Criteria Evaluation Meeting

JAFSG – Joint Airfield Frangibility Study Group

Joe Breen P.E.

Robert Dinan PhD

John Gregory P.E.

Dave Lindquist

OCTOBER 2015

Introduction

OVERVIEW

Members Presenting

- Dan Duke, Ph.D. P.E.
  - TriDynamic Solutions
- Robert T. Bocchieri, Ph.D.
  - Applied Research Associates
- Shane Shurtliff, P.E.
  - Select Engineering Services
- Ben Griffiths
  - Select Engineering Services

Presentation Agenda

Event/Paper	Time	Moderator or Speaker
Background/Overview	8:05am-8:40am	Dan Duke, Ph.D., Robert T. Bocchieri, Ph.D., Shane Shurtliff
Rigid Impactor Study	8:40am-9:00am	Dan Duke, Ph.D., Robert T. Bocchieri, Ph.D., Shane Shurtliff
Peak Force as a Defining Criteria for Frangibility	9:00am-9:40am	Dan Duke, Ph.D., Ben Griffiths
Morning Break	9:40am-10:00am	
Energy Limits and New Rating System for Frangibility	10:00am-10:40am	Dan Duke, Ph.D., Shane Shurtliff, Ben Griffiths
Impulse and Force Duration to Replace Force and Energy as Frangibility Criteria	10:40am-11:20am	Shane Shurtliff, Ben Griffiths
Vertical Force and Flight Stability Requirements for Frangible Structures	11:20am-12:00pm	Dan Duke, Ph.D., Robert T. Bocchieri, Ph.D., Shane Shurtliff
Lunch Break	12:00pm-1:40pm	
Frangibility Energy Calcs for NAVAIDS in FAA Defined RSA	1:40pm-2:20pm	Dr. Dale A. Delisle, Ph.D., P.E.
Allowable Failure Modes of Frangible Structures and the Need for Additional Impact Location Evaluations	2:20pm-3:00pm	Dan Duke, Ph.D., Robert T. Bocchieri, Ph.D., Shane Shurtliff
ILS Tower Design from Static and Frangibility Perspective	3:00pm-3:40pm	Helmut Lieb
Afternoon Break	3:40pm-4:00pm	
Speed Tolerances for Testing Frangible Structures	4:00pm-4:20pm	Ben Griffiths
As Tested Certification and Documentation Requirements	4:20pm-4:40pm	Dan Duke, Ph.D.,

Current Test Setup Criteria

- Aircraft mass of 6613.8 pounds (3000 kg)
- Traveling at 75.6 knots (140 kph)
- Impactor must be Semi-circular steel tube (rigid body) with dimensions of 3.28 ft (1.0 m) long or 5 times the cross section of tower, 9.8 in (250 mm) diameter, and 1.0 in (25 mm) wall thickness
- Load cells mounted as closely as possible to impactor. Minimum recording rate of 10 kHz
- High speed video to verify aircraft direction would not be adversely affected by structure
- Impact Location: 13.1 ft (4 m) above grade or 3.28 ft (1 m) from top, whichever is higher.

Current Approval Criteria

- Approval Criteria (AC 150/5345-45C, ICAO Part 6)
  - LIR structure must not exert a force greater than 10,116 lbf (45 kN)
  - Maximum energy imparted to aircraft should not exceed 40,566 ft-lb (55 kJ)
  - Failure mode must be fracturing , windowing, or bending
  - Electrical cabling must separate, not impede failure
  - No large fragments that could damage other parts of aircraft

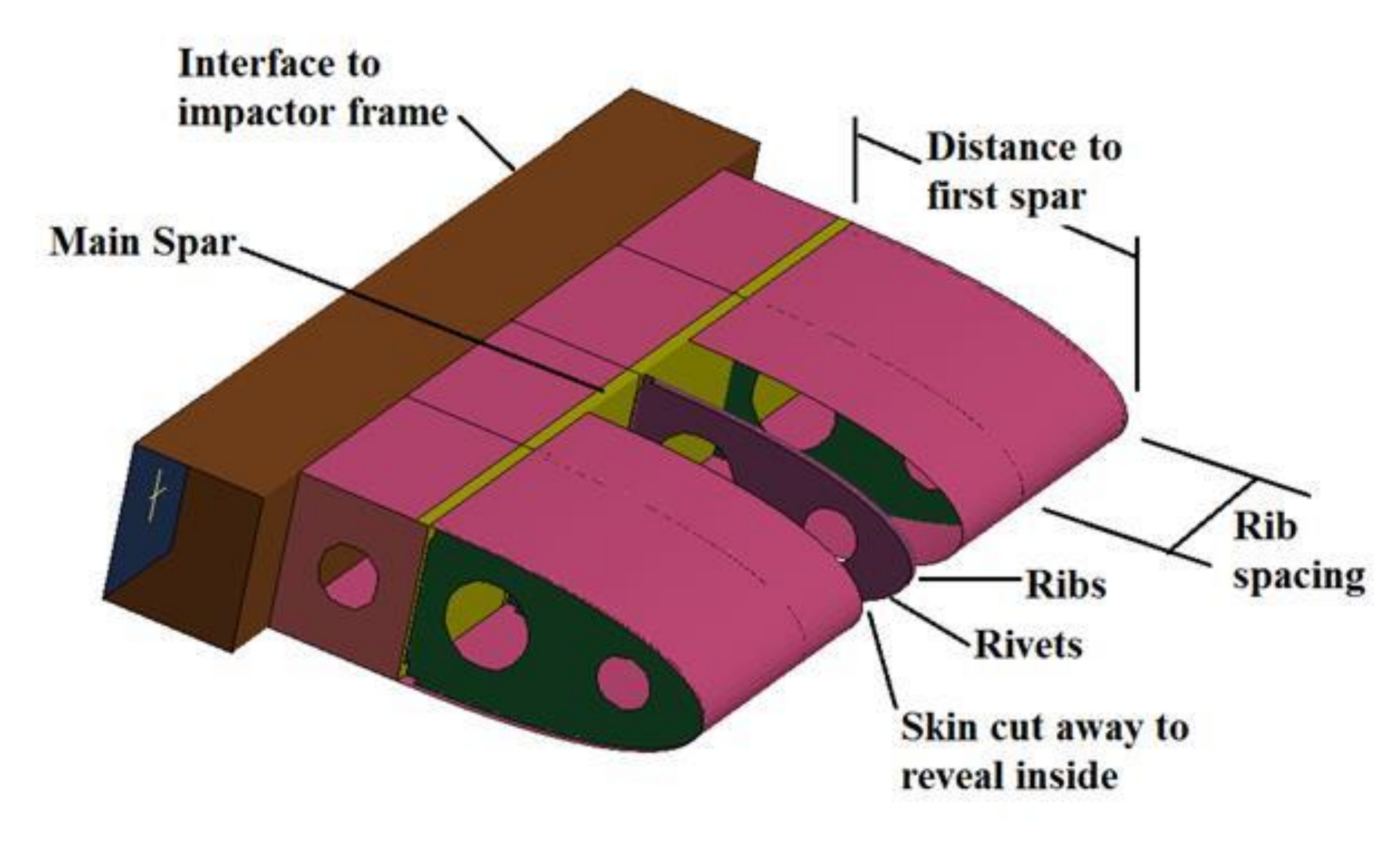
Dan Duke, Ph.D. P.E.

TRIDYNAMIC SOLUTIONS

Focus Areas

- Historical Developments
  - Evaluation of technical basis of methodology
  - Review of available test reports
- Simulation of Historical Tests
  - Model validation using test results
  - Comparison with available results
- Parameter Studies
  - Using validated models from historical tests
  - Sensitivity studies using multiple parameters
- Recommendations
  - Criteria change
  - Future research

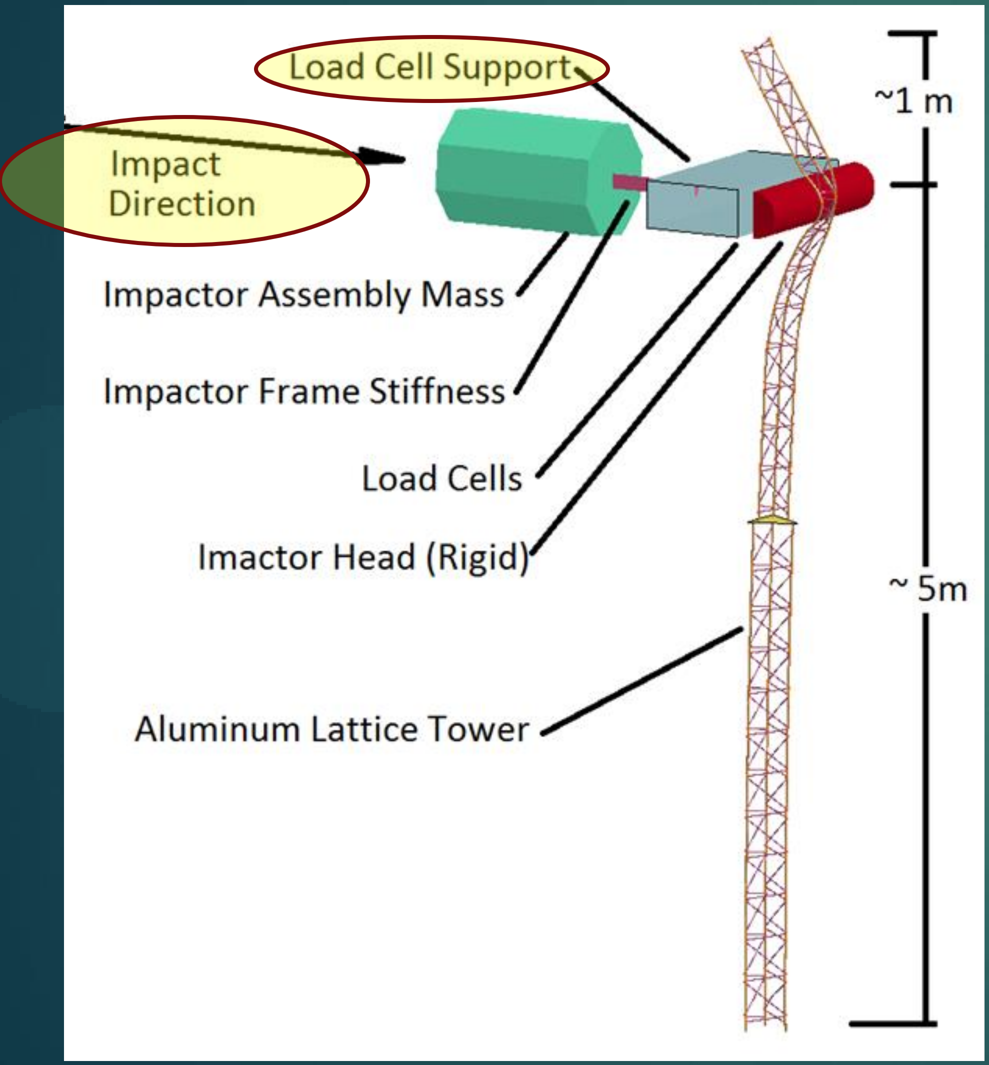
Variation in Impactor Heads

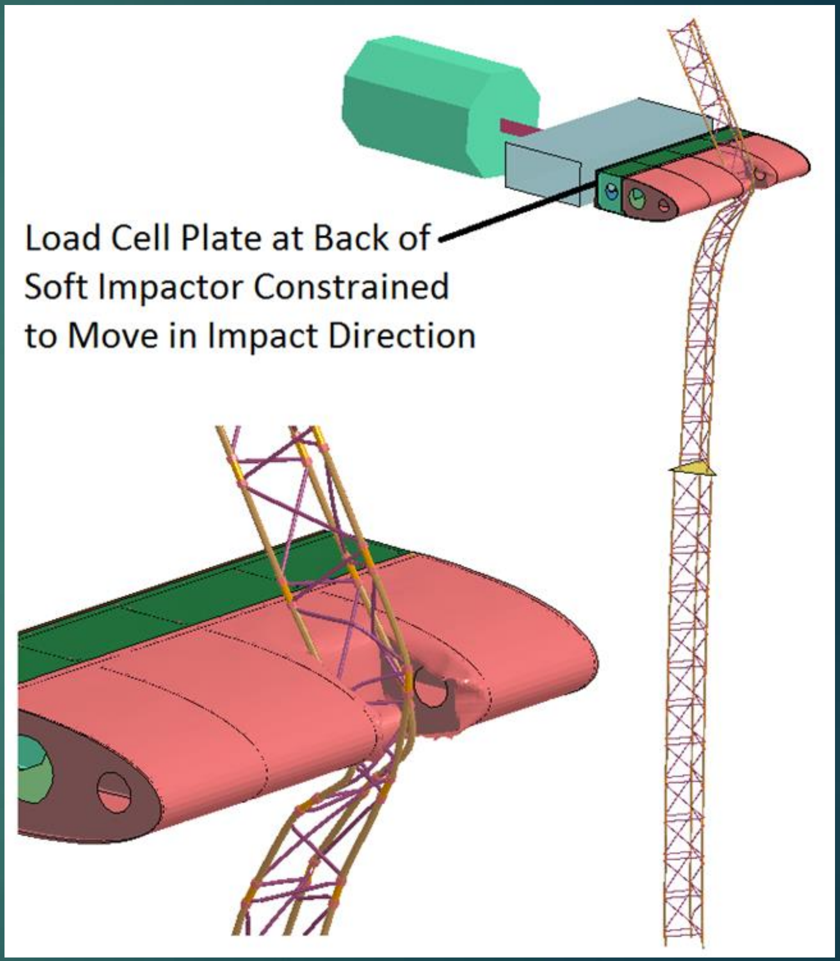


Variation in Impactor Heads

Impactor	Skin Thickness (mm)	Rib Thickness (mm)	Spar Thickness (mm)	Rib Spacing (mm)	Distance to First Spar (mm)	Stringer Stiffened Skin
NLR (1, 2, 3)	0.8	1.5	2.0	325,350, 325	340	-
TC - 1	0.5	0.5	1.0	290,305, 280,280	450	-
TC - 2	0.8	1.5	1.5	290,305, 280,280	450	-
SBCA	0.8	-	0.8	650	-	Y
FAA / NAEC	Piper Navajo Wing					Y
Rigid	Steel Pipe (25 mm thick)					

Validated Models





Impacted Devices

Device Type	Cross Section	Material	Tower mass (kg)
Aluminum Lattice	14.3 mm diameter verticals 7.9 mm diameter diagonals Equilateral triangle with 17.8 mm wide sides at top 3.0 m and 22.9 mm wide at bottom 3.0 m.	6061-T6 aluminum	14.9
Aluminum Pipe	145 mm diameter prismatic pipe with 3 mm wall thickness	6063-T6 aluminum	22.3
Composite Lattice	30 mm diameter vertical tubes with 2 mm wall thickness. 20 mm diameter diagonals with 2 mm wall thickness. Square with 400 mm sides.	Fiberglass Tubes 500 MPa Tensile Strength[1]	19.2
Composite Pipe	152.4 mm diameter pipe with 3.2 mm wall thickness. Frangible joints at 1.07 m (42 inch) spacing.	Fiberglass 353 MPa Effective Tensile Strength	17.5

[1] Material of construction not available. Selection based on similar products that may be used in this application.

Parameter Study Models

- Approximately 100 simulations with different parameter combinations
- 12 varied parameters:
  - Impact speed
  - Impactor mass
  - Impactor stiffness
  - Load cell mass
  - Load cell stiffness
  - Impact location
  - Impact point relative to joint
  - Tower height
  - Tower mass
  - Tower strength
  - Wing strength
  - Top mass

Example Test Matrix

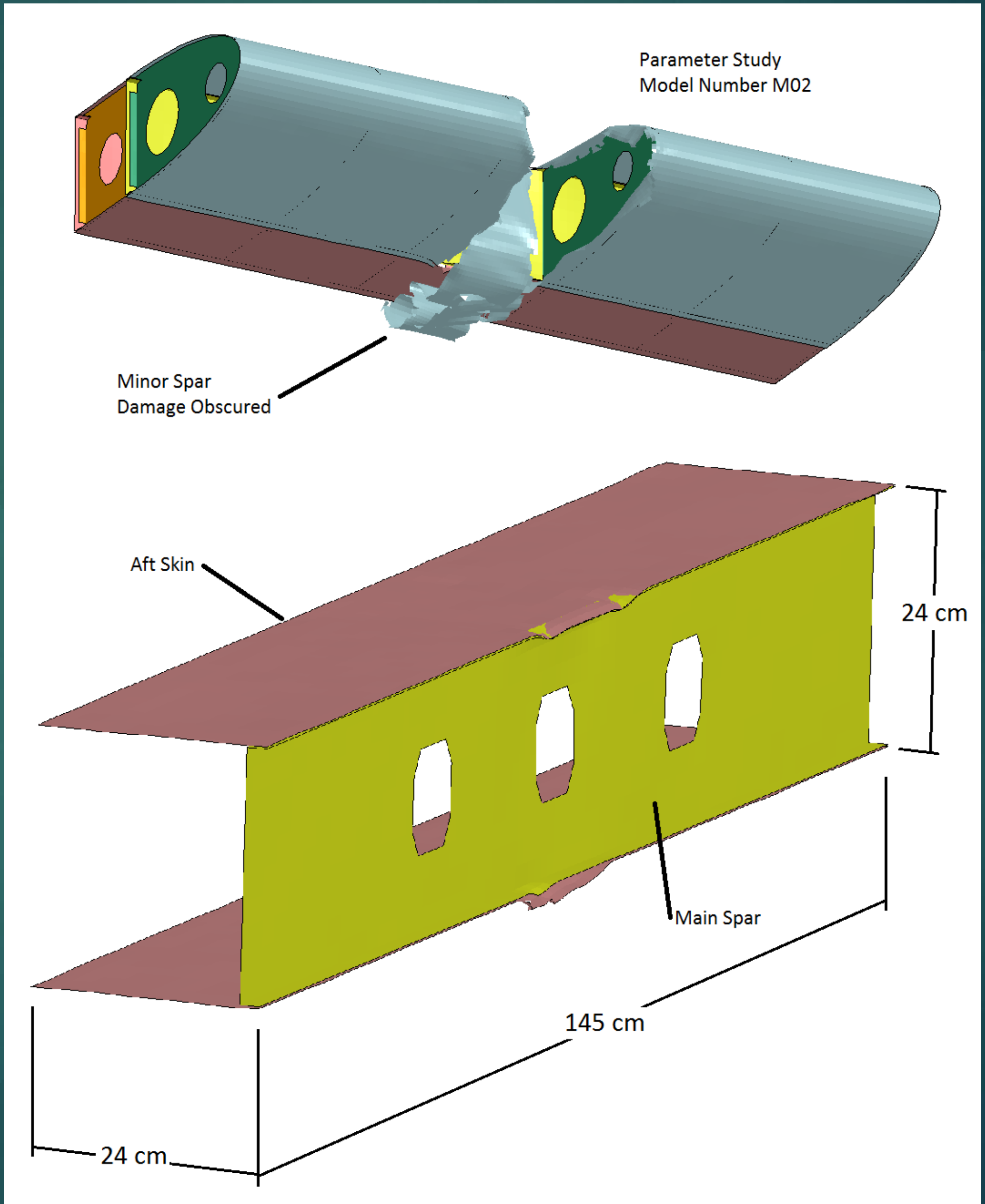
Model Name	Pole Height (m)	Distance from Top (m)	Top Mass (kg)	Impact Speed (kph)	Tower Type	Variation
M02	6	1	0	140	AL	No Top Mass
M04	6	1	0	140	AP	No Top Mass
M06	6	1	0	140	CL	No Top Mass
M08	6	1	0	140	CP	No Top Mass
M101	6	1	20	140	AP	Vary Tower Strength
M101a	6	1	20	140	AP	Vary Tower Strength
M102	6	1	20	140	AP	Vary Tower Strength
M103	6	1	20	140	CP	Vary Tower Strength
M104	6	1	20	140	CP	Vary Tower Strength
M105	6	1	0	140	AP	Vary Tower Strength
M106	6	1	0	140	AP	Vary Tower Strength
M111	6	1	20	140	AP	Vary Impactor Mass
M112	6	1	20	140	AP	Vary Impactor Mass
M113	6	1	20	140	CP	Vary Impactor Mass
M114	6	1	20	140	CP	Vary Impactor Mass
M115	6	1	20	140	AP	Vary Impactor Mass
M116	6	1	20	140	CP	Vary Impactor Mass
M121	6	1	20	140	AP	Vary Tower Mass
M122	6	1	20	140	AP	Vary Tower Mass
M122a	6	1	20	140	AP	Vary Tower Mass

Wing Damage Severity Categories

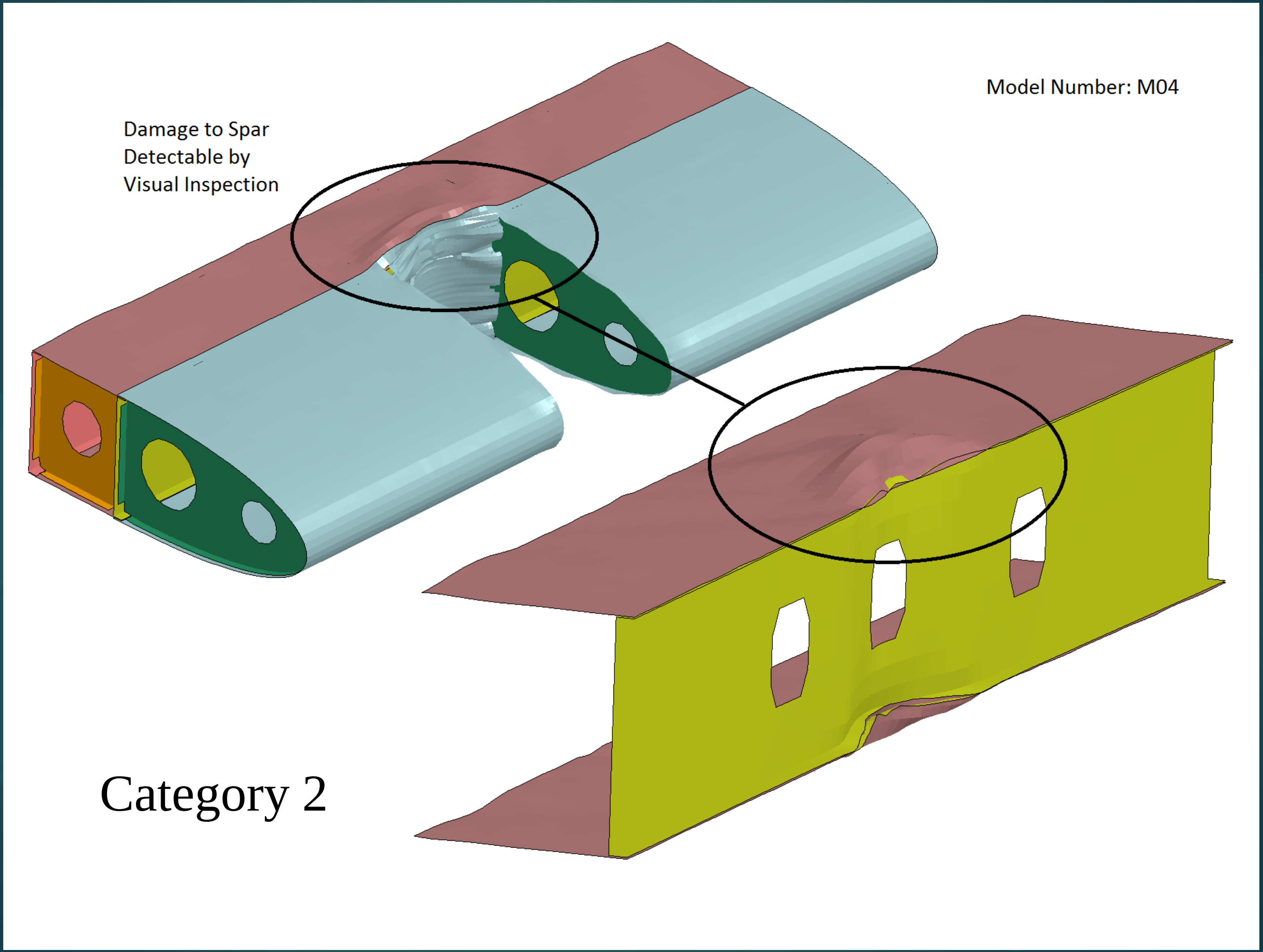
Category	Description
0	No visually distinguishable damage to main spar in the form of bent plates, dents or tears. No tearing, buckling or wrinkling of skin aft of the main spar. Forward skin and ribs may be dented or torn. Connection (rivets) of forward skin to ribs and main spar may be damaged. Connection of aft skin and ribs to main spar intact.
1	Minimal damage to the main spar that may not be detected by visual inspection without careful disassembly of the wing. Damage in the form of small dents primarily local to the flanges of the main spar (area of discrete dents less than 20 cm^2). Forward skin may be collapsed or peeled back to the main spar and may be pulled past the top or bottom of main spar. Connection (rivets) of forward skin to ribs may be damaged. Away from impact point connection of forward skin and ribs to main spar intact. Damage to the aft skin limited to small area of bending local to the possible small dents in the main spar.
2	Significant damage to the main spar in the form of bending of the main spar web and flanges. Significant area of aft skin wrinkled in the area of the damage to the main spar flange (area of discrete dents less than 100 cm^2). May have other small dents or tears in the aft skin. Forward skin torn, collapsed or peeled back to or past the main spar. Much of the damage clearly visible without disassembly other than possibly adjusting remnants of the damaged forward skin.
3	Major damage to the main spar in the form of bending or tearing of the main spar web and flanges. Large area of aft skin wrinkled near the damage to the main spar. May have full panels of aft skin between ribs or significant areas in multiple panels that are wrinkled. Much of the damage clearly visible without disassembly other than possibly adjusting remnants of the damaged forward skin.

Wing Damage Severity Categories

Category 1

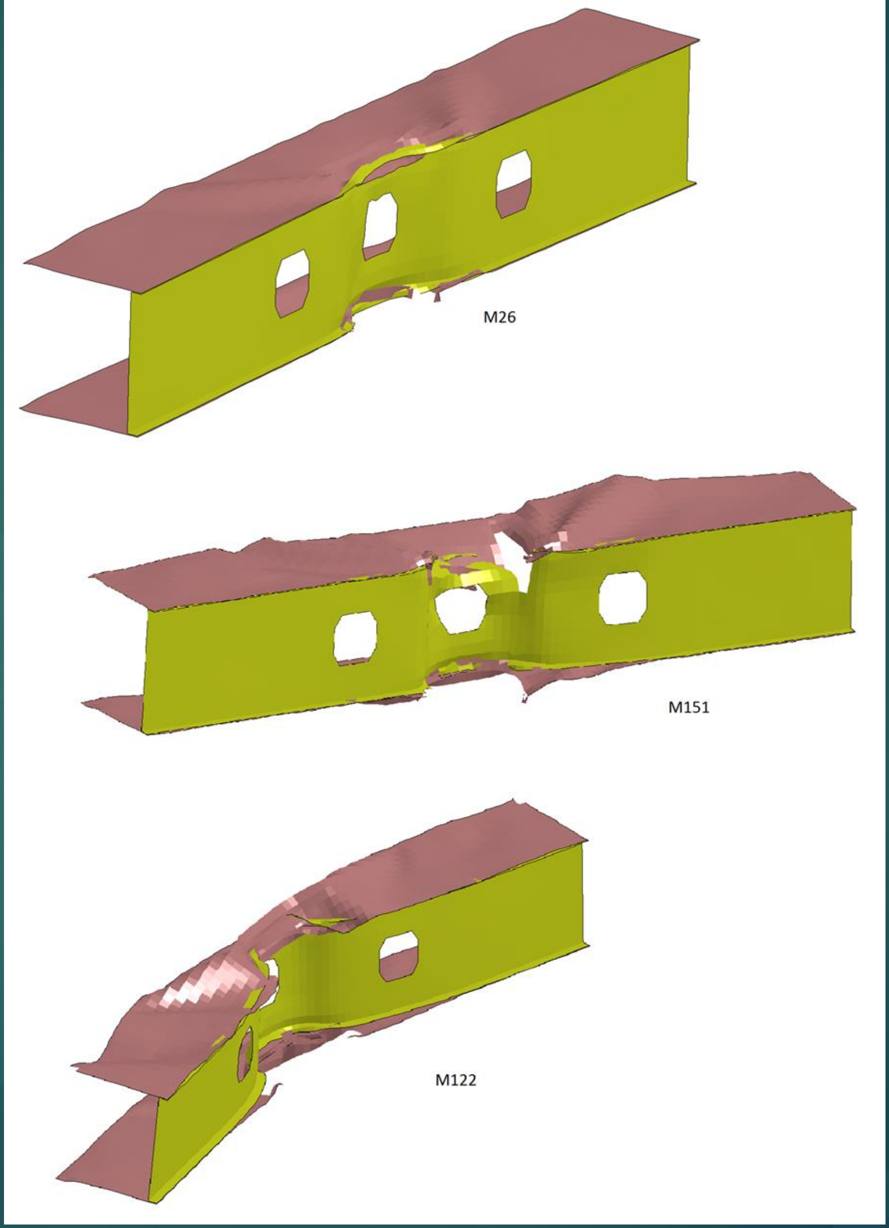


Wing Damage Severity Categories



Wing Damage Severity Categories

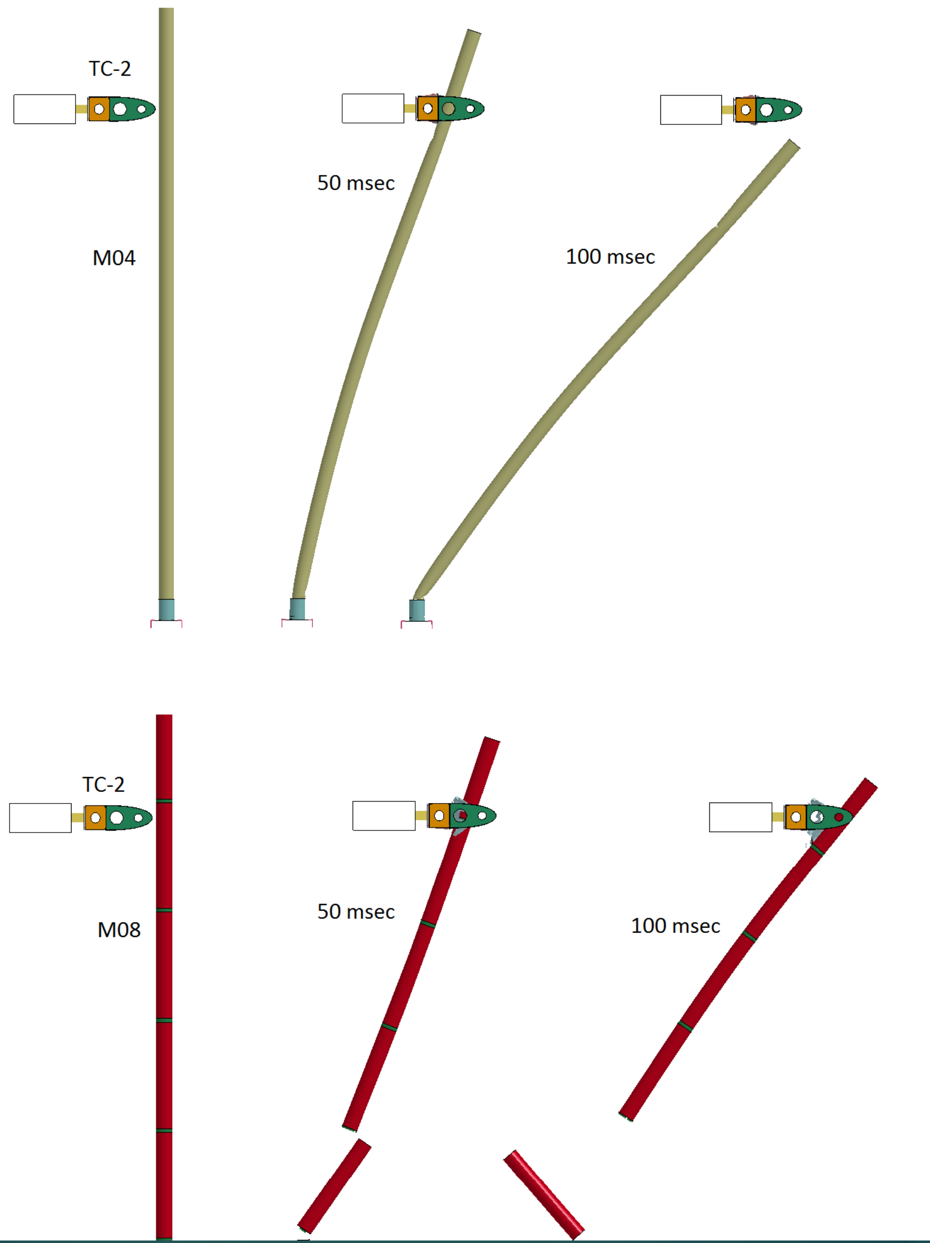
Category 3



Tower Response Categories

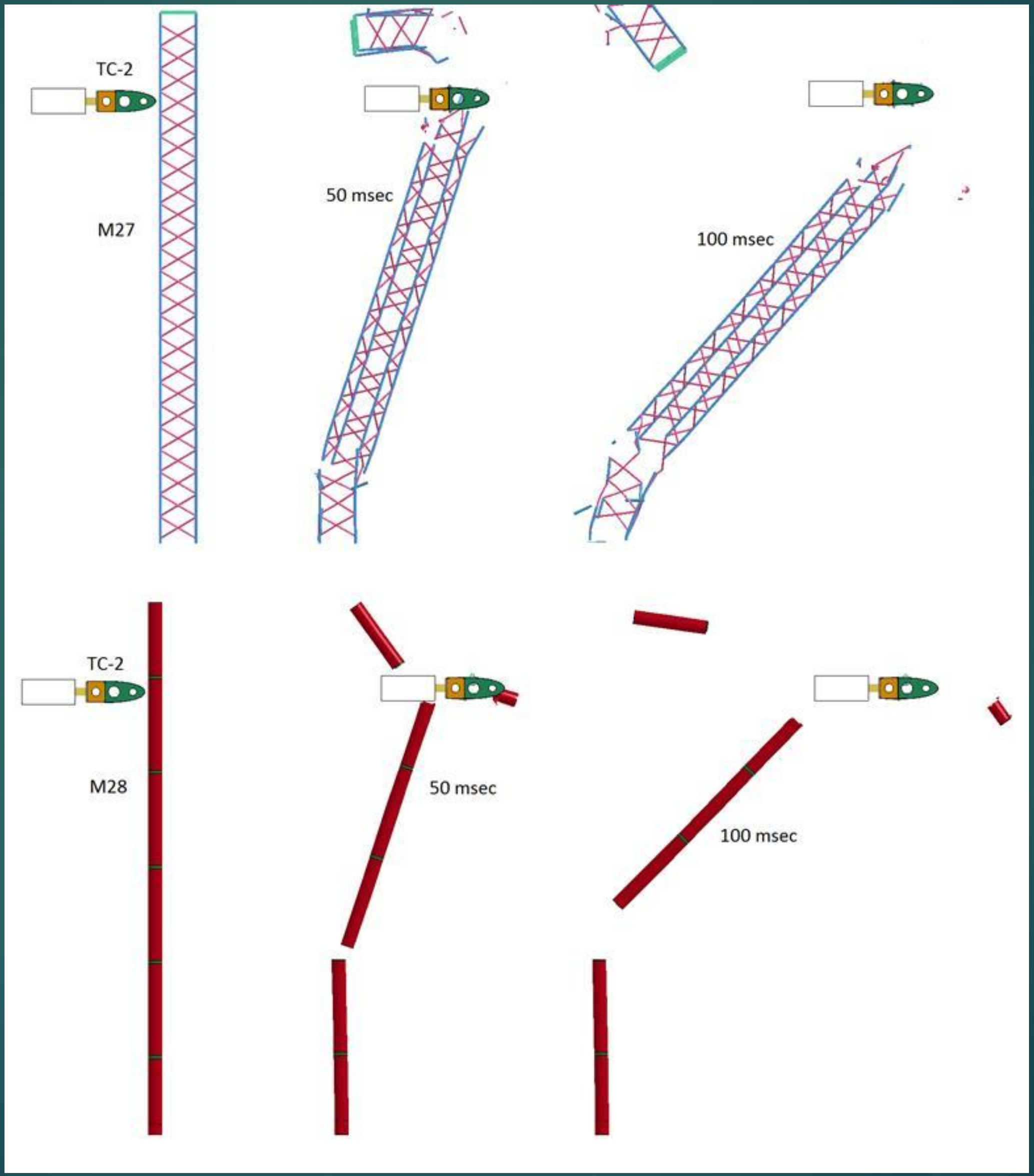
Category	Response Type	Description
PO	Push Over	The tower is pushed or knocked out of the path. The tower may have minor damage at the point of impact. Failure at a frangible joint, support or other structural collapse below the point of impact.
LW	Local Windowing	The tower fails local to the impact or at frangible connections near the impact point. The upper and lower parts of the tower typically break into segments or collapse but on a more global scale.
WT	Wrap and Tear Through Wing	The device is damaged local to the impact. The upper portion of the tower wraps over the top of the impactor. As the impactor passes the upper portion of the tower is pulled down and through the impactor typically tearing impactor components in the process. The tower may break away at a point below the impact point.
WE	Wrap and Remain Engaged	Local damage to tower. Top part of the tower wraps around impactor while remaining connected to the lower part of tower. The tower breaks away at a point below the impact point. The upper part of the tower remains engaged with impactor. The upper and lower part of the tower may separate soon after wrapping. If the separation results from the main spar impacting the tower and resulting in a Damage Severity Category of 2 or 3 then the Response Type is to be judged as WE. If the resulting Damage Severity Category is 0 or 1 then the Response Type may be judged as LW.

Tower Response Categories



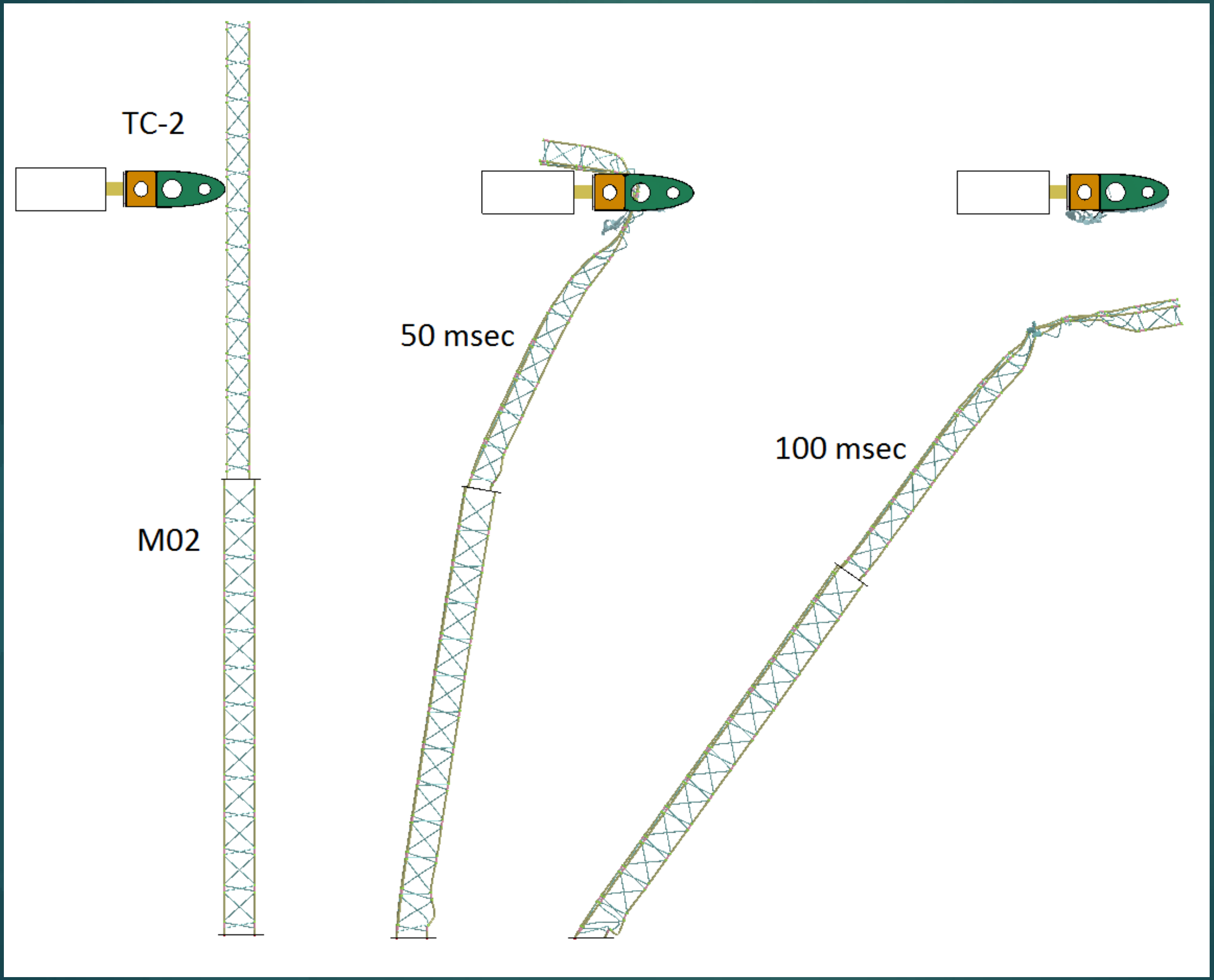
PO
Push Over

Tower Response Categories



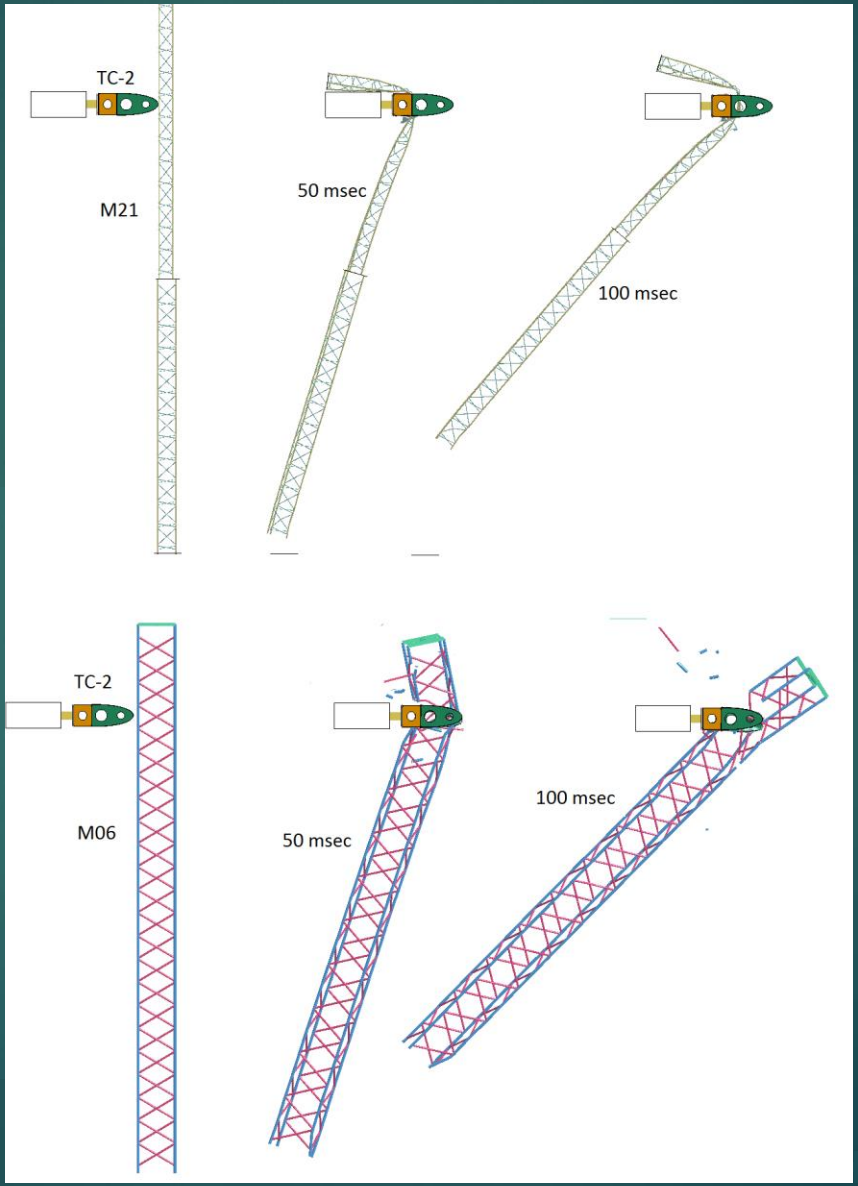
LW
Local
Windowing

Tower Response Categories



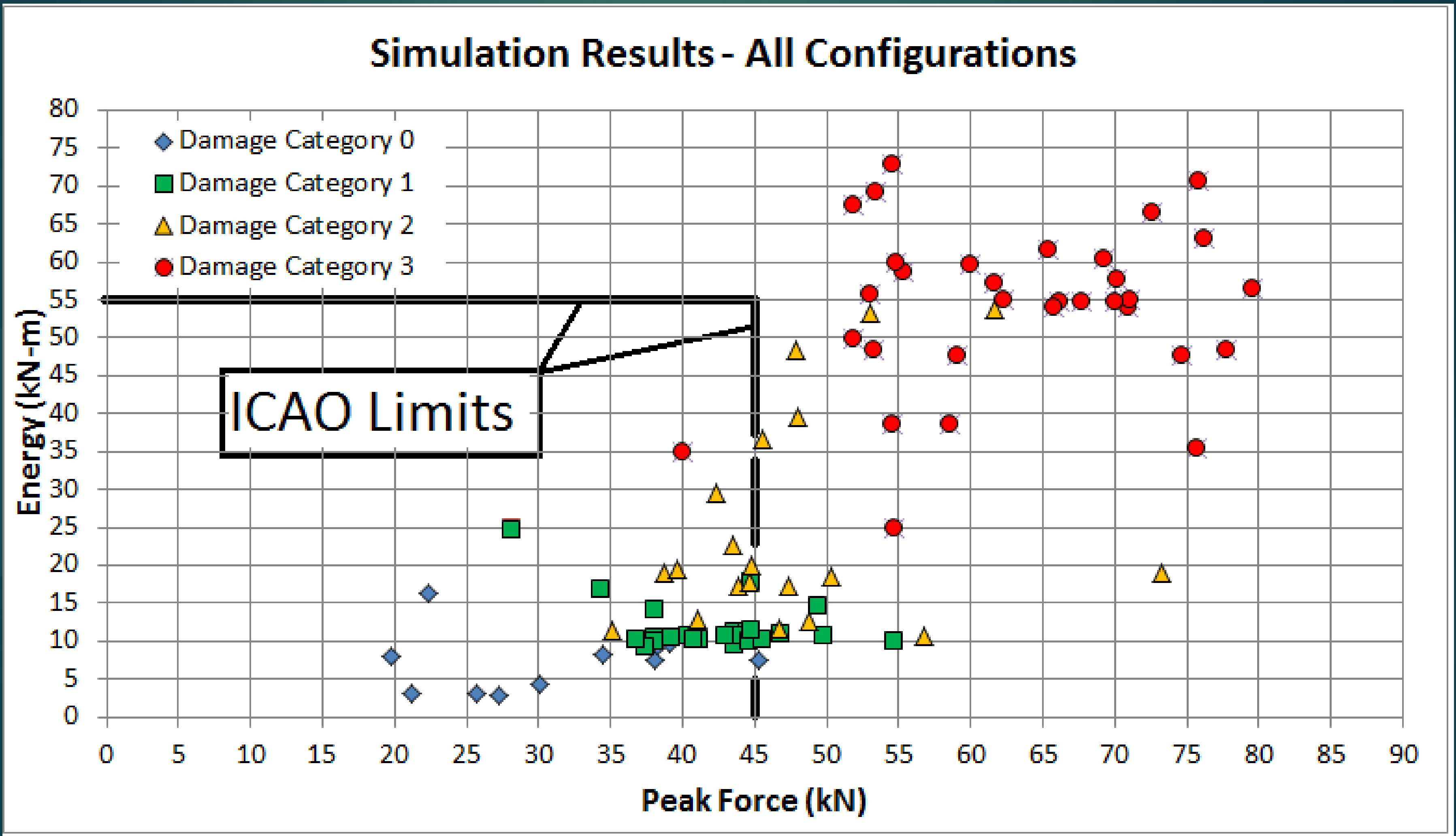
WT
Wrap and Tear
Through Wing

Tower Response Categories



WE
Wrap and
Remain
Engaged

Parameter Studies: Damage

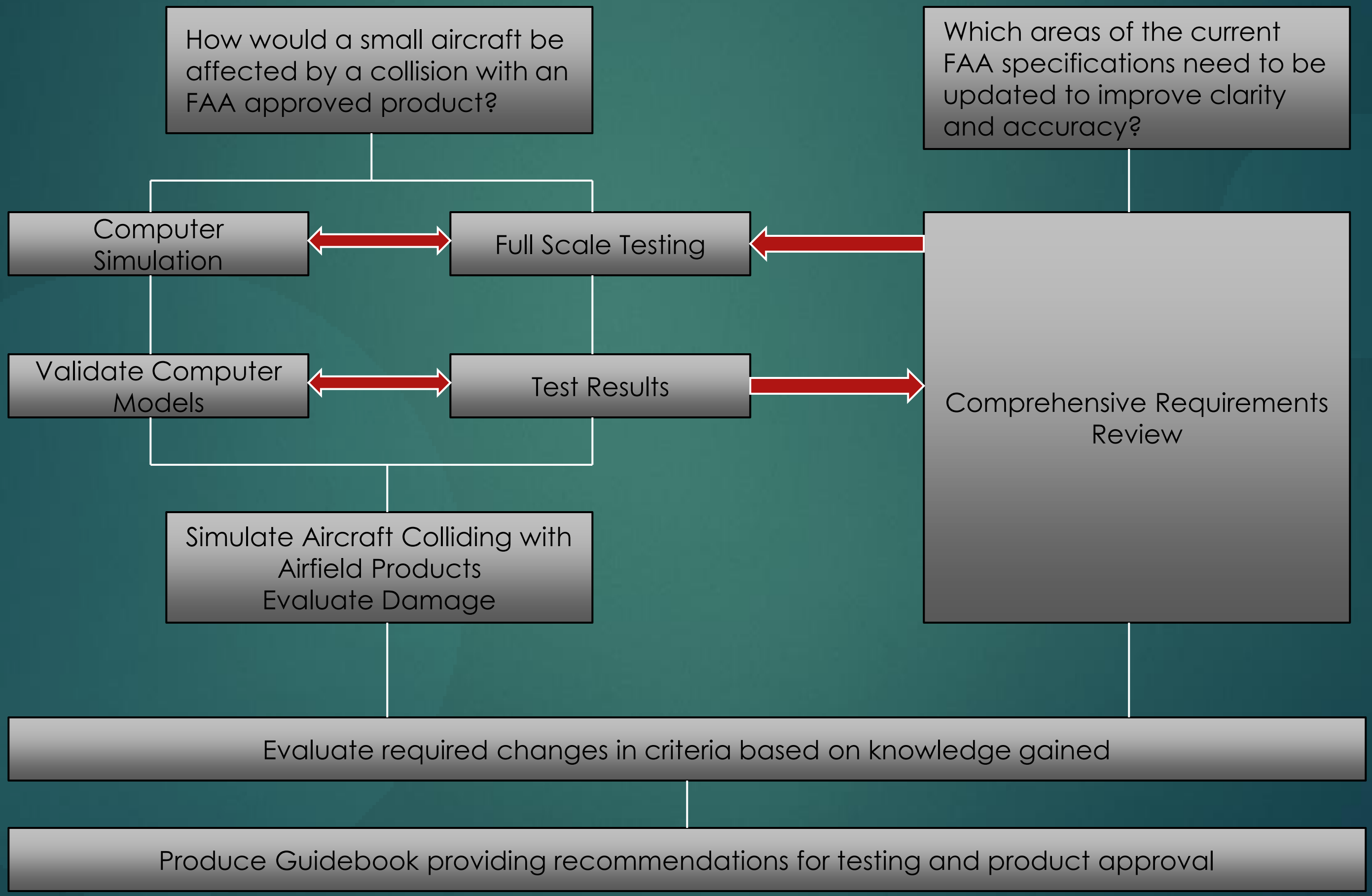


Shane Shurtliff, P.E.

SELECT ENGINEERING SERVICES, INC.

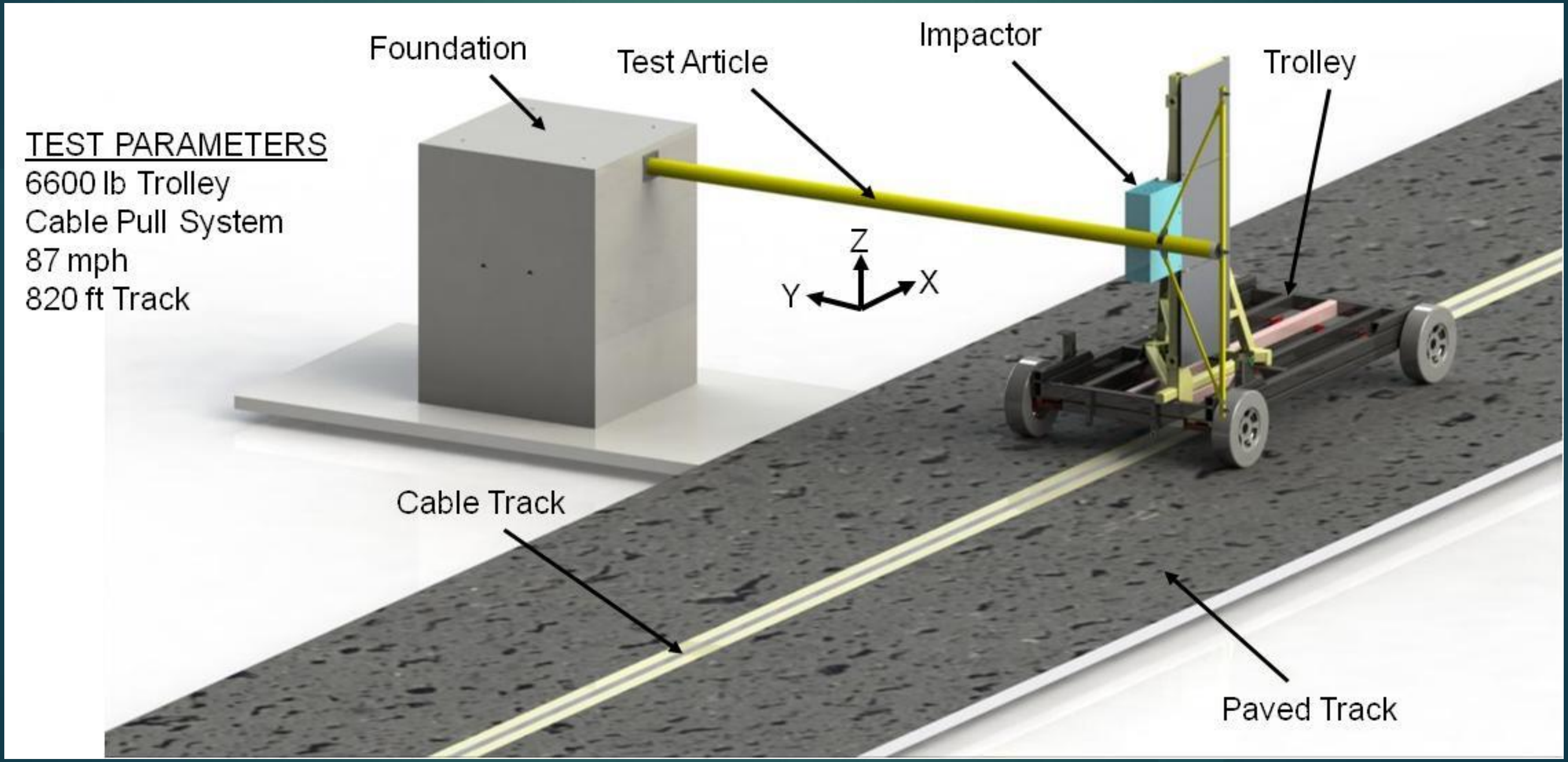
FAA Frangibility Study

- Project Work Plan

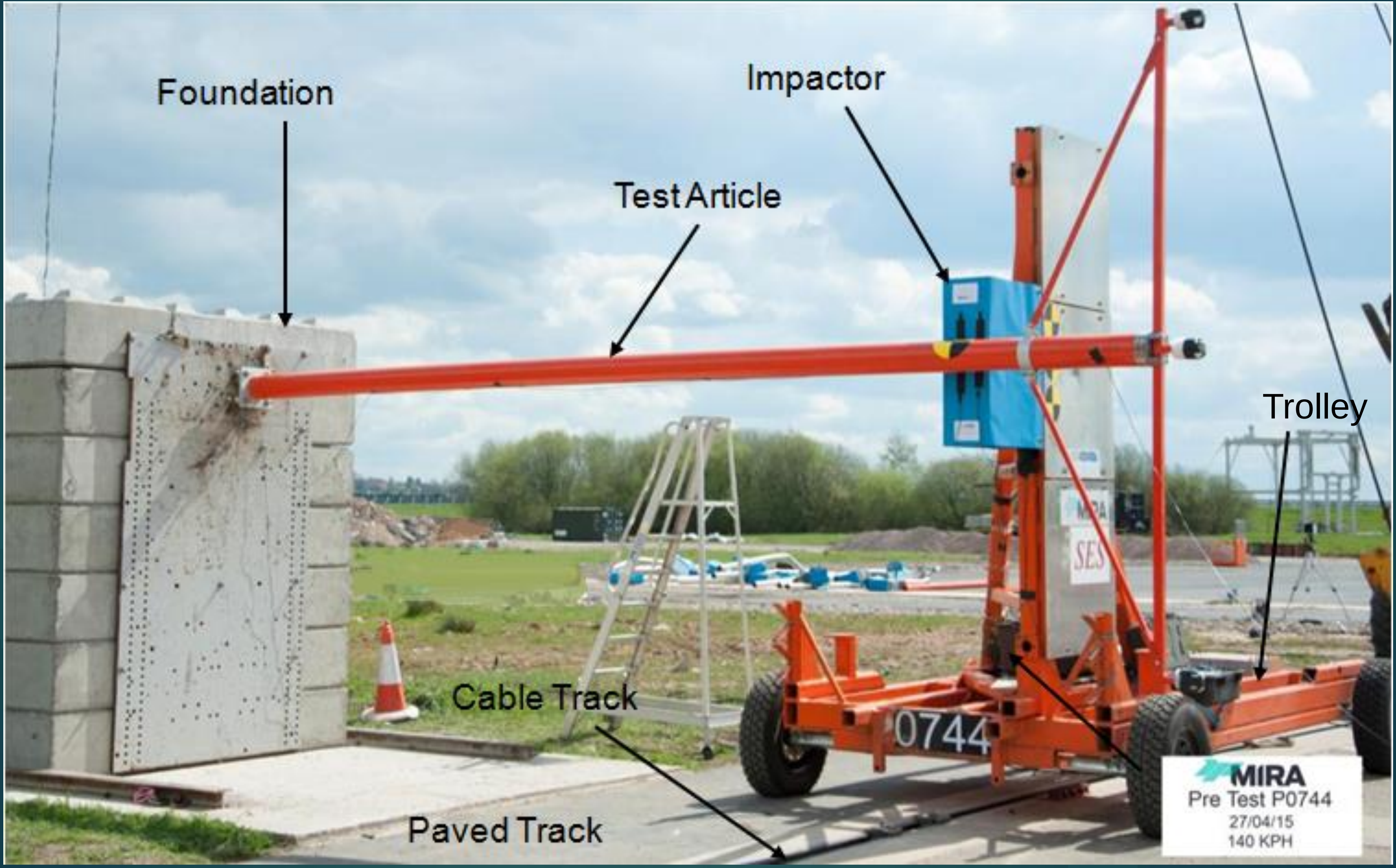


Test System

- NO HUMAN ONBOARD
- NO POWER THROUGH IMPACT
- VERY RIGID STRUCTURE



Test System



Foundation
Impactor
Test Article
Trolley
Cable Track
Paved Track
0744
MIRA
Pre Test P0744
27/04/15
140 KPH

Test System

Test System

FAA Frangibility Study

- Full Scale Testing effort between USAF and FAA
  - 50 Full Scale Tests
  - Over ½ Billion Data Points
  - 75,000 High Speed Video Frames
  - 83 GB of Data

Robert Bocchieri, Ph.D.

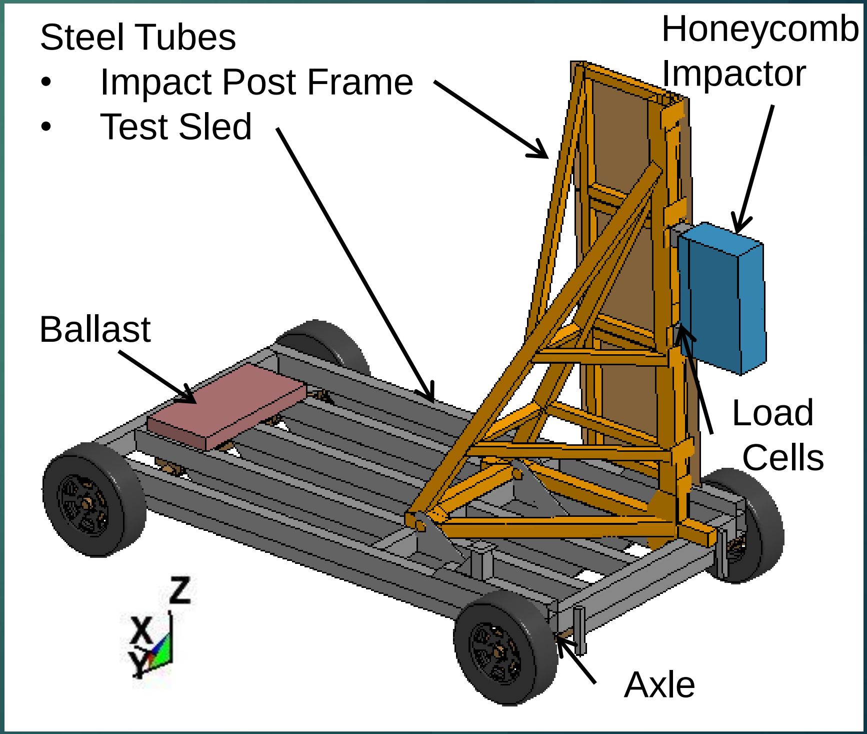
APPLIED RESEARCH ASSOCIATES, INC.

Outline

- Overview of trolley LS-DYNA model with rigid and honeycomb (HC) impactors
  - Honeycomb Material modeling
  - Validation simulations: Trolley impact with HC impactor on aluminum pole
- FAA ALS structure LS-DYNA modeling
  - Composite materials modeling
  - Joint model and validation
  - Trolley impact simulations compared with tests
- Product C LS-DYNA modeling
  - Force history and impact energy comparison with tests

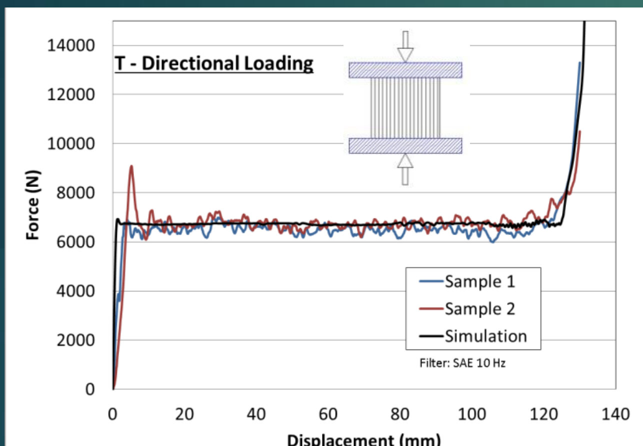
Trolley LS-DYNA Model

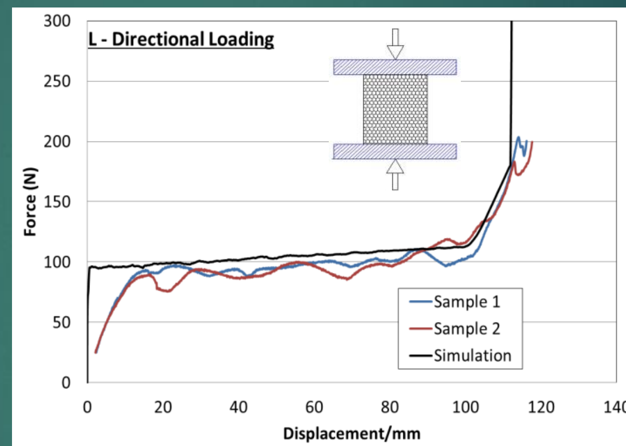
- LS-DYNA model of trolley with honeycomb and rigid impactors was developed.
  - All parts deformable except wheels, tires and suspension
- Weight and CG
  - Ballast explicitly modeled
  - Frame scaled slightly to match overall weight
- Simplifications:
  - Trolley is constrained to translate only in X-dir by constraining the wheels.
  - No suspension response
- Section planes through load cells to measure net loads.



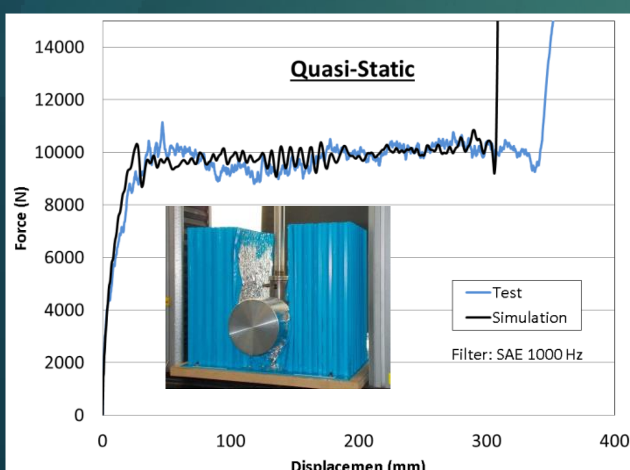
Honeycomb Constitutive Modeling

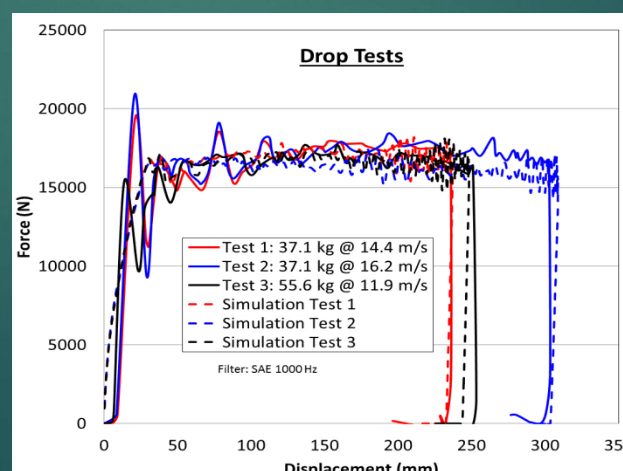
- *MAT_MODIFIED_HONEYCOMB model parameters fit to test data from Cellbond





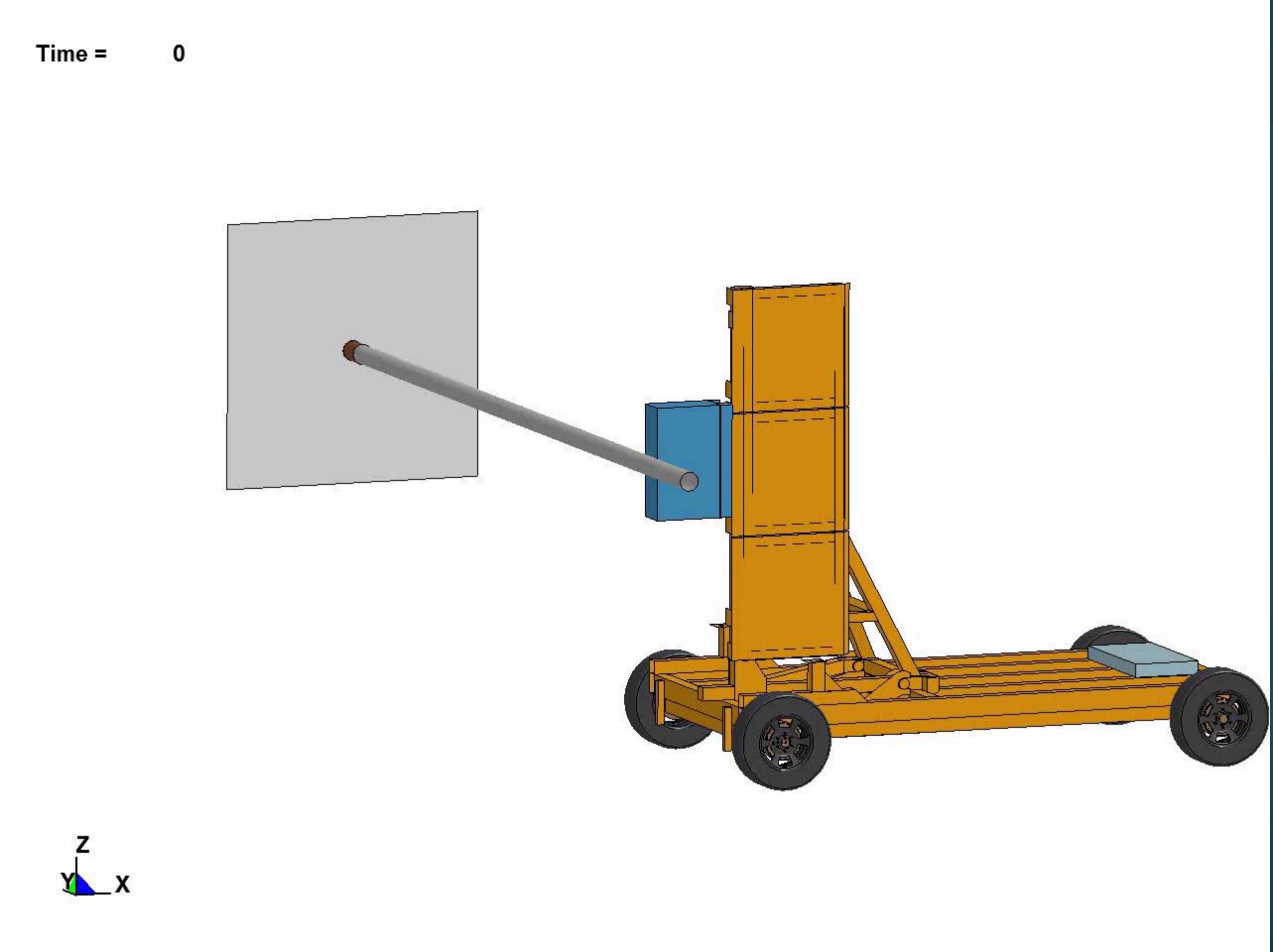
Quasi-static Crush Tests





Crush-Shear Tests (note rate effect)

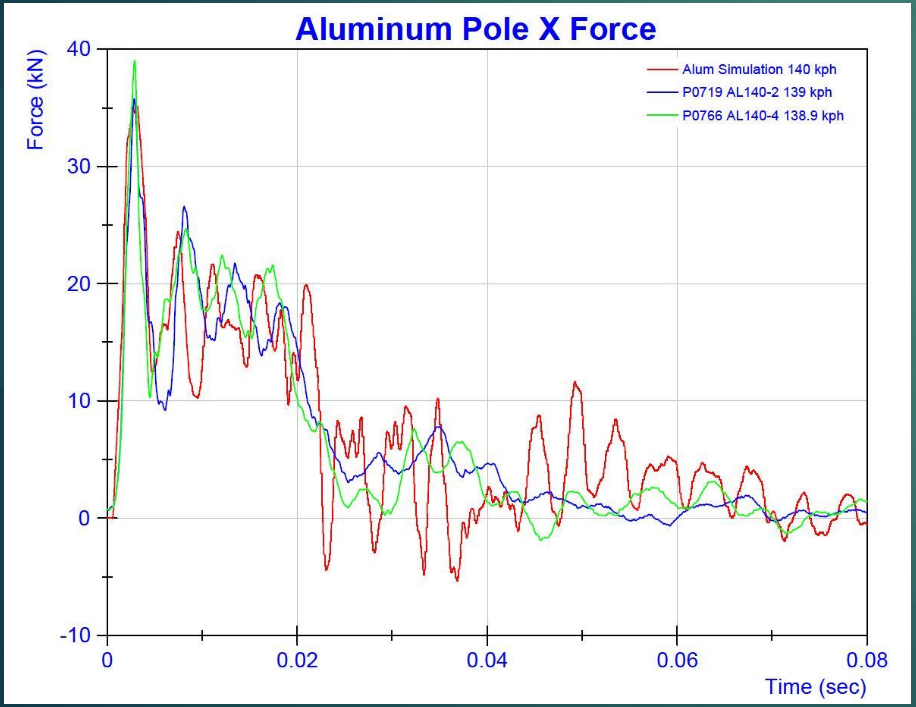
Aluminum Pole Impact – HC Impactor

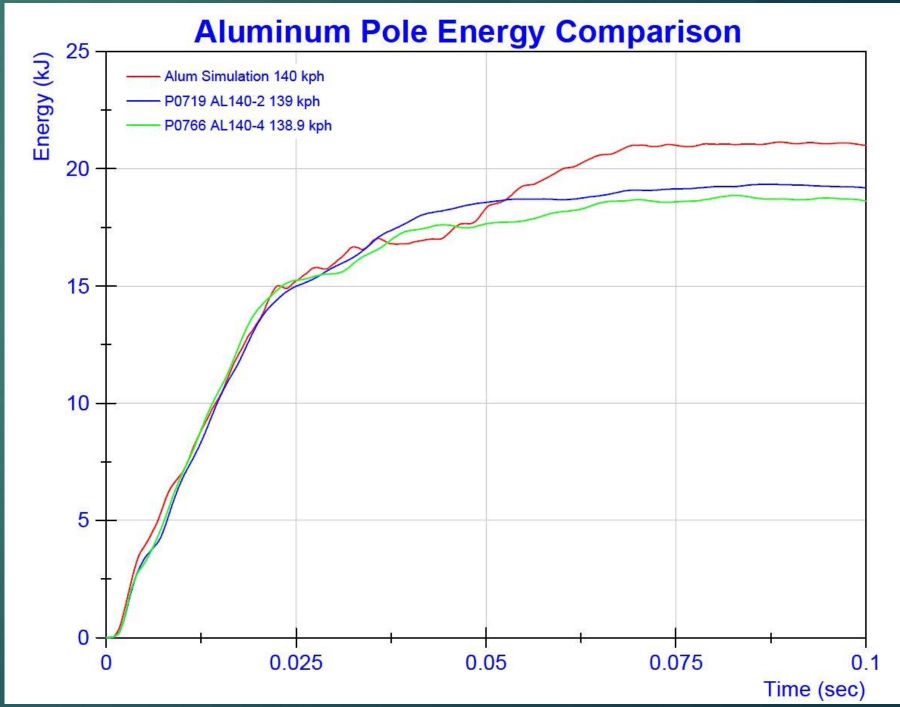


Aluminum Pole Impact – HC Impactor

Aluminum Pole Impact

- Initial peak forces, sustained load and duration compare well with tests.
- Energy absorbed during impact also compares well with tests
- Rate effects at these higher rates were estimated to best match the aluminum pole



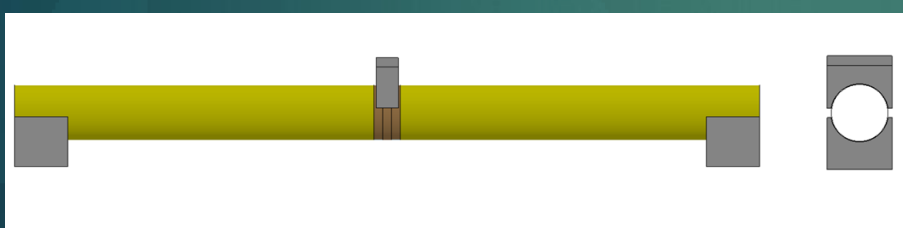


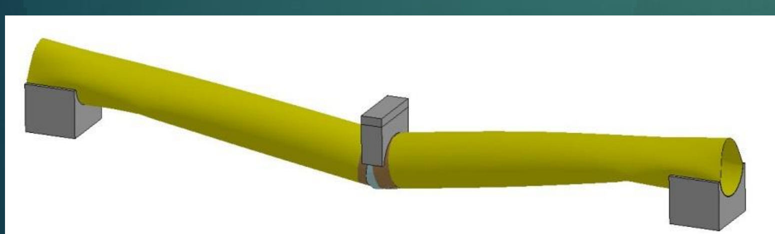
Composite Materials Constitutive Modeling

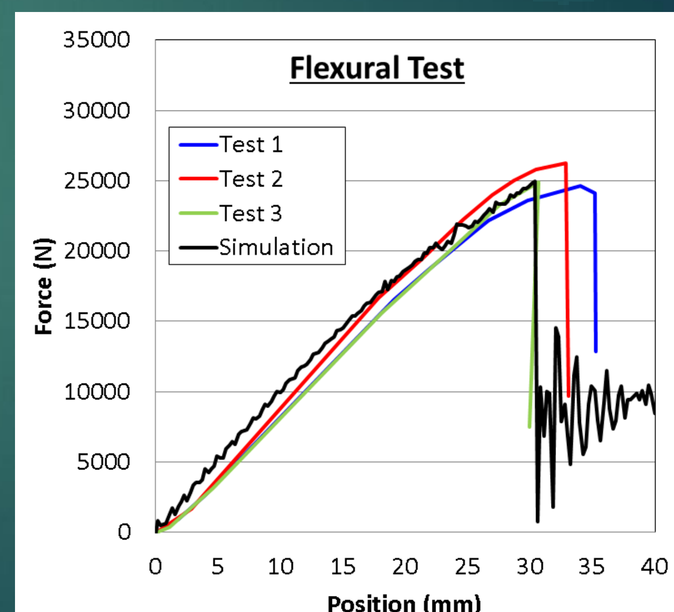
- Composite materials in the poles were modeled using
  - *ENHANCED_COMPOSITE_DAMAGE (unidirectional ply materials)
  - *MAT_LAMINATED_COMPOSITE_FABRIC (fabric ply materials)
- Some material data were provided by manufacturers when available
  - In some cases estimated properties or layups were used for particular composite properties where data not available
    - E.g., tensile strengths often available but not compression strengths
    - Ply properties estimated from structure properties
- Delamination not modeled at this time
  - Probably leads to more localized damage in the simulations and less damping.

FAA ALS Pole Joint Modeling

- Jaquith pole joint modeled with tiebreak strength values between adjacent tubes fit to test data from D-6155-18A flexural test.
  - After joint failure, adjacent tubes maintain contact and slide apart.
  - Dynamic joint strength increased by 25% to better match pole impact data.

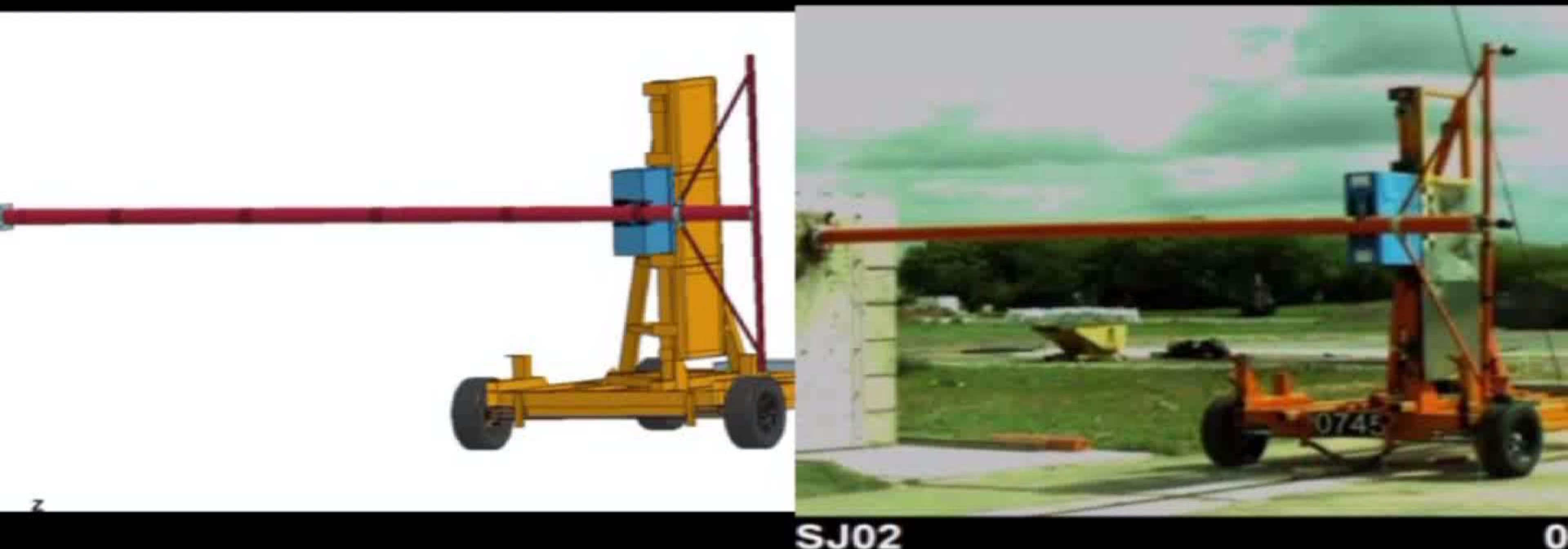






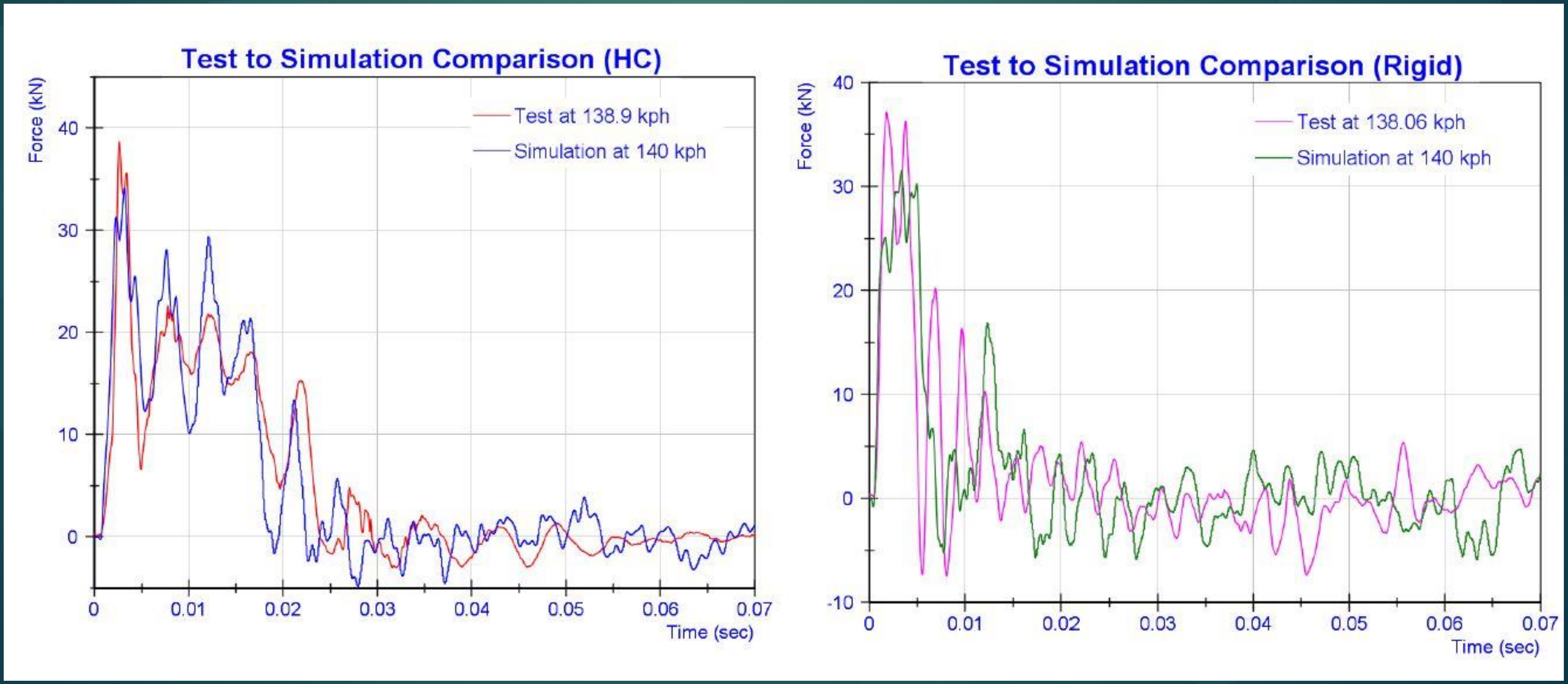
FAA ALS Structure Impact Simulation – Rigid Impactor

FAA ALS Structure Impact Simulation – HC Impactor



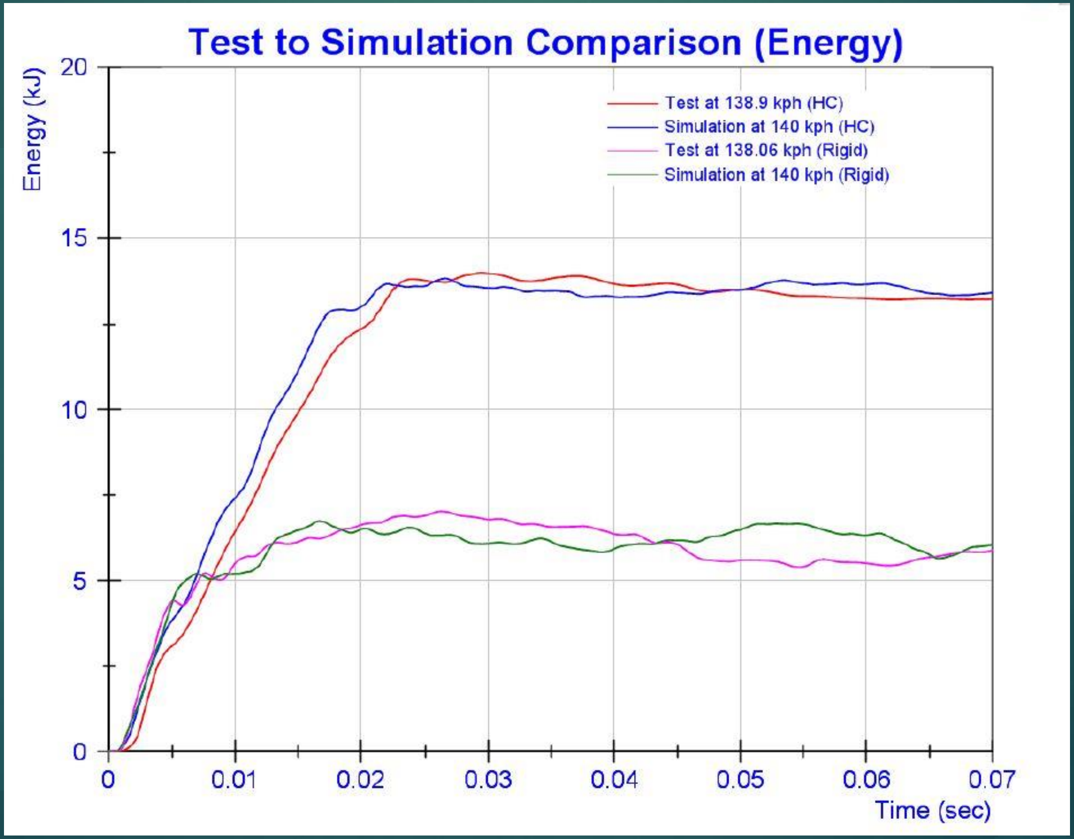
FAA ALS Structure Impact Simulation Comparison

- Compared simulation with test that had similar joint responses.
  - Recall there were variations between tests.
  - Initial peak forces, sustained load and duration compare well for rigid and HC impactors.



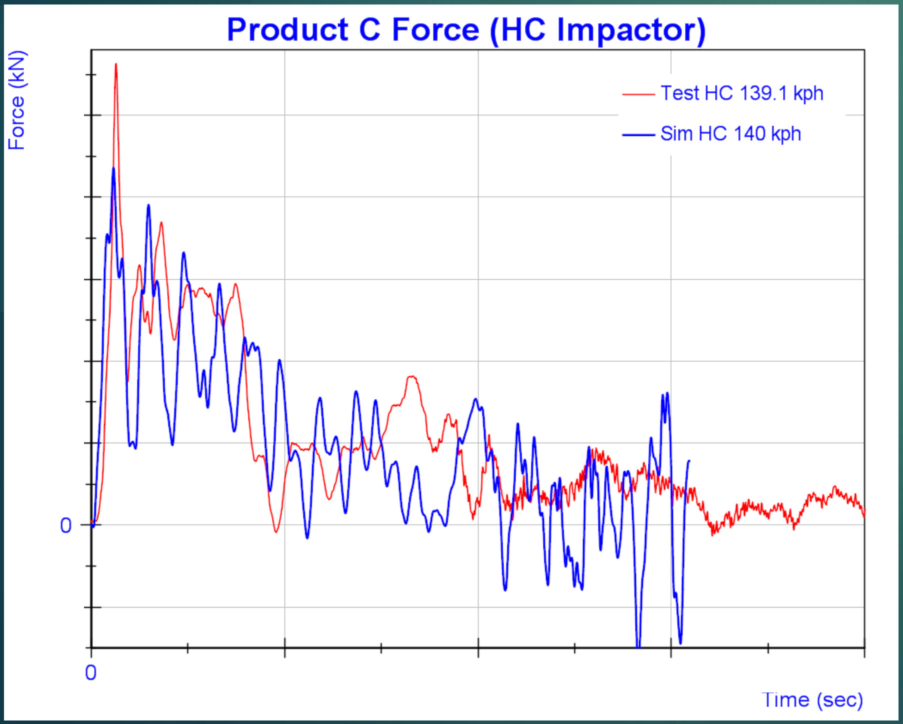
FAA ALS Structure Impact Simulation Comparison

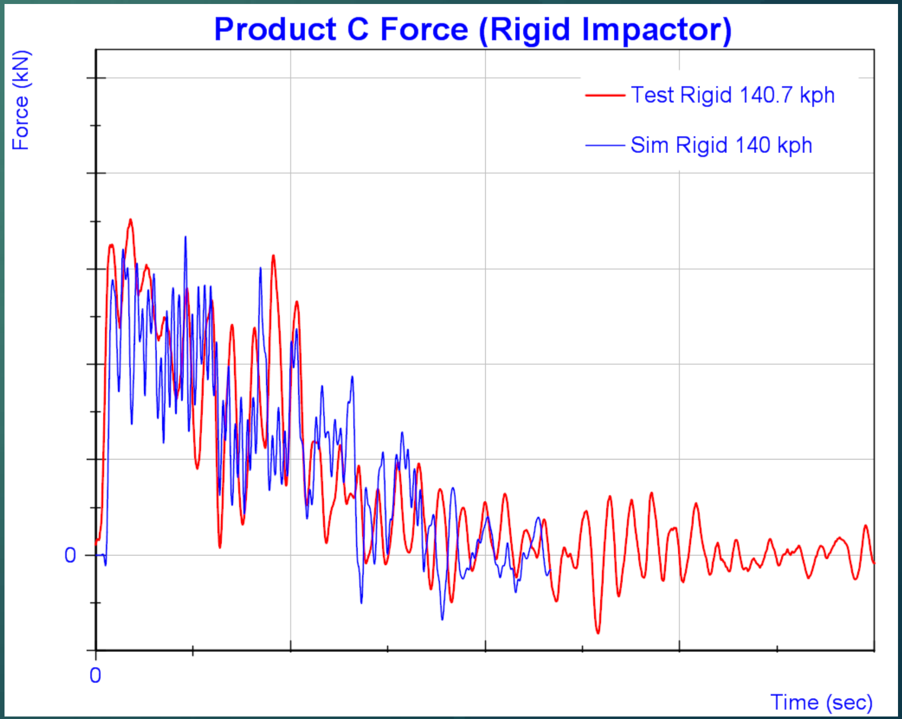
- Energy absorbed during impact also compares well with tests.



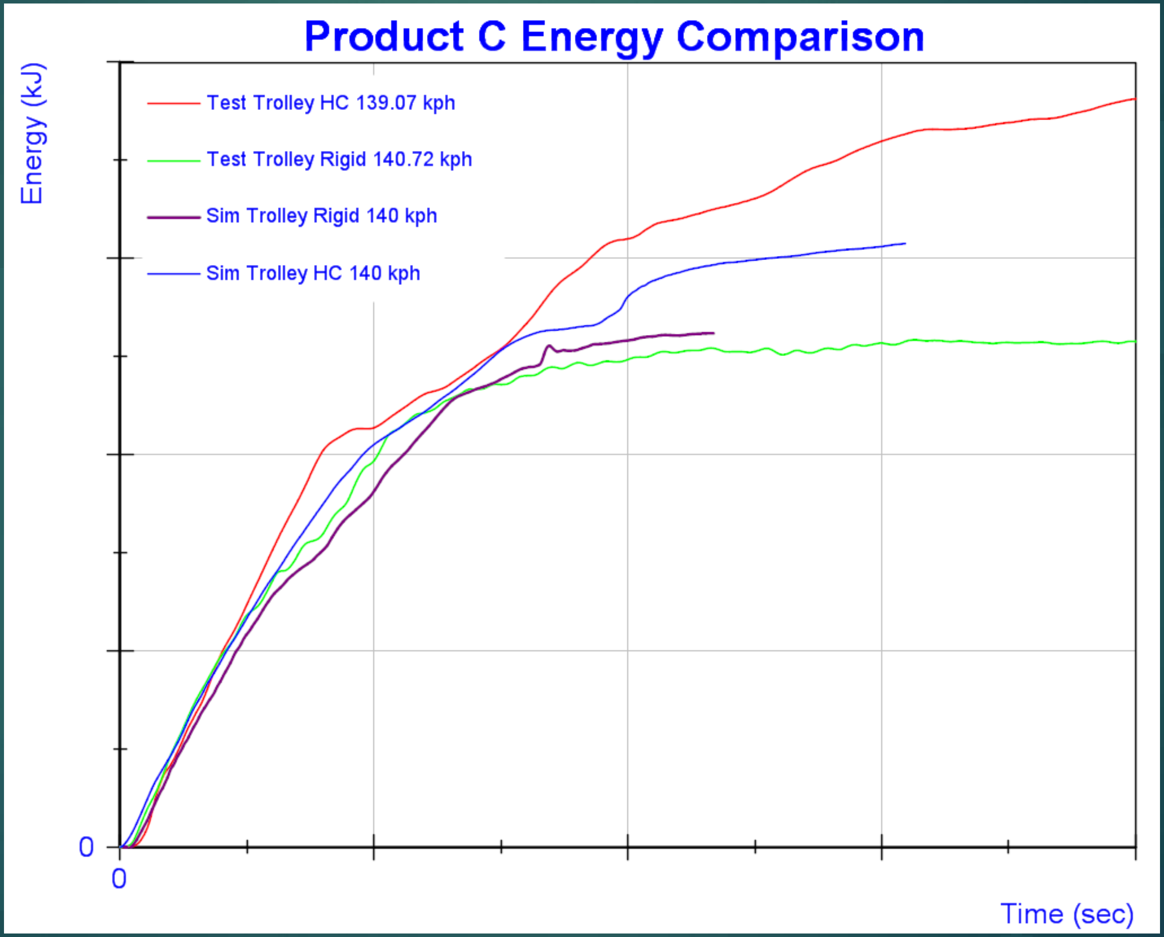
Product C Structure Impact Simulation Comparison

- Product C also had significant variation in tests
  - Compared simulation with test that had similar joint responses.
- Aside from some higher frequency vibrations in the simulations, overall agreement is good.





Product C Structure Impact Simulation Comparison



Summary

- Developed LS-DYNA models for the test trolley with both impactor types
  - Validated model response with component tests and aluminum pole impacts
  - Recommend continued improvement to the HC model to correct some instabilities seen at large crush and long times
- Developed LS-DYNA models for two lighting structure products
  - Validation of the FAA ALS and Product C response using test data from trolley tests with the rigid and HC impactors
  - Product B model is still under development due to additional material data requirements
  - Recommend continued improvement to these models by reducing uncertainties in material and joint behavior
- Validated trolley model ready for use in further product evaluations
- Validated lighting structure models ready for use in evaluating Piper Navajo impact response