balanced differential equation. This addition is highly dynamic and nonlinear in nature. A detailed discussion of how sloshing effects can be added to the buoyancy exact balanced differential equation can be found in Reference 9. Note that Equation 3 (pg. 11) of Reference 9 describes the basic terms required to account for a dynamic waterline (transversal waves) and leaked water sloshing (longitudinal waves). Figure 19 illustrates these waves.

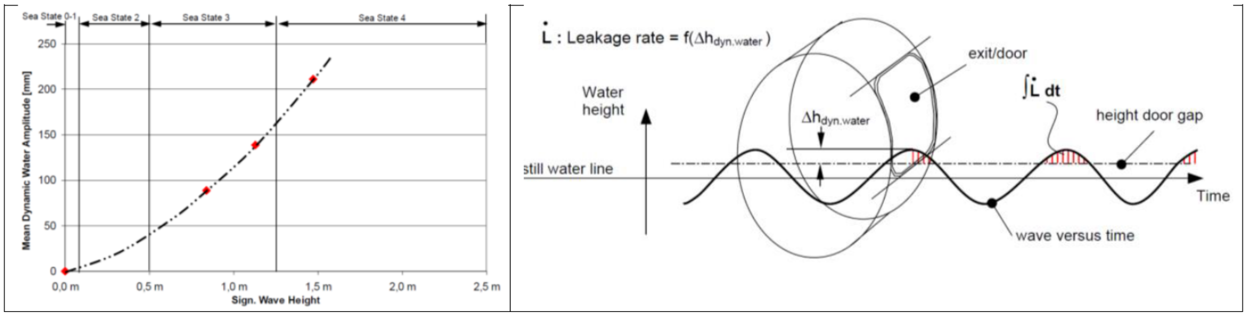

Figure 19 – Aircraft Ditching Impact Loads and Flotation Analysis
**Reference 9, pg.3*

Once the balanced differential equation has been established, it is possible to solve this equation in the time domain using a computational method for numerical integrator analysis.

Before entering the balanced differential equation into a numerical integrator, it is good practice to convert the balanced differential equation into a Laplace Transform format. In addition to reducing the possibility of conversion errors between the balanced differential equation and the numerical integrator, conversion to a Laplace Transform format provides the analyst with a better understanding of the terms and variables utilized by the numerical integrator. This understanding is important because the values generated by the numerical integrator for these variables, in a nonlinear time history format, are the bases for calculating the amount of time the airframe will remain sufficiently buoyant to allow for a successful evacuation.

Many numerical integrators commonly used in the aerospace industry to solve these balanced differential equations utilize the Runge–Kutta method. This numerical integrator method provides features that allow the analyst to easily add complex differential equations, as well as select specific output variables, such as the aircraft's buoyancy waterline.

The proper selection of the integrator's time step is critical. Time steps that are too small may introduce noise into the buoyancy equation's results. Time steps that are too large may skip peaks in dynamic responses present in the balanced differential equation. While some versions of these numerical integrators include variable step features, many versions include the use of a single defined time step. Some numerical integrators may include specific instructions on how to calculate a correct integration time step.

For nonlinear analysis methods that utilize the Runge–Kutta method, it is considered good practice to dither the time step, i.e., run the numerical analysis with small changes to the selected time step and ensure there are no dramatic changes in results due to small time step changes. If dramatic changes in results do occur, a new time step should be selected.

A common check for step size using the Runge–Kutta numerical integrator is to make sure all nonlinear output responses include smooth curves as opposed to jagged steps. Jagged steps in output curves indicate that peaks in the numerical integrator's results have been missed. See Figure 20.

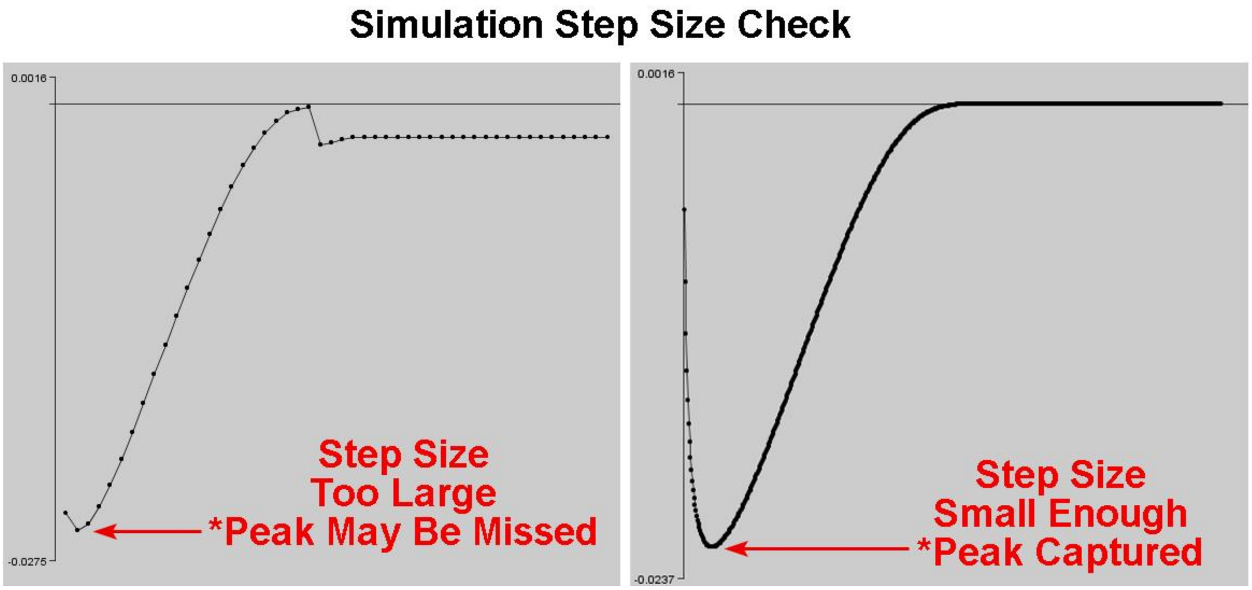

Figure 20 – Response Curves When Step Size Is Too Large vs. Small Enough

As previously stated, the primary focus of Flotation Phase analysis is determining the length of time the aircraft can be predicted to remain sufficiently buoyant to allow evacuation to take place. These results are then used in the Evacuation Phase to ensure the necessary evacuation procedures can be executed before the aircraft loses sufficient buoyancy.

EVACUATION PHASE

The requirement for the airplane manufacturer to conduct an evacuation demonstration in 90 seconds for airplanes having a seating capacity of more than 44 passengers was established in Title 14 Code of Federal Regulations Part § 25.803 (Reference 10). Compliance with this requirement must be shown by actual demonstration using the test criteria outlined in Appendix J of Part § 25.803 unless the Administrator finds that a combination of analysis and testing will provide data equivalent to that which would be obtained by actual demonstration. The analysis as currently outlined does not require complex numerical solutions or simulations and is, therefore, not applicable to this paper.

REQUIREMENTS FOR APPLICANT'S ANALYSTS

Recommended Qualifications for the Applicant's CFD Analysts

CFD modeling and simulation requires a specialized skill set and, as such, must be performed by individuals who possess those specialized skills. Individuals possessing the necessary skills to generate an accurate CFD ditching maneuver analysis set should be able to demonstrate the following:

- Possession of a bachelor's or master's degree in either aeronautical engineering, aerospace engineering, mechanical engineering, mathematics, physics, or a related field
- A strong understanding of aerodynamics/fluid dynamics
- A minimum of 5 years of experience in CFD modeling and simulation in support of FAA and/or military airworthiness certification, including:
    - model development
    - mesh optimization
    - turbulence model selection
    - flow solver submittal
    - post-processing of modeling results

Recommended Qualifications for the Applicant's FEA Analysts

FEA modeling of a dynamic, highly kinetic simulation requires a specialized skill set and, as such, must be performed by individuals who possess those specialized skills. Individuals possessing the necessary skills to generate an accurate FEA ditching maneuver should be able to demonstrate the following:

- Expert knowledge of Statics and airframe load paths
- Expert knowledge of Solid Mechanics, including material models
- Expert knowledge of airframe composite materials (fabric and core)
- Expert knowledge of Dynamics
- Ability to lump structure to support coarse-mesh idealization of an airframe
- Ability to generate detailed mesh of complex parts
- Ability to idealize airframe structure using 2D plate elements

PERTINENT QUESTIONS FOR FAA REVIEWERS

FAA Questions for CFD Model Development

1. What solver is being used?
2. Is an appropriate turbulence model being used?
3. Has the CFD methodology (surface model development, grid/mesh development, flow solver, and individual) been accepted by the FAA for past analysis?
4. What was the source of the surface geometry used to develop the model? (i.e., original equipment manufacturer (OEM) loft data (2D drawings)? 3D laser scan?)
   Applicant should be able to describe the source data for the surface data. If the data were from OEM 2D loft data, this will require a substantial number of drawings and a CAD package that allows loading the loft data and developing surface models for various sections of the aircraft (fuselage, wings, empennage, nacelles). This is a very labor- and time-consuming process. If it is from 3D data, then the applicant should be able to explain the scan process, density of scan points on the target surface, and locations of increased density to capture high slope gradients (1 point/0.25 inch)

5. How was the surface model accuracy verified?
   Applicant should have verified the major dimensions of the aircraft (fuselage length, fuselage diameter, wingspan, wing root length, wing tip length, vertical tail vertical height, horizontal tail span, horizontal tail root length, horizontal tail tip length) and all dimensions of the deflecting flight control surfaces (flaps, rudder, elevator, stabilator). Dimensions should be within ±0.2% of actual dimensions. Flap deflection angles should be compared to measured deflections.

6. How was the wing displacement modeled? (i.e., 1g cruise deflection? 1g ground condition with wing empty of fuel? 1g ground condition with fuel?)
   The production aircraft wing will flex and twist in flight due to wing loading, which is a function of the gross weight, load factor, and dynamic pressure (airspeed). OEM loft geometry is typically given for a 1g cruise condition for some nominal gross weight. CFD models are usually modeled to this 1g configuration. Matching the actual aircraft loads would require models developed for a range of airspeeds, weights, and load factors. For this effort, our area of interest is limited to airspeeds below 200 KCAS.

7. What method is used to determine convergence of the flow solver?
   A grid study can be used to determine the optimum grid/mesh size. The number of grid points/mesh sizes is increased (or decreased) by some scale. The convergence of the solver run can be determined by monitoring the variation in forces between each solver iteration. The solution is considered converged when the variations between iterations are within a defined minimum percentage, usually 1% of the measured axial force (Fx, Fy, Fz).

FAA Questions for FEA Model Development:

1. What FEA solver was used to develop and analyze the Impact and Landing Phase airframe responses? Does it meet the requirements listed in the FEA Solver Selection section?
   Applicant should be able to identify the employed solver. If the abilities of the solver identified are not known to the FAA, the applicant should provide a list of the solver's abilities that addresses all requirements listed in the FEA Solver Selection above.

2. What element formulations were used in the FEA model development? Do these formulations conform to the requirements provided in the Element Formulations section of the FEA Model Design Guidance section?
   If an applicant has not used plate elements for impact surfaces and/or has used fastener element derivations that do not include the ability to define stiffness properly, as recommended in the Element Formulations section above, they must provide an explanation as to how the potential errors discussed in the Element Formulations section were avoided.

3. How were complex parts that introduce load paths into the airframe represented? Was additional component testing performed for complex parts that could cause unacceptable damage if separated from their attachments?
   If an applicant has represented complex parts as mass items at the parts' CGs using load distribution elements, they should provide evidence that these complex parts do not introduce stiffness into the airframe.

4. How were boundary conditions for the Impact/Landing Phase simulation defined? Were carveout models employed to develop any of these boundary conditions?
   The applicant should be able to demonstrate how these boundary conditions were defined. If these boundary conditions vary from Approach Phase results, this deviation should be questioned. If a carveout model was employed, the applicant should be able to demonstrate that this process was used according to the guidance given in the Carveout Models section above.

5. What attachment configurations were employed? Do these configurations conform to the requirements discussed in the Attachment Configurations section above?
   The applicant should be able to identify the attachment configurations employed. If these attachment configurations vary from the recommendations in the Attachment Configuration section, they must provide an explanation as to how the potential errors discussed in the Attachment Configurations section were avoided.

6. How was the mass of the airframe structure included in the FEA model of the airframe? Was the mass of nonstructural items included? If a carveout model approach was used, was the excluded mass of the excluded airframe structure properly included?
   The applicant should be able to identify the total mass of the airframe FEA model. The applicant should be able to identify the separately calculated masses that were included in the total airframe model mass, as well as how those masses were calculated.

7. Do the FEA airframe model's material definitions include full material curves up to and including rupture?

The applicant should be able to identify all model material definitions. If these definitions do not include rupture, the applicant must provide an explanation as to the potential errors discussed in the Material Curves Up To and Including Rupture section above.

8. What method was used to model the interaction between the sea/water FEA model and the airframe FEA model?
   The applicant should be able to identify all interaction methods employed. If the method employed was not the CEL method or SPH method, as discussed in the Interaction Between a Hydrodynamic Sea and Metallic / Composite Airframe Structure section above, the applicant must provide an explanation that demonstrates the appropriateness of the method(s) employed.

References

1. 14 CFR Part 25.801 Amdt 25-72; Ditching; FAA 8/20/1990
2. DOT/FAA/AR-95/54, Transport Water Impact and Ditching Performance, FAA, March 1996
3. AIAA-NASA Drag Prediction Workshop; DPW-8 Gridding Guidelines; 7/1/2024
4. NASA Technical Note D-2241, “Comparison of Flight Pressure Measurements With Wind-Tunnel Data And Theory for the Forward Fuselage of the X-15 Airplane At Mach Numbers From 0.8 To 6.0”, NASA, Jan 1964
5. AIAA G-077-1998 Guide for the Verification and Validation of Computational Fluid Dynamic Simulations
6. ASME V&V 10-2006 Standard for Verification and Validation in Computational Solid Mechanics, The American Society of Mechanical Engineers, 2006
7. Verification and Validation in Scientific Computing, Oberkampf and Roy, Virginia Polytechnic Institute and State University, 2010
8. Ditching Investigation of a 1/20-Scale Model of the Space Shuttle Orbiter, NASA Contractor Report NASA CR-2593, 1975
9. Aircraft Ditching Impact Loads and Floatation Analysis, DOI: 10.13009/EUCASS2019-826, 8th European Conference for Aeronautics and Space Sciences (EUCASS)
10. 14 CFR Part 25.803 Amdt 25-72; Emergency Evacuation