Crash Simulation of Transport Aircraft for Predicting Fuel Release

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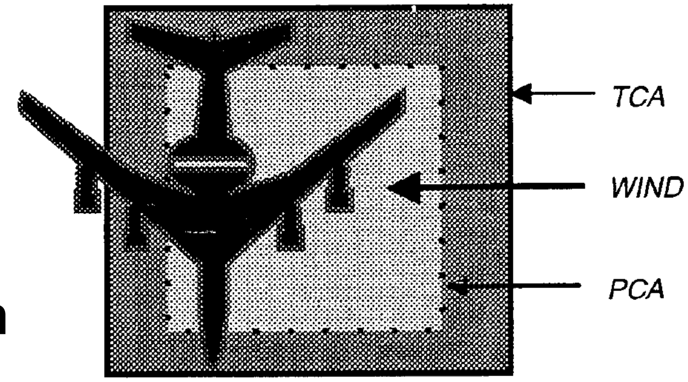
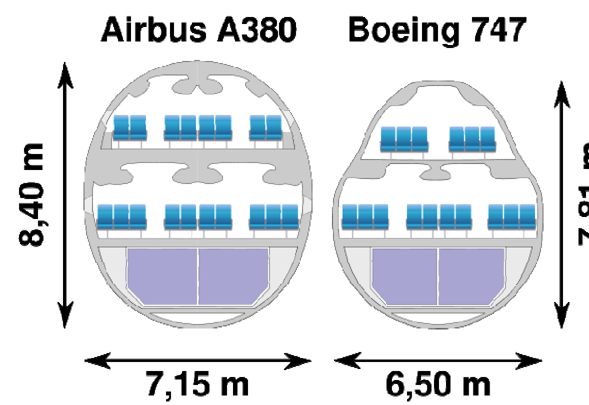
Introduction

- The theoretical critical area/practical critical area (TCA/PCA)[1] 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
  - use of multiple decks
  - differences in structural crashworthiness
  - use of composite materials

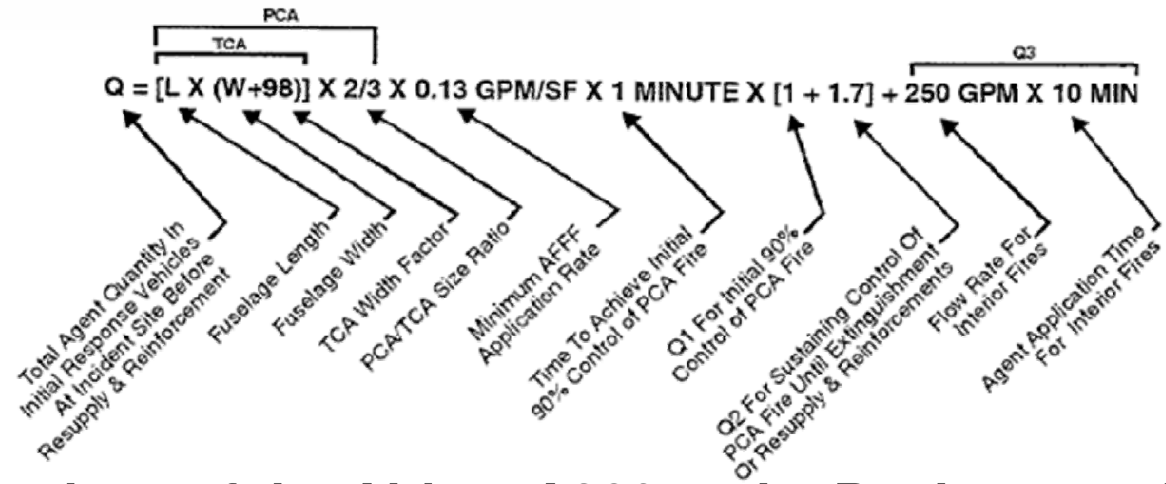




[1] Hall, G.F., B.R. Partin, J.H. Storm, "Large Frame Aircraft (LFA) Fire Fighting Validation: TCA/PCA Methodology Evaluation", Air Force Wright Laboratory Final Report WL-TR-95-3071, January, 1995.

Current PCA/TCA Methodology

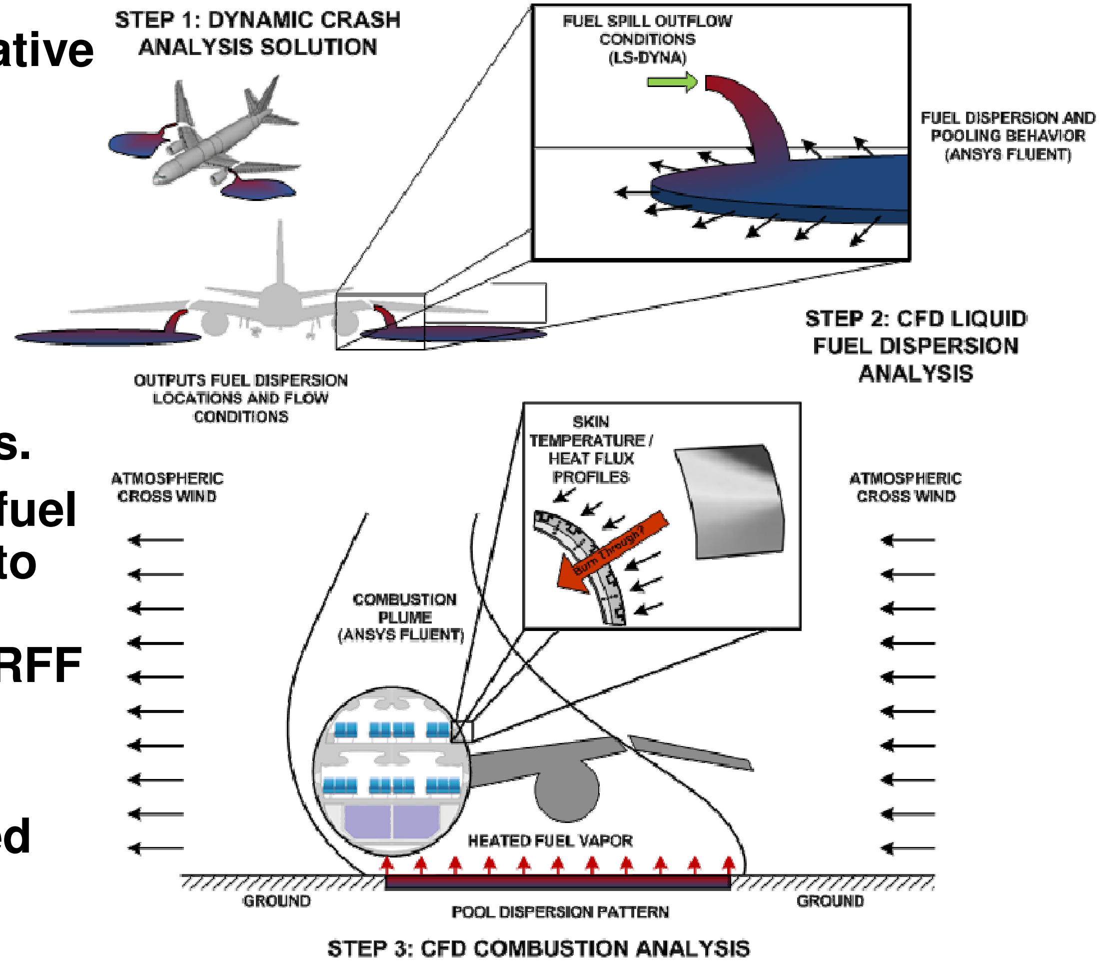
- Definition of minimum agent quantity calculation variables:



- Comparison of the Airbus A380 to the Boeing 747 yields roughly the same agent requirement.
  - (Airbus A380: L=73m, W=7.15m, Boeing 747: L=70.6m, W=6.15m).
- Airbus A380 carries about 50% more fuel and passengers.
- The A380 clearly has a greater potential for requiring a significantly greater quantity of total agent in initial response vehicles.

Project Objective and Approach

- **<u>Objective</u>: Provide an alternative methodology to PCA/TCA method.**
- **<u>Technical Approach</u>:**
  - **Perform high-fidelity nonlinear dynamic finite element analysis of survivable plane crashes.**
  - **Predict time dependent fuel distribution as an input to fire modeling efforts at AFRL for determining ARFF requirements.**
  - **Provide bounds on the quantity of fuel dispersed during various types of aircraft incidents.**



  - **Leverage modeling methods developed in WTC aircraft impact analyses.**

FE Analysis Code: LS-DYNA

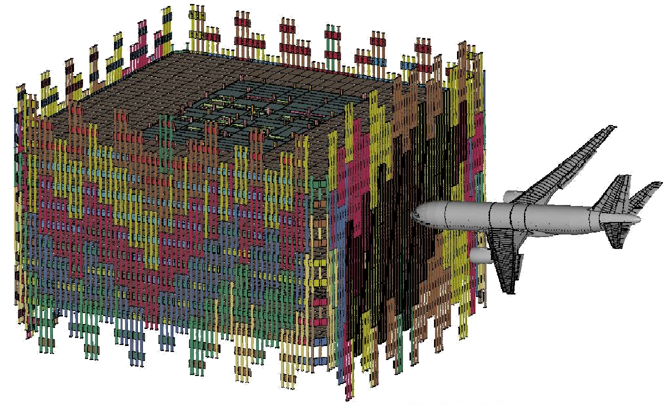
- LS-DYNA is a general purpose nonlinear dynamic finite element program.
  - Explicit code architecture
- FE Analysis incorporating
  - Large strains/displacements
  - Nonlinear material behavior/failure
  - Dynamic response
  - Advanced ALE and SPH capabilities for modeling Fluid-Structure Interaction (FSI).
- Ideal for crash, impact, blast and penetration applications.
- Livermore Software Technology Corporation (LSTC) commercialized LS-DYNA based on development of the DYNA3D code at Lawrence Livermore National Laboratory by LSTC's founder, John O. Hallquist.
- LS-DYNA is optimized for shared and distributed memory Unix, Linux, and Windows based, platforms.

LSTC Livermore Software Technology Corp.

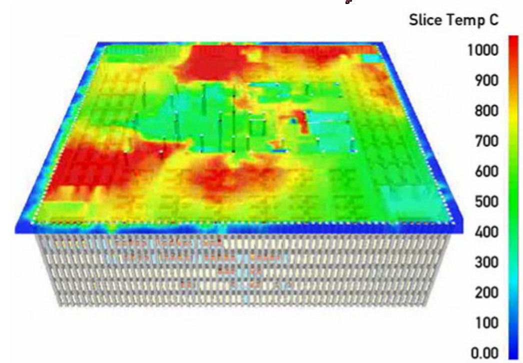
NIST Federal Building and Fire Safety Investigation of the World Trade Center Disaster

- **ARA conducted Aircraft Impact Analyses**
  - **Impact analyses provided predictions of structural damage and fuel dispersal.**
- **National Institute of Standards and Technology (NIST) conducted Fire and Collapse Analyses**
  - **Fire analyses performed using fuel dispersal predicted from impact analysis.**
  - **Structural collapse predicted from impact and fire analyses.**

Aircraft Impact Analysis



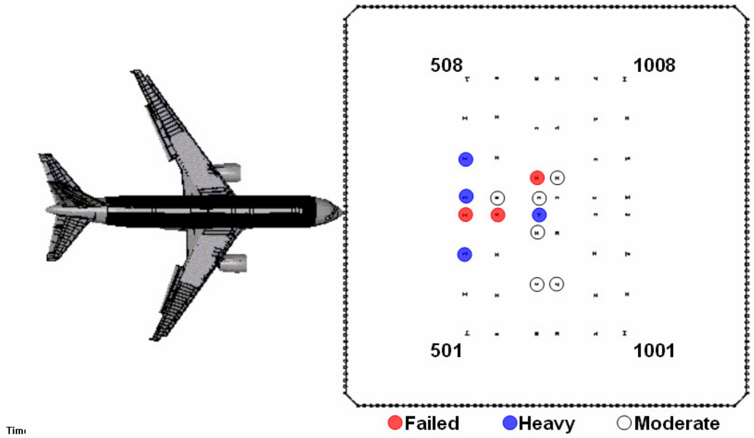
Fire Analysis



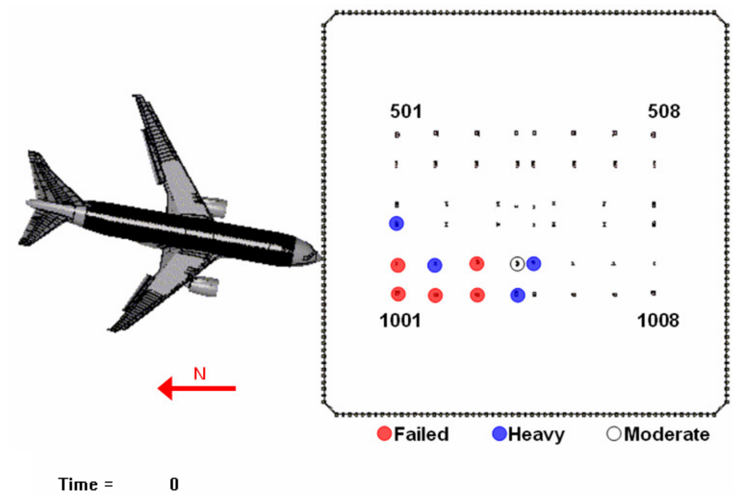
Structural Collapse Analysis

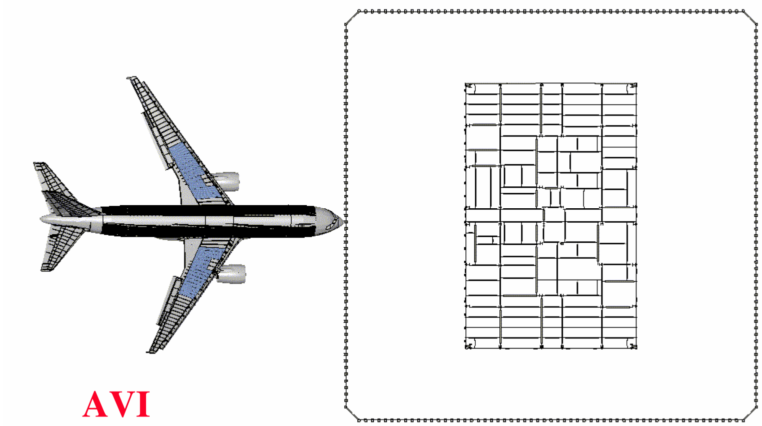
Fuel Dispersal and Core Damage

WTC 1



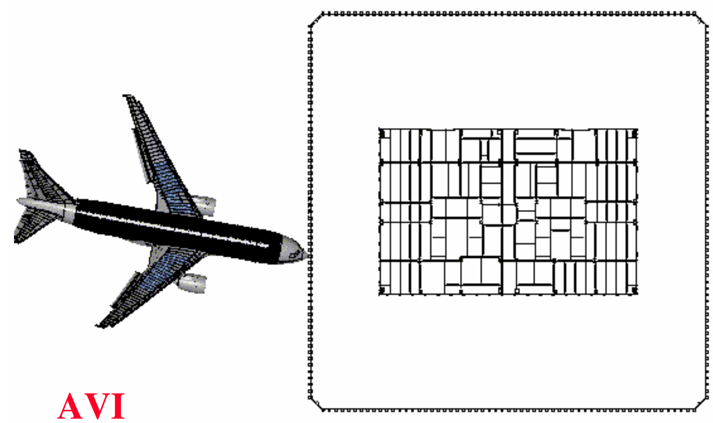
WTC 2





AVI

Interior Tower Contents Transparent



AVI

Interior Tower Contents Transparent

Project Plan

- Phase 1:   Proof of Concept – Validation against full-scale crash tests.


- Phases 2 & 3: Evaluate fuel dispersal for other transport aircraft
  - Potentially Airbus A380 and Boeing 787.


Phase 1 – Proof of Concept
Validation with a Full-Scale Crash Test

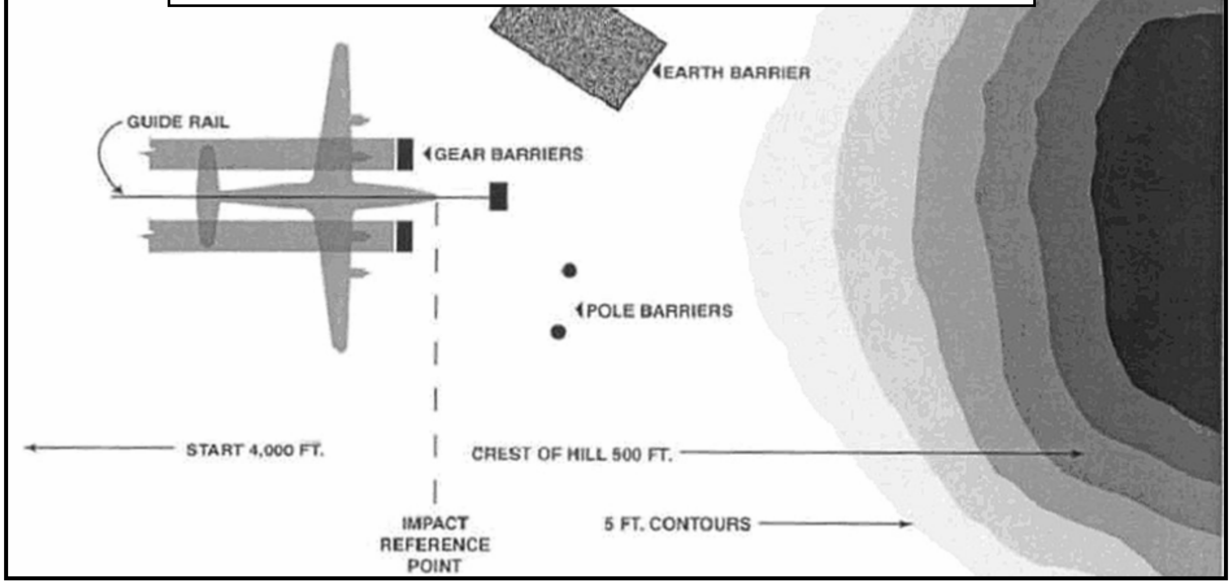
Lockheed Constellation Model 1649

- **The FAA conducted full-scale crash tests of commercial transport aircraft in 1965.**
- **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.**

[2] Reed, W.H., S.H. Robertson, L.W.T. Weinberg, L.H. Tyndall, "Full-scale Dynamic Crash Test of a Lockheed Constellation Model 1649 Aircraft", FAA-ADS-38, October, 1965.

Phase 1 – Proof of Concept
Validation with a Full-Scale Crash Test

Plan view of Constellation crash test site



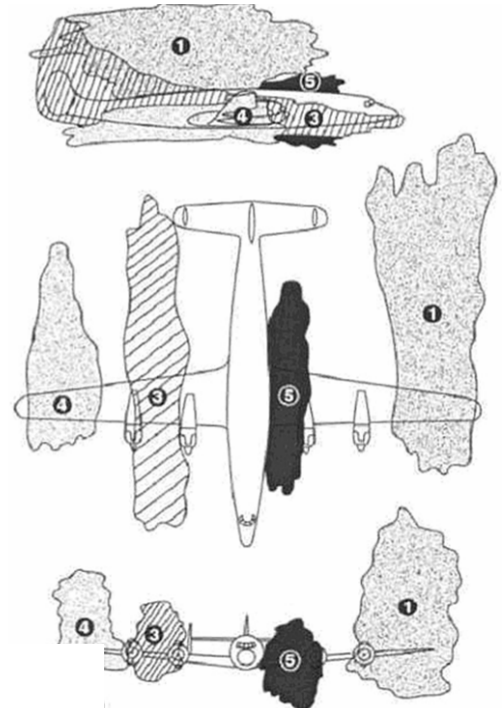
- Initial impacts at 112 knots removed the landing gear, resulting in the aircraft to be airborne.
- Once airborne, the left wing struck an earthen barrier and the right struck two vertical telephone poles.
- The constellation had only integral fuel tanks and no bladder tanks.

Phase 1 – Proof of Concept

Validation with a Full-Scale Crash Test

- **Results from this test will be used to validate and refine the computational models.**
- **A well-controlled full-scale crash test focused on determining fuel dispersal is a better approach than making comparisons with real crash incidents.**
- **Accelerometer data, photographic documentation of the crash event and the rate of fuel dispersal from the simulation will be compared with the documented test results.**
- **Modeling methodologies developed and validated in this phase will be used in subsequent phases to evaluate aircraft of interest.**

Fuel spillage occurring 2.24 seconds after gear impact



1. Left outboard tank – water.
5. Left root tank – water.
3. Right tank between engine and nacelles – gel.
4. Right outboard tank – water.

Phase 2 – Evaluate Fuel Dispersal from a Modern Transport Aircraft

Airbus A380

- Implement the validated modeling methodologies from Phase I for assessing fuel dispersal from a modern transport aircraft (e.g., A380).
- The focus will be on determining bounds for the rate of fuel dispersal for common impact-survivable crash scenarios
- Focus on:
  - Fuel tank puncture from uncontained engine failure fragments.
  - High impact landing (Hard Landing).
  - Ground collision with another structure.

Example Aircraft Crash Incidents

Incident Aircraft	Date and Accident Report	Location	Crash Details
Boeing 737-236	August 22, 1985 8/88	Manchester Int. Airport England	Engine fragment penetrated fuel panel
Boeing 727-232	August 31, 1988 AAR-89-04	Dallas-Fort Worth Airport	Struck ILS at takeoff
Douglas DC-10	July 19, 1989 AAR-90-06	Sioux City	Engine fragment destroyed all hydraulic systems. Right wing tip, main landing gear, and nacelle contacted runway at touchdown causing tumbling.
Boeing 737-300	February 1, 1991	Los Angeles International Airport	Impacted a Fairchild Metro III turbo-prop on runway after touchdown.
Lockheed L-1011	July 30, 1992 AAR-93-04	John F. Kennedy International Airport	Hard landing on right main landing gear causing failure of wing spar.

- **Review of aircraft accident reports of potentially survivable events indicate that there are generally three types of events (engine fragment, hard landing, ground collision).**
- **Many of these incidents are considered fire-incident milestones.**

Phase 2 - 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**	**Airplane Configuration/ Impact Conditions**	**Terrain**	**Hazard**
Ground to Ground (overrun)	Takeoff abort/landing overrun	On runway or within 3000 ft. of end runway	60-100	< 5 fps	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 fps < 12 fps	Gear extended. Symmetrical	Runway Soft Ground	None
Air to Ground (Impact)	Final Approach	On runway or between outer marker and missed approach point	> 126 kts	> 12 fps	Gear extended & retracted. Symmetrical & Unsymmetrical	Hard Ground Hilly Rocky	Trees Poles Slopes Ravines Buildings

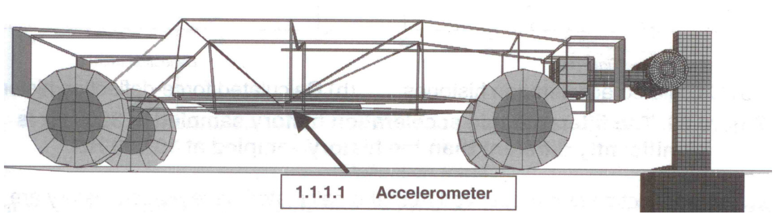
[3] A Study of Transport Airplane Crash-Resistant Fuel Systems", DOT/FAA/AR-01/82, NASA/CR-2002-211437, March 2002.

Analysis of Hard Landings and Impact with Ground Hazards

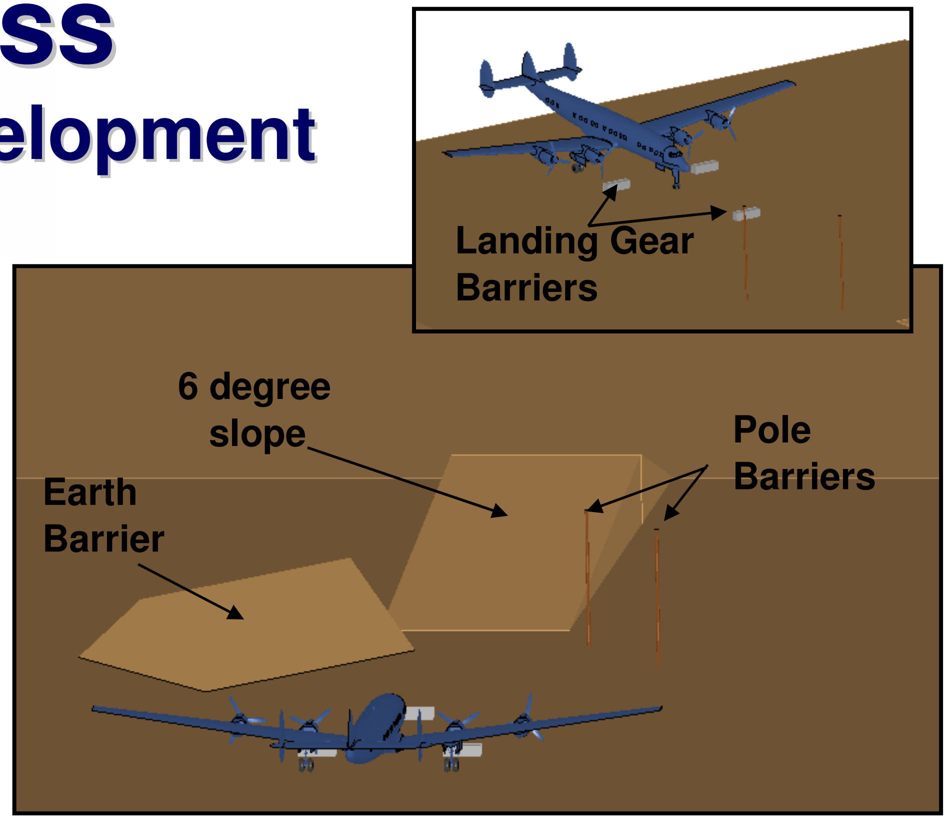
- Various parameters will be considered in developing bounds on fuel dispersal.
  - aircraft speed
  - ratio of forward velocity to sink rate
  - aircraft weight and fuel load
  - gear configuration
- The variations in crash conditions will be limited to impact-survivable events and aircraft operational requirements, using the impact conditions recommended by SAFER Committee.

Phase 1 Progress

Crash Site Model Development



Bogie and Pole Models Used to Validate Wood Material Model used for Pole Barriers[4]



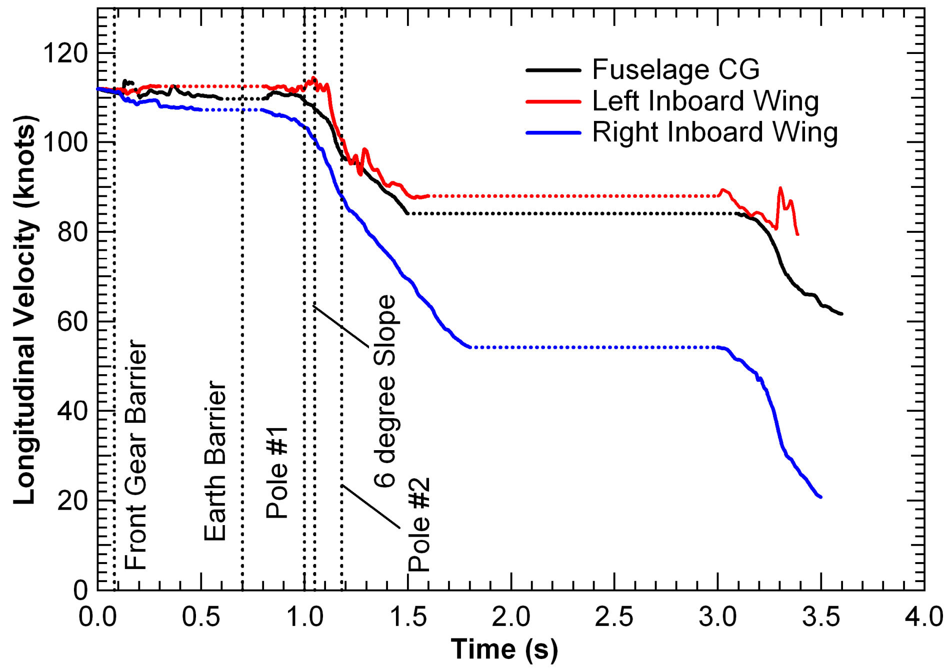
- Model of the crash site completed including earth, pole, landing gear barriers and 6 and 20 degree slopes.
- Created model of a typical telephone pole (40 ft. tall, 10 in. diameter) made of Southern Yellow Pine using LS-DYNA wood material model created for FHWA crash and impact applications.
  - "This material model was developed specifically to predict the dynamic performance of wood components used in roadside safety structures when undergoing a collision by a motor vehicle."

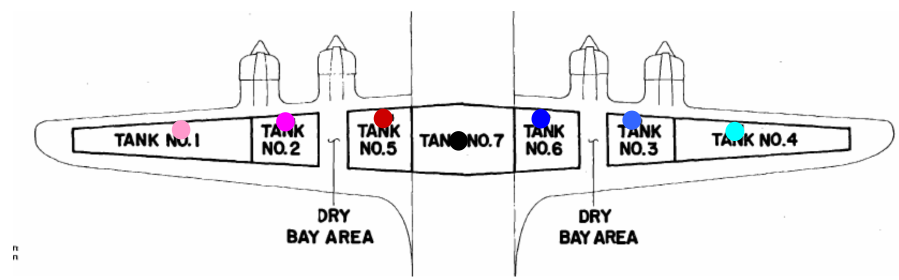
[4] Manual for LS-DYNA Wood Material Model 143, Publication No. FHWA-HRT-0R-097, Aug. 2007

Phase 1 Progress
L-1649 Crash Test Reconstruction

- **Accelerometer data and high-speed film being used to reconstruct response of each aircraft component during crash.**
- **Accelerometers were placed at three locations on each wing and five locations in the fuselage.**

Longitudinal Velocity





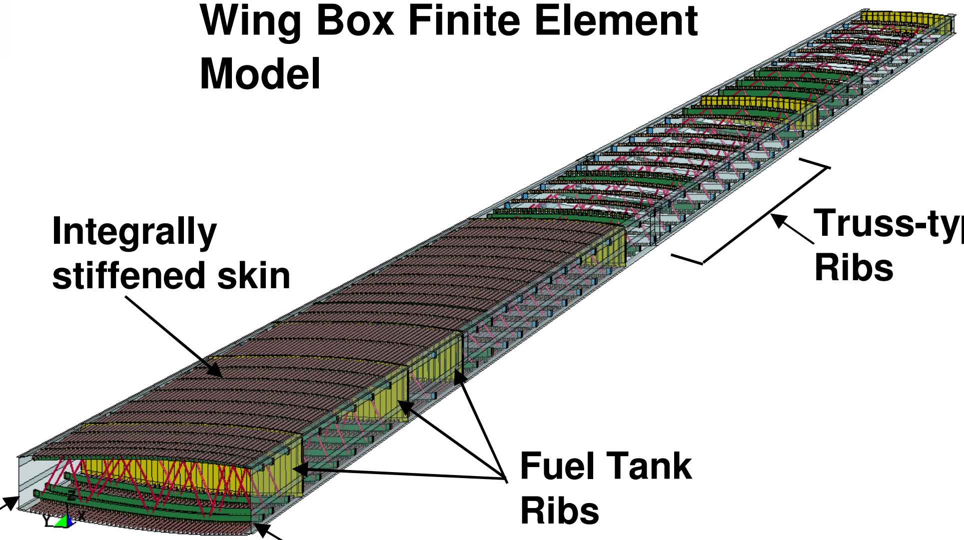
Accelerometer Locations

Phase 1 Progress

L-1649 Model Development

Exterior Surface Geometry

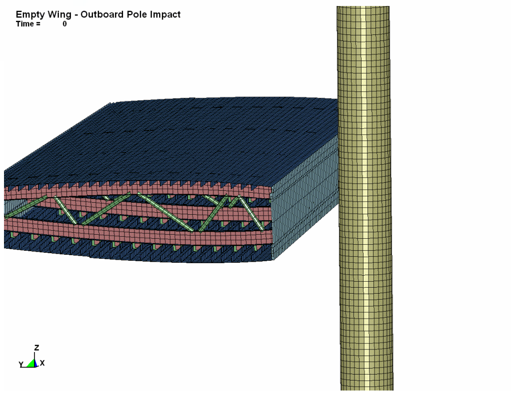
Wing Box Finite Element Model



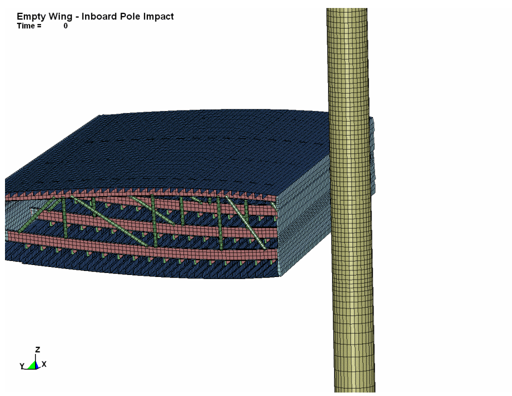
- Modified available electronic surface geometry to be suitable for creating a computational mesh of the aircraft.
- Structural model for wing box with integral fuel tanks is largely complete.

Phase 1 Progress

Preliminary Impact Analyses – Pole Barriers



Outboard Pole Impact



Inboard Pole Impact

- **Inboard wing tank compromised after impact with ground, outboard by pole impact.**

Conclusion

- An alternative to the PCA/TCA methodology for determining ARFF requirements is under development.
- Method is based on conducting high-fidelity LS-DYNA crash simulations of impact-survivable aircraft accidents.
  - Utilizes modeling techniques applied in the WTC Disaster investigation.
  - Provide bounds on fuel dispersal which will serve as input to fire modeling efforts.
  - ARFF vehicle and agent requirements can then be defined.
- Technical Approach involves validation against full-scale crash tests and evaluation of two aluminum-framed transport aircraft.
- Future work will include aircraft with a more significant use of composite materials (e.g. Boeing 787):
  - Will require additional validation against composite structure crash tests.