Crash Simulation of Transport Aircraft for Predicting Fuel Release

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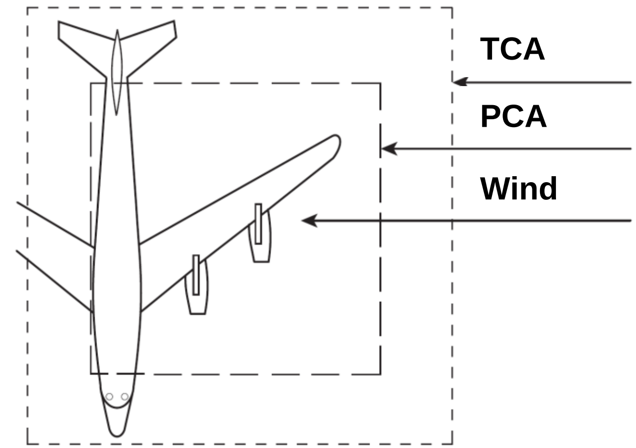
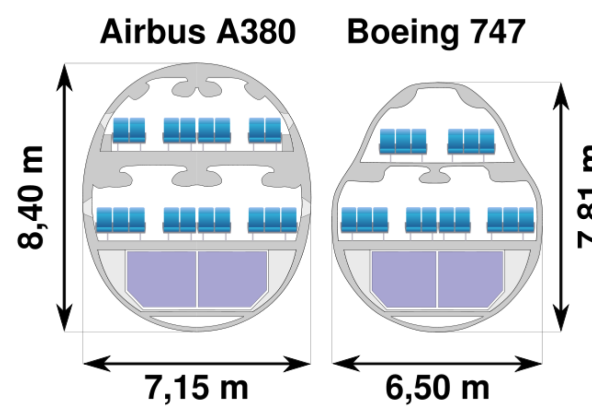
2014 FAA Worldwide
Airport Technology Transfer Conference
August 5-7, 2014

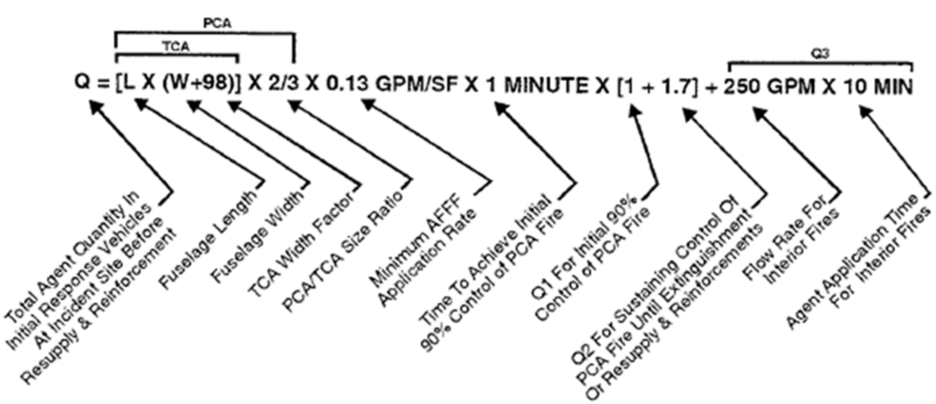
Background

- **The theoretical critical area/practical critical area (TCA/PCA) method has been used for nearly 40 years to determine Aircraft Rescue and Fire Fighting (ARFF) requirements for transport aircraft.**
- **The validity of the TCA/PCA approach**
  - Is questionable when applied to new transport aircraft
  - Does not accommodate modern designs



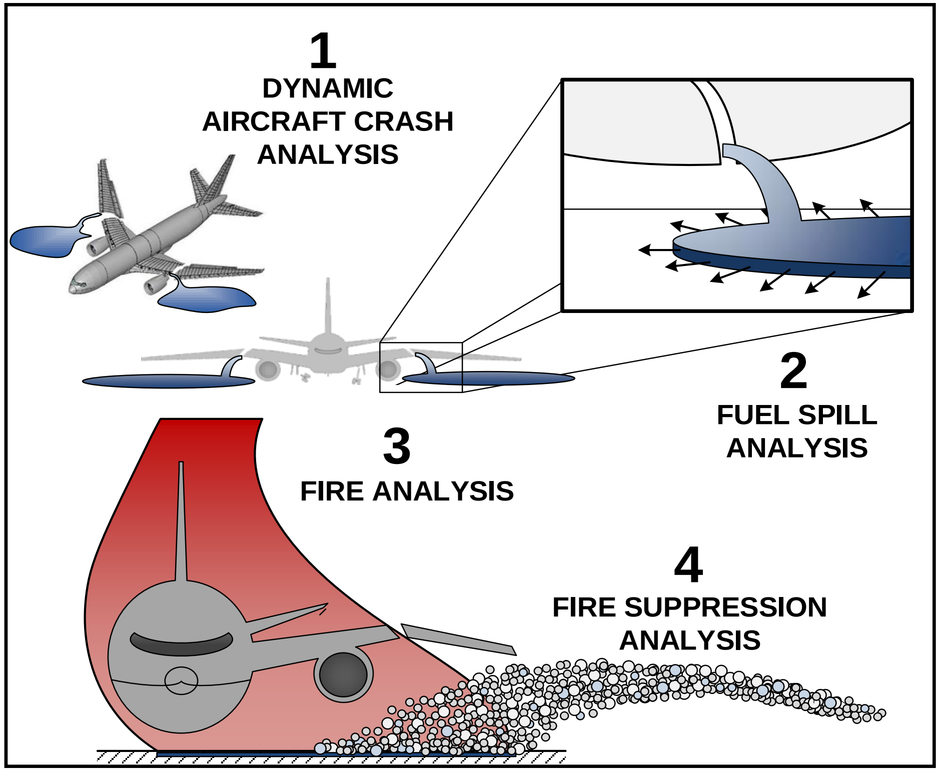
Fixed-Wing Aircraft





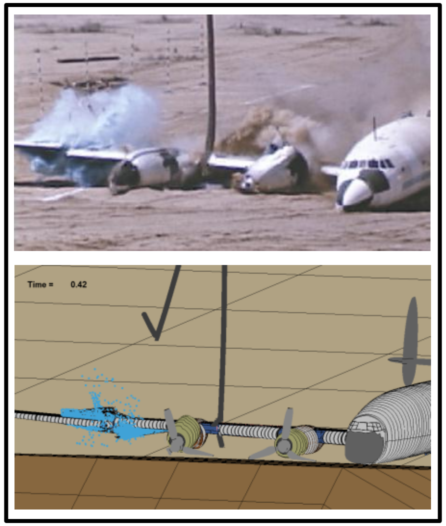
Aircraft Crash – Fuel Spill – Fire – Suppression (ACFFS) Modeling

- The ARFF Research Program is developing the capability to model all aspects of ACFFS
- This capability will enable the consideration of critical aspects that affect fire severity and suppression
  - Fuel distribution in tanks & on ground post-crash
  - Post-crash aircraft & ground geometry
  - Wind velocity effects
  - Suppression technologies
- Modeling allows a large number of scenarios to be considered



ACFFS Program Objective and Technical Approach

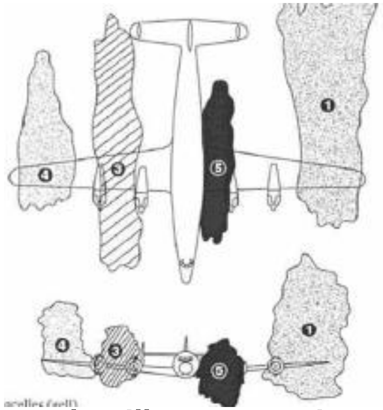
- **<u>Objective</u>:** Predict the severity of ACFFS scenarios so that an alternative to the TCA/PCA method can be developed
- **<u>Technical Approach</u>:**
  - Perform high-fidelity, nonlinear, dynamic, finite-element (FE) analysis of survivable plane crashes
  - Perform high-fidelity computational fluid dynamic (CFD) analysis of fire and suppression
  - Evaluate severity of ACFFS scenarios and identify worst cases
  - Validate modeling methodology using crash, fire, and suppression experiments



Project 1: Crash Simulation of Transport Aircraft for Predicting Fuel Release

- **<u>Objective</u>:** Predict structural breakup, fuel release and fuel distribution and dispersion for survivable crash events; provide these results as inputs to fire and suppression modeling
- **<u>Technical Approach</u>:**
  - Perform high-fidelity nonlinear dynamic finite element (FE) analysis of survivable plane crashes
  - Validate full-scale crash modeling and liquid release from wing tanks with experimental data
  - Provide bounds on the quantity of fuel dispersed during various types of aircraft incidents

L-1649 Full Scale Crash Test

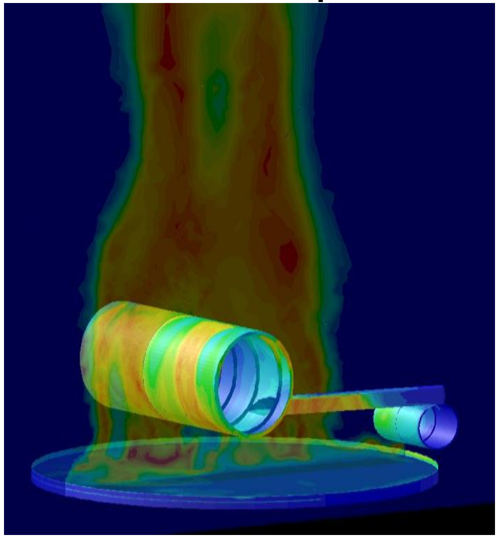


Fuel spillage occurring 2.24 seconds after gear impact

Projects 2&3: Fuel Spill and Fire Simulation of Transport Aircraft Crash

- **Objective:** Predict aircraft surface thermal profiles and surrounding flame temperatures for survivable crash events
- **Technical Approach:**
  - Determine aircraft fuselage thermal sensitivity to static/dynamic pooling fire conditions using high-fidelity computational fluid dynamic (CFD) analysis
  - Validate fire modeling methods using multiscale experimental aircraft mockup pool fire data
  - Estimate aircraft heat exposure ranges based on different crosswind conditions for various types of aircraft crash incidents

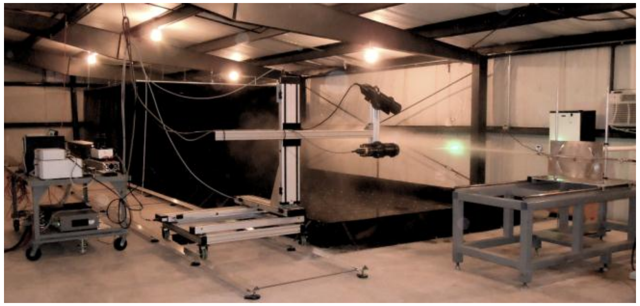
Small-scale NLA Mockup Test Set-up



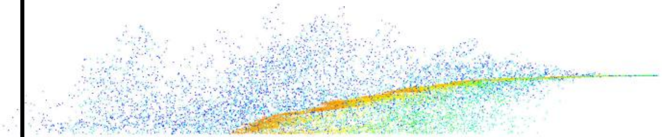
Small-scale NLA Mockup Fire Model Solution

Project 4: Fire Suppression and Consequence Analysis

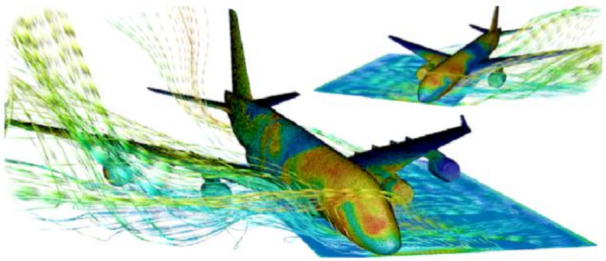
- **<u>Objective</u>:** Predict firefighting agent delivery flow requirements necessary to suppress aircraft pool fire environments for survivable crash events
- **<u>Technical Approach</u>:**
  - Develop and validate a firefighting agent application simulation strategy using high-fidelity computational fluid dynamic (CFD) methods
  - Validate fire suppression modeling approach using experimental aircraft mockup pool fire and suppression data
  - Estimate required emergency response needs for various aircraft incidents based on realistic aircraft crash, fuel spill, fire, and fire suppression simulation results



Firefighting Agent Application Model Validation Laboratory



Fire Suppression Model Development



Application to Aircraft Fire Incidents of Interest

Project 1: Crash Simulation Overview

- **Phase 1: Validate modeling methodology using full-scale crash tests**

FAA-ADS-38:

Reed, W.H. et al, "Full-scale Dynamic Crash Test of a Lockheed Constellation Model 1649 Aircraft," October 1965.

- **Phase 2: Evaluate fuel dispersal for current transport aircraft**

Federal Aviation Administration

Phase 1 – Validate Modeling Methods Using Full-scale Crash Tests

Lockheed Constellation Model 1649

(Gross Weight = 159,131 lbs)

- The FAA conducted full-scale crash tests of commercial transport aircraft in 1964
- These test programs were designed to simulate typical crash conditions during survivable takeoff and landing accidents and collected considerable data on crash loads, accelerations, and fuel containment
  - Dyed water was used in lieu of fuel so that that damage was due solely to the impact events and not a subsequent fire
- The Constellation was made from higher-strength, low-elongation aluminum, similar to more modern aircraft

Phase 2 – Evaluate Fuel Dispersal from Modern Transport Aircraft

Airbus A380


Boeing 777

- Implement the validated modeling methodologies from Phase I for assessing fuel dispersal from a modern transport aircraft
- The focus is on determining bounds for the rate of fuel dispersal for common impact-survivable crash scenarios
- Focus on:
  - High-impact landing (hard landing)
  - Ground collision between similar aircraft

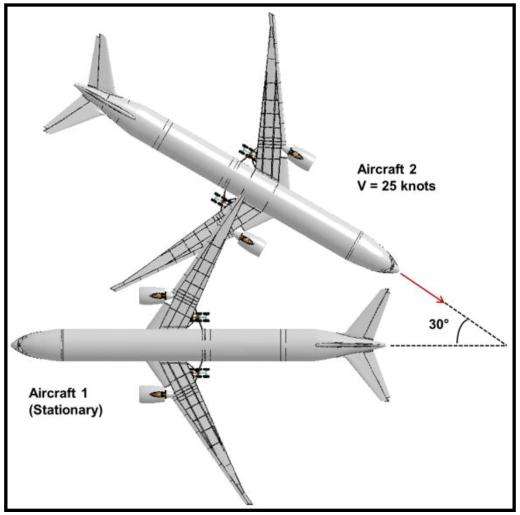
Impact-Survivable Crash Scenarios

- **Developed by recommendation of the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee for use in future crashworthiness R&D efforts**

		Impact Conditions					
Candidate Scenario	**Operational Phase**	**Distrance from Airport**	**Forward Velocity (kts)**	**Sink Rate (fps)**	**Airplane Configuration/ Impact Conditions**	**Terrain**	**Hazard**
Ground to Ground (overrun)	Takeoff abort/landing overrun	On runway or within 3000 ft of end of runway	60-100	< 5	Gear extended Symmetrical	Runway Hard Ground	Ditches Trees Mounds Light Stanchions
Air to Ground (Hard Landing	Landing-hard Landing-undershoot	On runway or within 300 ft of threshold	126-160	> 5 < 12	Gear extended Symmetrical	Runway Soft Ground	None
Air to Ground (Impact)	Final Approach	On runway or between outer marker and missed approach point	> 126	> 12	Gear extended & retracted Symmetrical & Unsymmetrical	Hard Ground Hilly Rocky	Trees Poles Slopes Ravines Buildings

Bounds on Fuel Dispersal

- Crashes are highly nonlinear events with many interacting effects that can change the fuel release outcome
- A Computational Design of Experiments approach is being used to quantify the dominant parameters and develop worst-case bounds
- Various parameters will be considered in developing bounds on fuel dispersal
  - Aircraft speed, forward velocity, sink rate
  - Aircraft weight and fuel load
  - Impact conditions
  - Uncertainty in aircraft characteristics
    - Material & connection strengths and nonlinear behavior
    - Embrittlement from connections

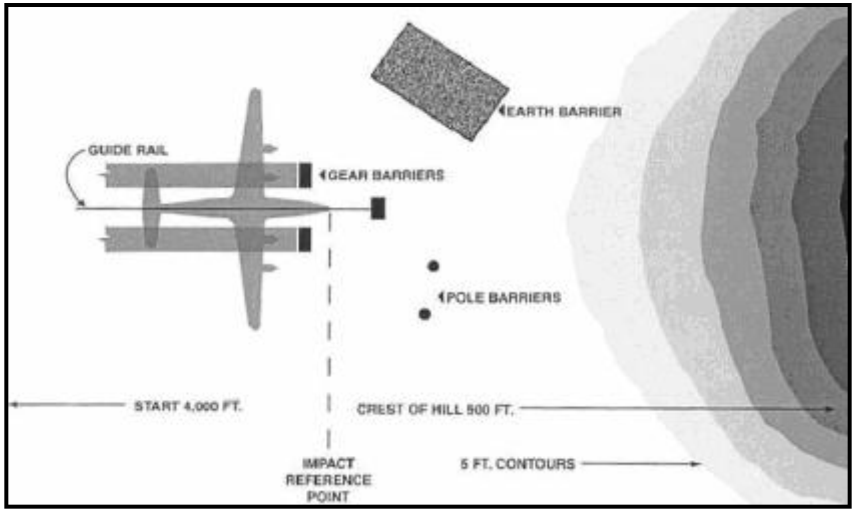


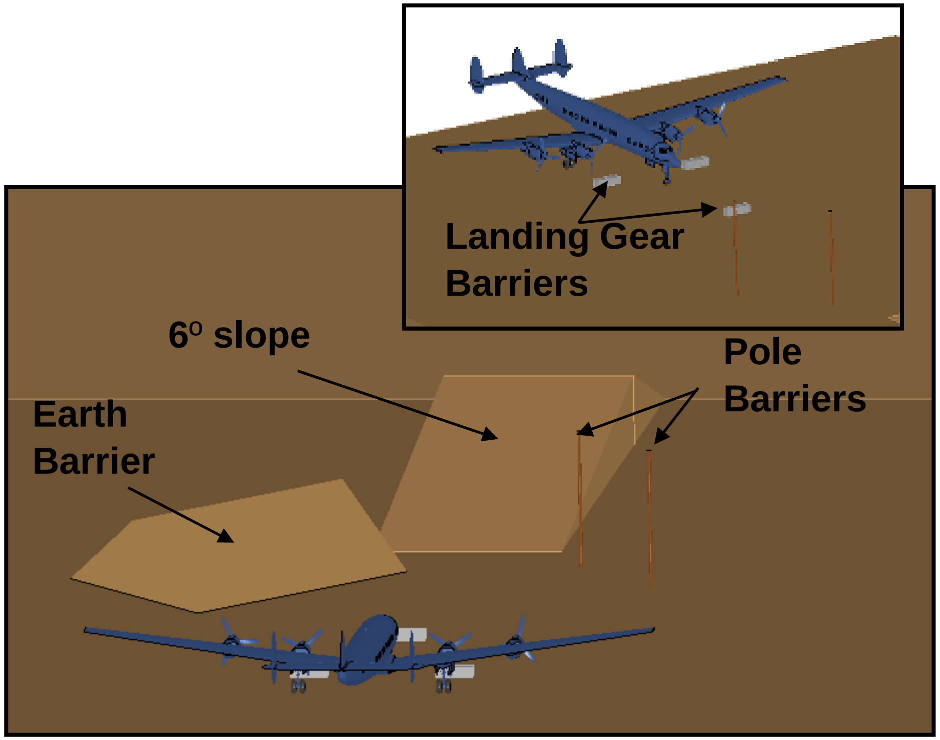
Taxi Impact of Similar Aircraft

Full-Scale Crash Test Validation

Crash Site Model Development

Plan view of L1649 crash test site



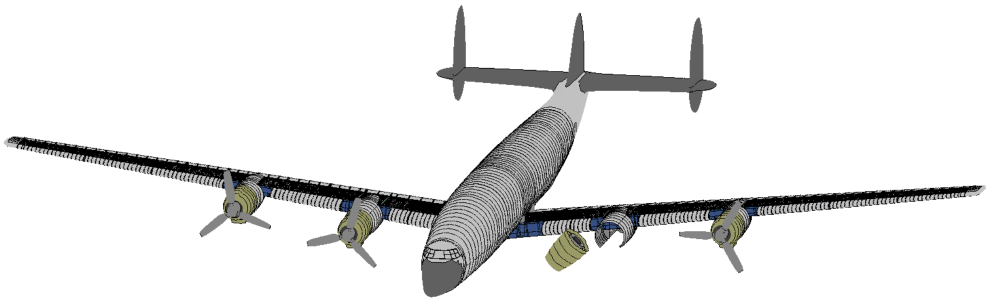


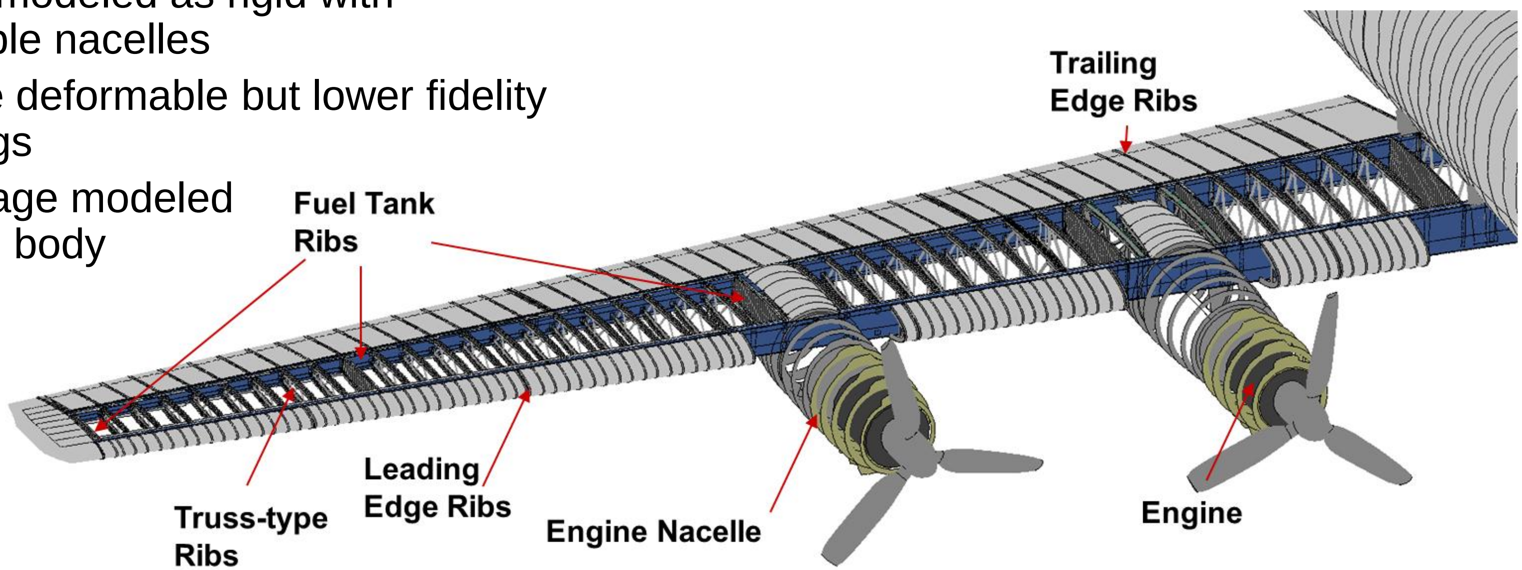
- Initial impacts at 112 knots removed the landing gear, causing the aircraft to be airborne
- Once airborne, the left wing struck an earthen barrier and the right struck two vertical telephone poles
- Final impacts with a 6º slope followed by a 20º slope stopped the aircraft

L-1649 Model Development

- Wing structures modeled with high fidelity
  - Detailed models of wing ribs, spars, skins of integral fuel tanks
  - Failure strengths of connections
  - Nonlinear connection behavior
  - Embrittled material around connections
- Engines modeled as rigid with deformable nacelles
- Fuselage deformable but lower fidelity than wings
- Empennage modeled as a rigid body

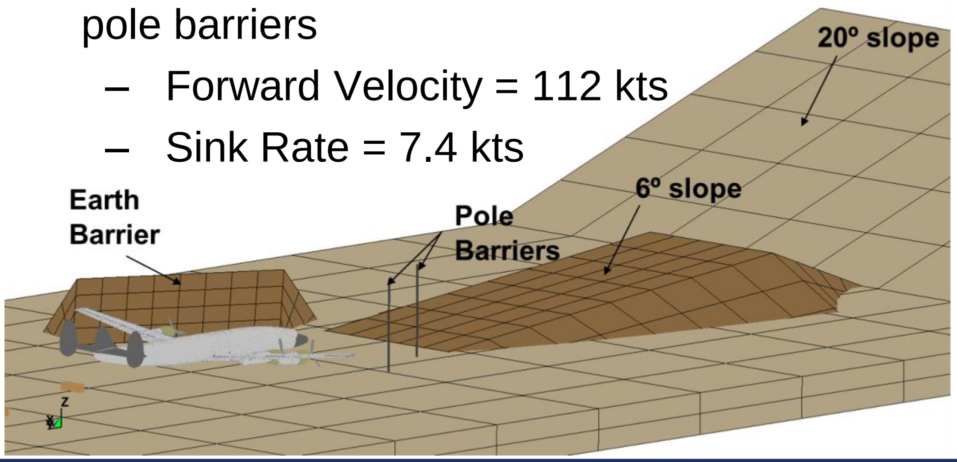
Complete FE Model of L-1649

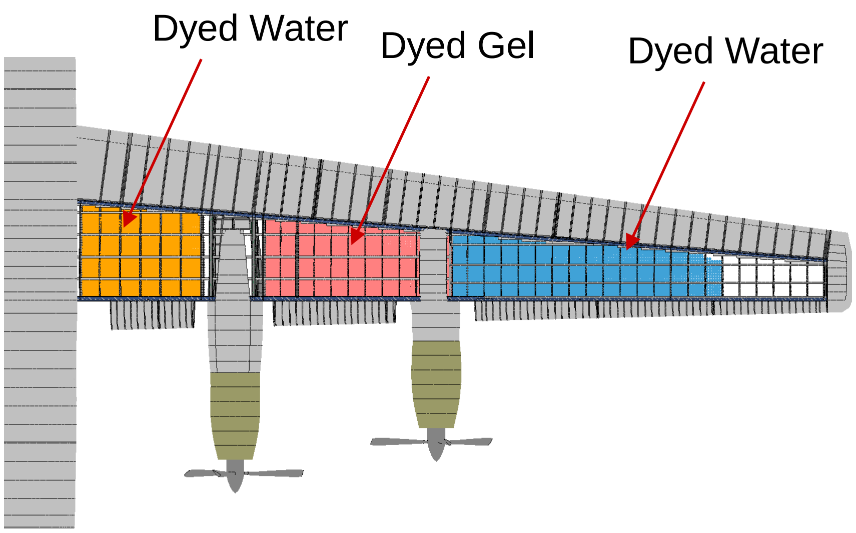


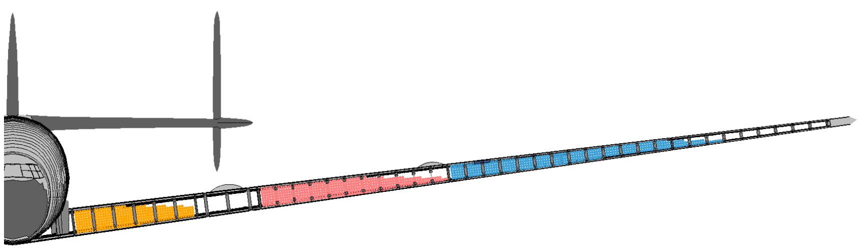


L-1649 Liquid Modeling and Crash Conditions

- Dyed water and gel explicitly modeled in integral tanks using Smoothed-Particle Hyrdrodynamic (SPH) particles
  - Fluid coupled with surrounding structures and can be released upon loss of tank containment
  - Does not account for aerosolization and drag once released in air
- Simulation started just prior to impact with pole barriers
  - Forward Velocity = 112 kts
  - Sink Rate = 7.4 kts





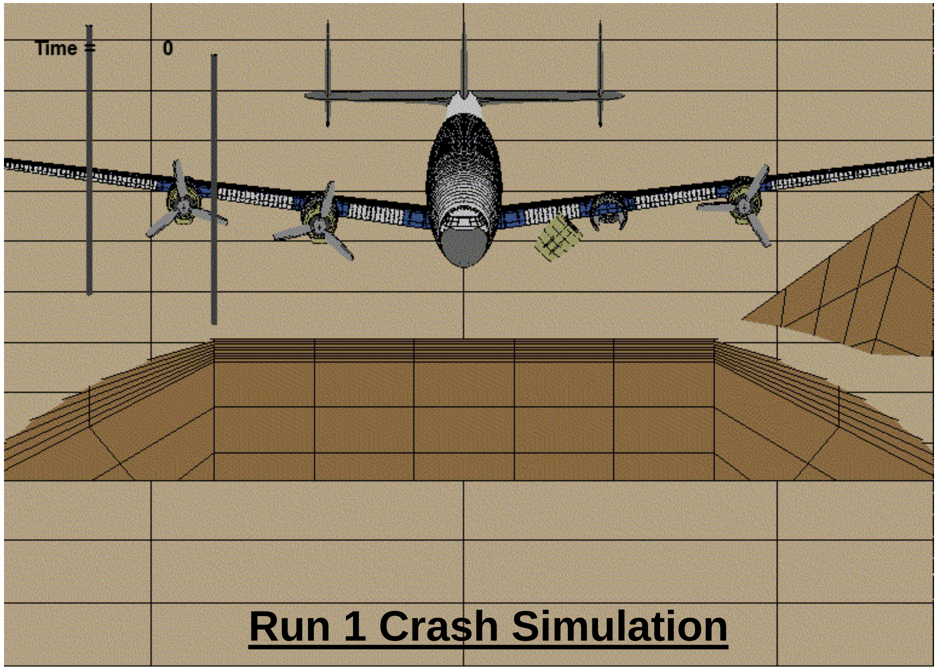


L-1649 Crash Simulation and Uncertainty Analysis

- Uncertainty Analysis: Performed matrix of 8 simulations of the full-scale crash event
  - Varied uncertainties in aircraft characteristics and crash test conditions
  - Provides bounds on crash response and quantifies significance of uncertainties on fuel release

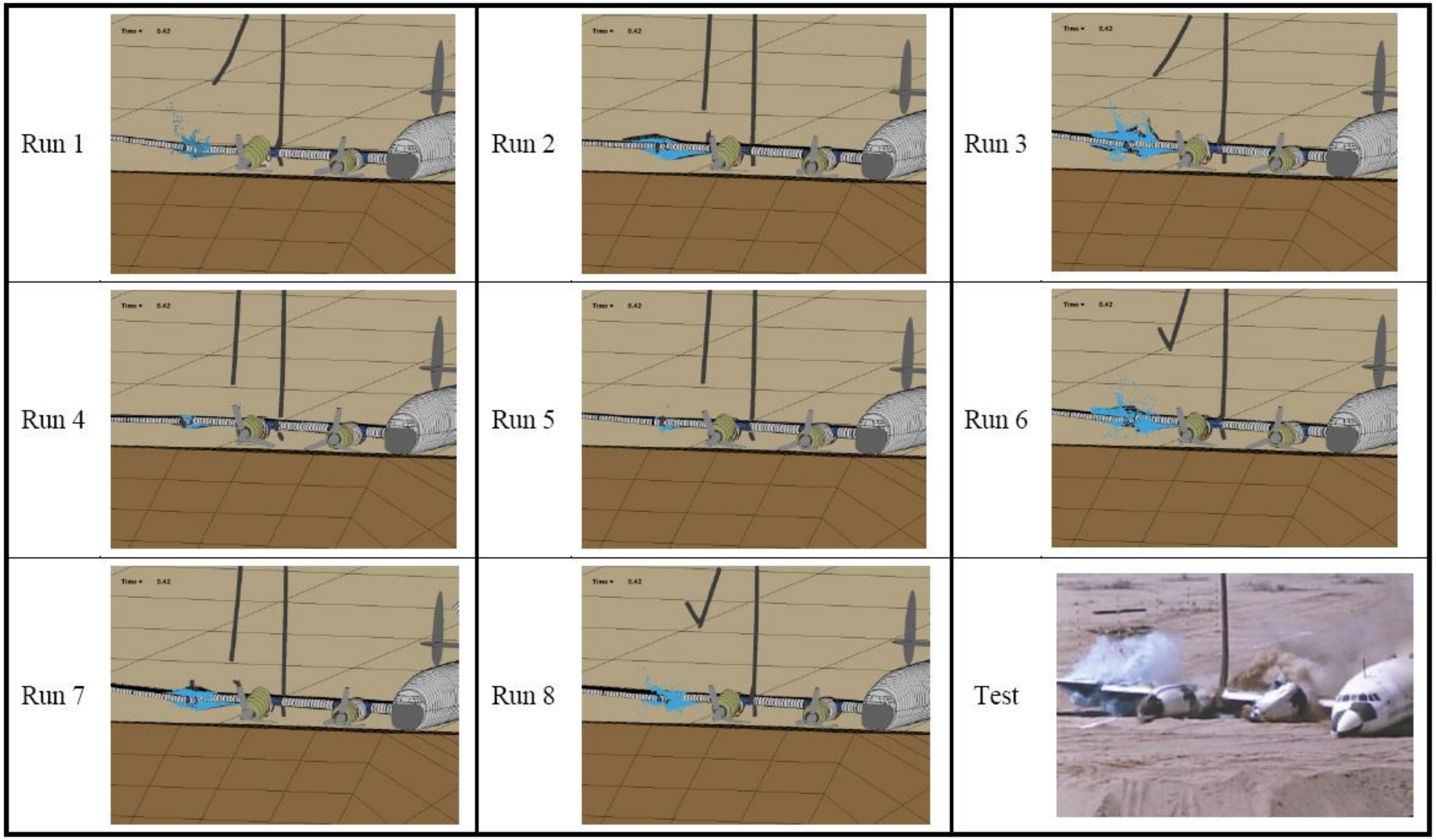
ID	Parameter		Low	High
1	Material Yield Stress		Allowable	125%
2	Material Failure Strain	7075-T6 Al	3.4%	8.2%
		2024-T4 Al	9.2%	12.4%
		Embrittled Al	NLL	115%
		17-7PH Steel	1.8%	2.2%
		AM350 Steel	3.0%	3.6%
3	Connection Strength		Allowable	150%
4	Connection Ductility		2 mm	10 mm
5	Berm Location		+0.5 m	current
	Berm Angle (degrees)		-7.5	7.5
	Pole Strength		low grade	structural grade
6	Ground Friction Coefficient		0.8	1.2

NLL-Net Ligament Loss

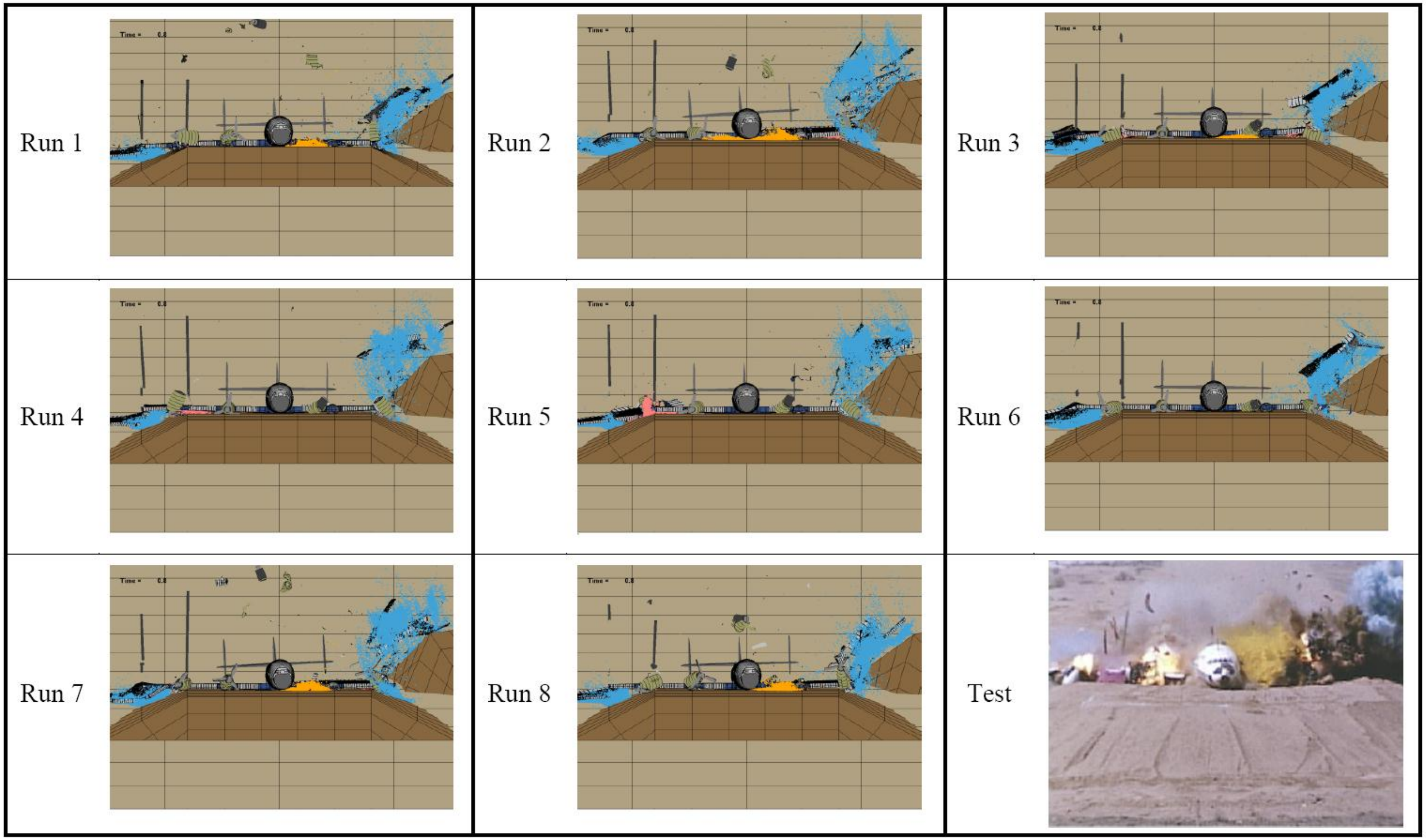


Run 1 Crash Simulation

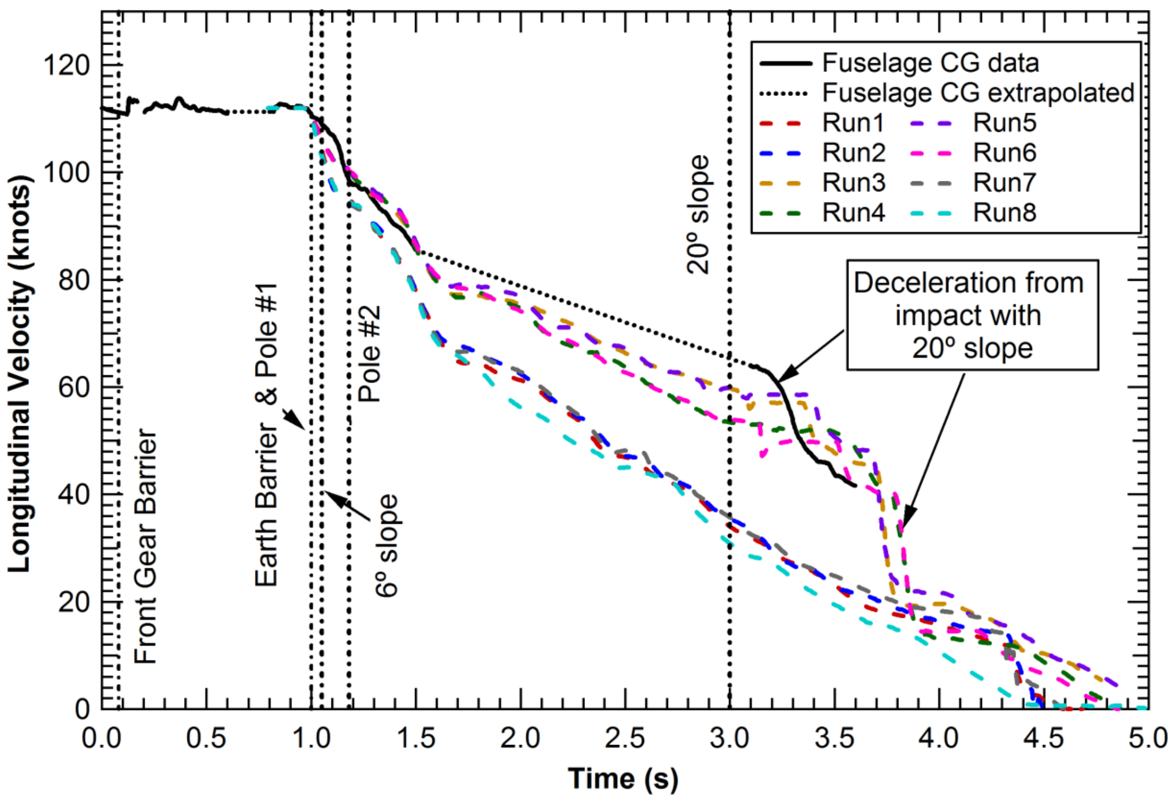
L-1649 Crash Simulation Comparison with Test Results



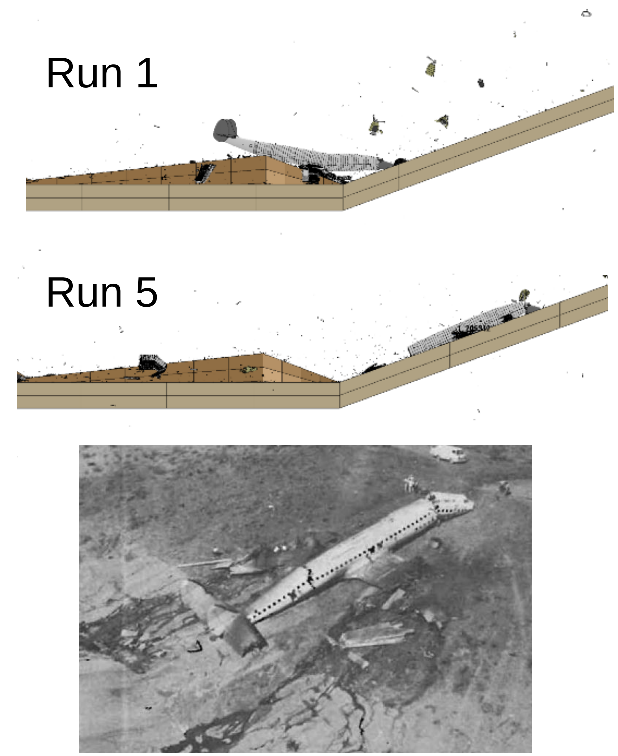
L-1649 Crash Simulation Comparison with Test Results



L-1649 Crash Simulation Comparison: Fuselage Deceleration

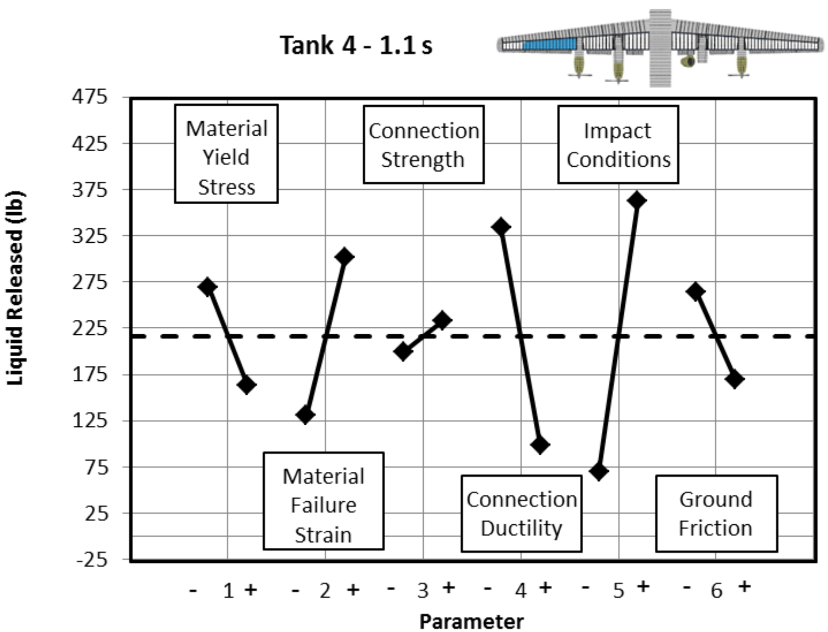


Final Position



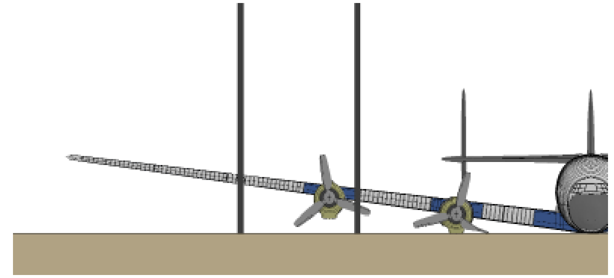
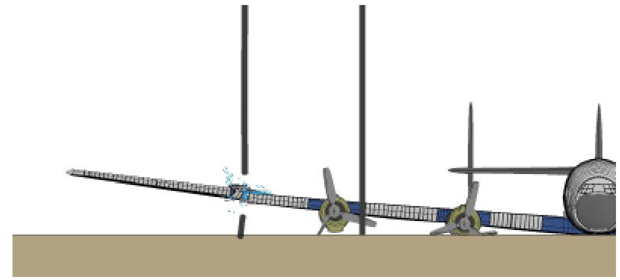
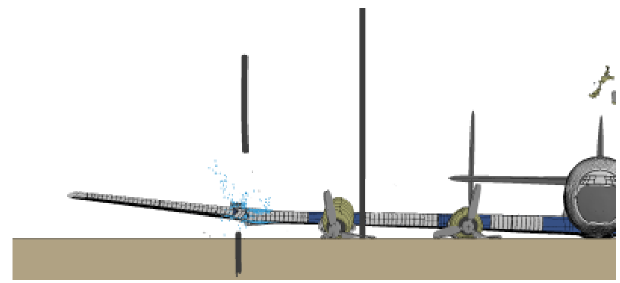
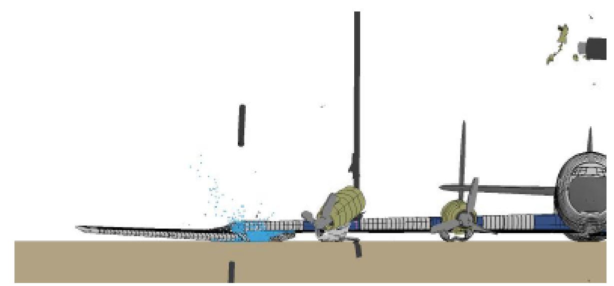
- Overall good agreement with primary impact events
- Effective ground friction less than lower bound modeled

Liquid Release Sensitivity Study



Liquid Release: Main Effects Plot –

Tank 4 at 1.10 s

1.00 s Just prior to telephone pole impact.	
1.10 s Telephone pole impacts Tank 4. Inboard nacelle impacts the ground. Fuselage nose begins to ride up the 6° slope.	
1.19 s Outboard nacelle impacts the ground. Fuselage rides up the 6° slope. Wing begins to flex downward.	
1.30 s Fuselage rides further up the 6° slope, lifting the wing. Wing flexes downward, causing Tank 4 to impact the ground.	

Phase 1 Summary

- The objective of this first phase of research was
  - (1) Validate full-scale crash modeling for predicting fuel release
  - (2) Refine modeling methods for simulation of full-scale crashes of transport aircraft for predicting fuel release in survivable events
- Both of these objectives have been met and significant insight into the important aspects of modeling fuel release was achieved
  - The range of simulated responses bounds the measured response from the crash test
  - Several key aspects of the model methodology were identified to improve the performance of the crash simulations of modern transport aircraft and reduce the uncertainty in the results

Refinement of Modeling Methods

- Ductility of connections is important to achieve a realistic response
- The degree of connection ductility has a significant effect on liquid release
- Incorporation of structural embrittlement of the perforated plates from connections is essential in simulating realistic degrees of damage
- Ground interaction and high-fidelity modeling of the engines is needed
- Reducing the uncertainty in this behavior will tighten the bounds on predicted fuel release