NASA Fundamental Aeronautics- Rotary Wing Crashworthiness

NASA Perspective on Certification by Analysis

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Use of Dynamic Analysis Methods for Aircraft Seat Certification

Wichita, KS

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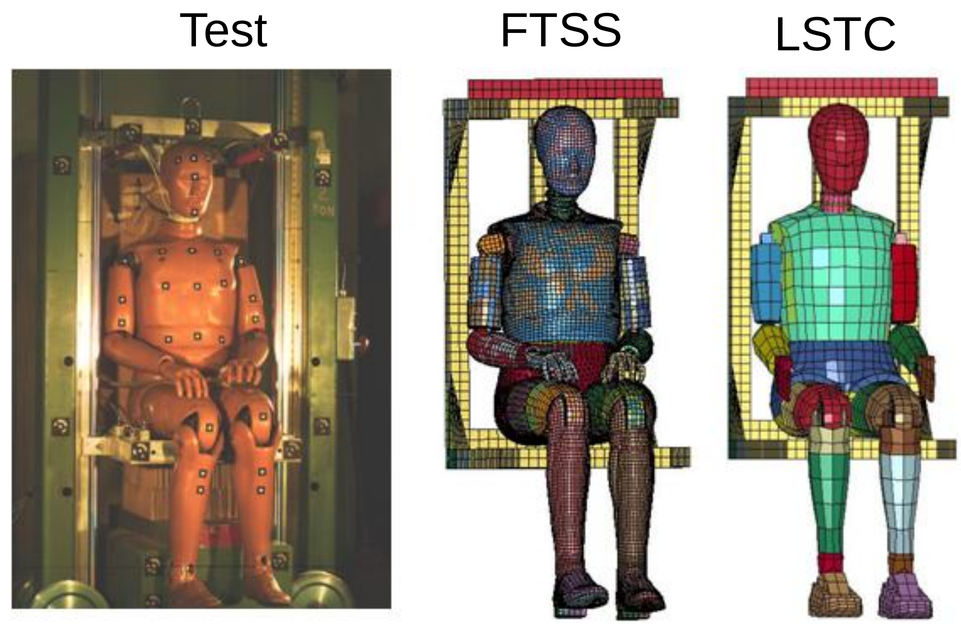
Outline

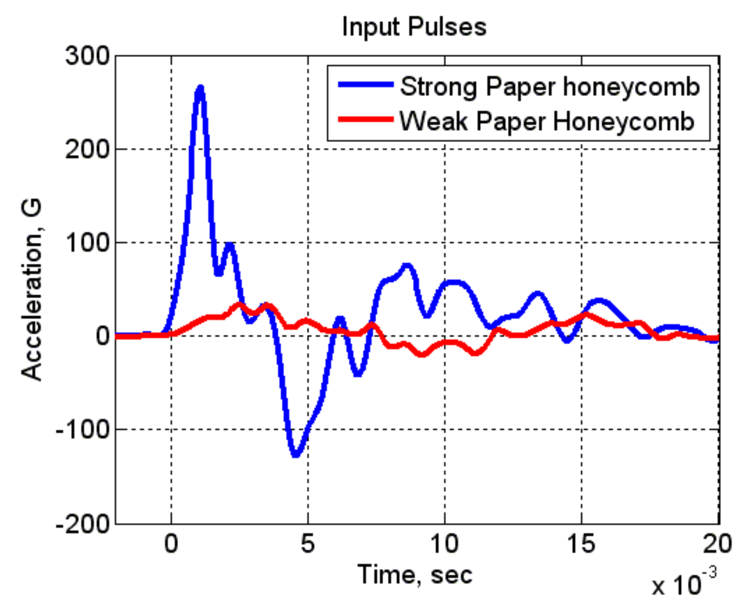
- Introduction
- Vertical Impulsive Testing and Analysis of ATD's
- Multi-Dimensional Calibration of Full-Scale Crash Test Article
- Remarks

Vertical Impulsive Testing of Hybrid II and III ATDs

- Three standard configurations
  - Hybrid III Straight Spine (Aero)
  - Hybrid III Curved Spine (Auto)
  - Hybrid II Straight Spine
- Two loading conditions
  - High Magnitude, short duration
  - Low Magnitude, High duration
- 2 Finite Element Models
  - LSTC
  - FTSS

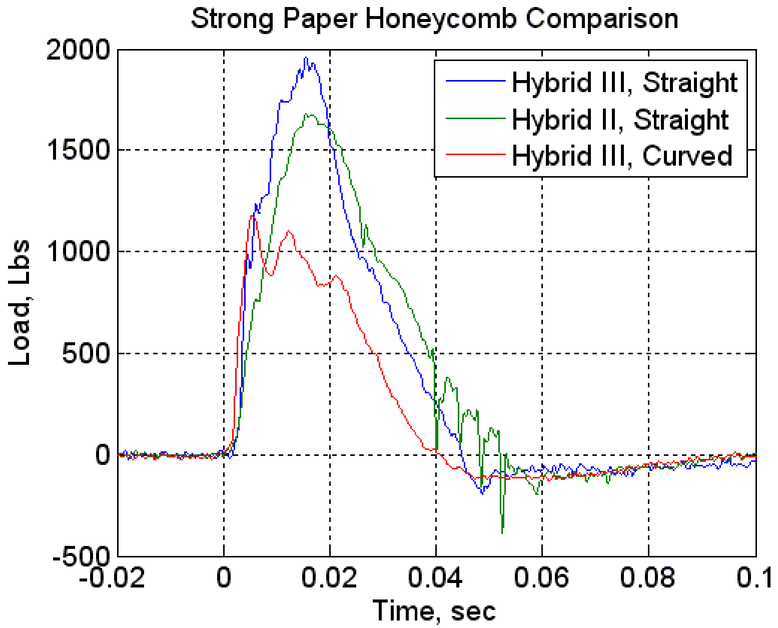


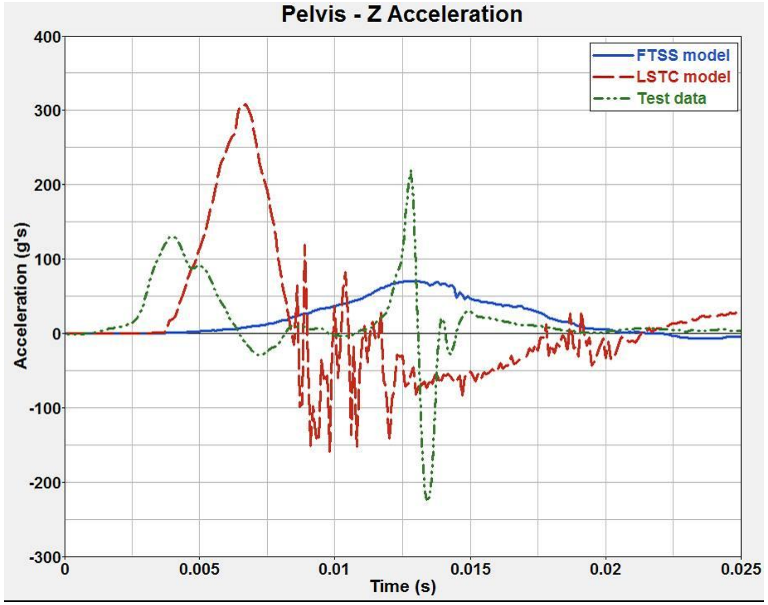
- Examined
  - FTSS vs. LSTC Model
  - Test vs. Model
  - Test Configurations



Vertical Impulsive Testing of Hybrid II and III ATDs

- Lumbar loads show results for both pass and fail on FAR 27.562
- Pelvis accelerations show considerable scatter
- Calibration of Hybrid III ATD FEM performed to improve response
  - Mesh refinement
  - Components switched form rigid to deformable
  - Foam constitutive model
  - Load transfer from pelvis to torso
  - Preloading of ATD on seat

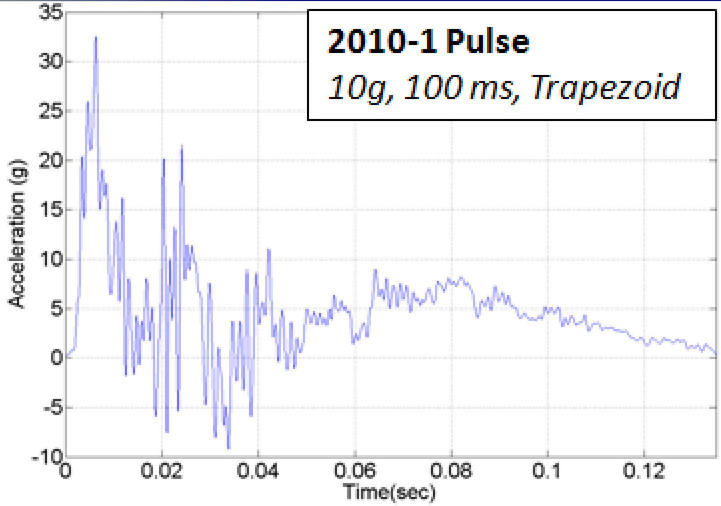


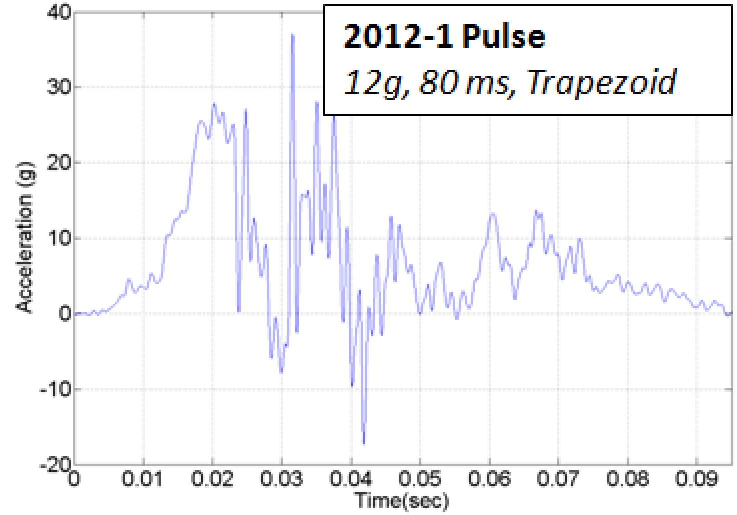


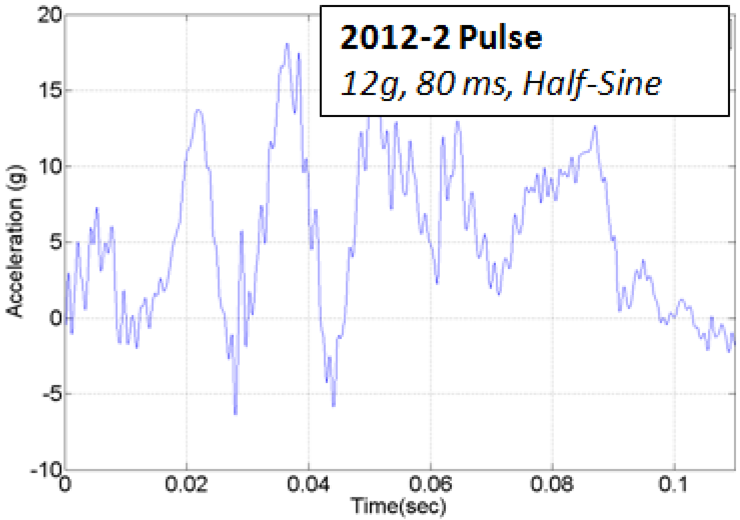
Vertical Impulsive Testing of THOR/NT ATD

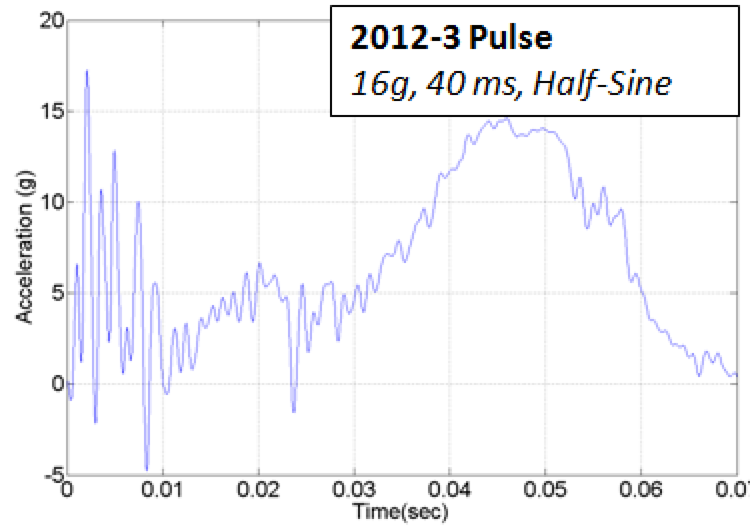
- THOR-NT developed by NHTSA
- All existing THOR's currently scheduled to be upgraded to the THOR-K version
- (16) drop tests performed with the 50th percentile THOR-NT ATD in the 14-ft Vertical Drop Tower in Building 1262 at LaRC
- Purpose of the tests
  - Validate THOR finite element models currently in development
  - Compare results to similarly conducted tests previously completed with Hybrid II and III ATDs
  - Add additional data to the growing test database for THOR development.
- JSC and LaRC are interested in evaluating many of these recently developed ATDs under spacecraft and aircraft landing loads.

Vertical Impulsive Testing of THOR/NT ATD



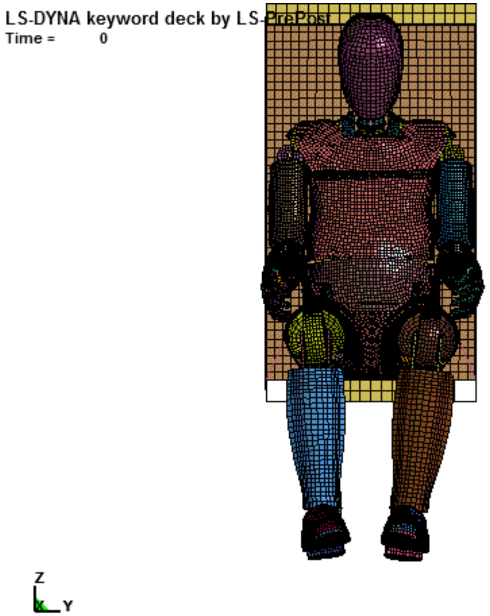


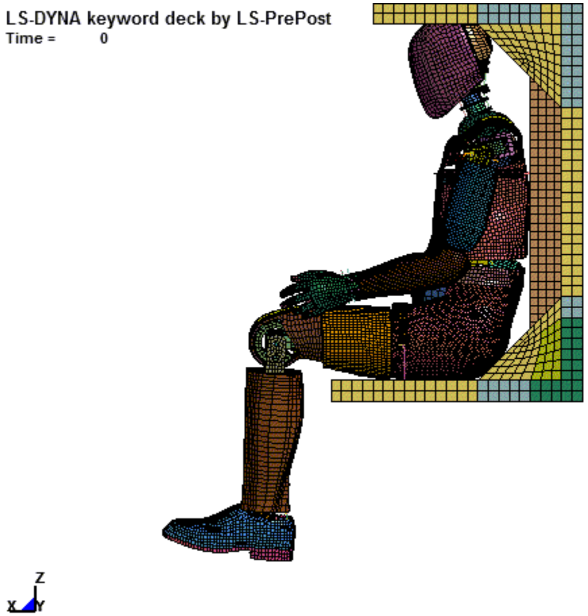




Chair Pulses representative of FAR, DOD, and NASA Orion Requirements

Vertical Impulsive Testing of THOR/NT ATD

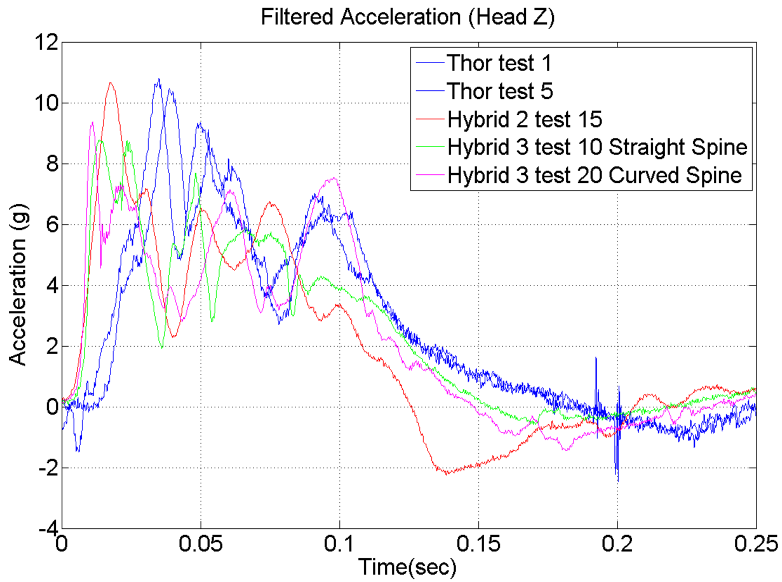


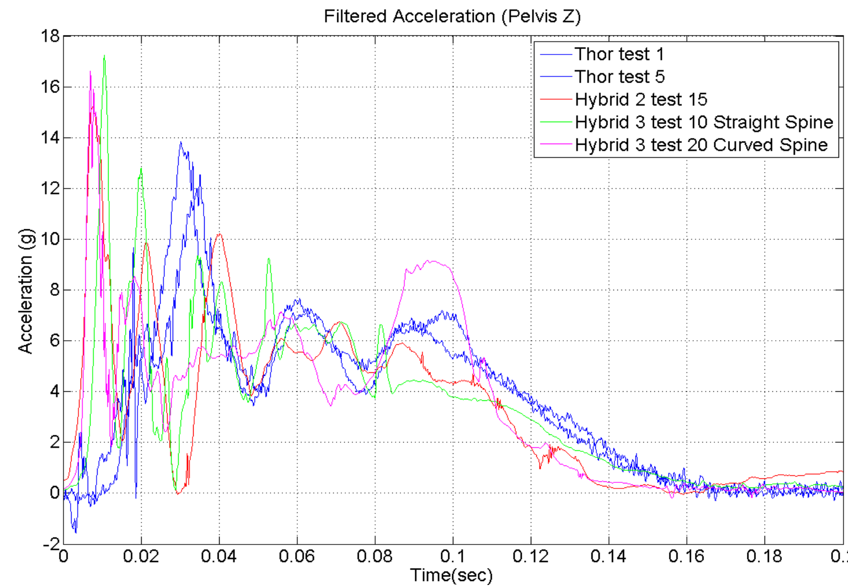


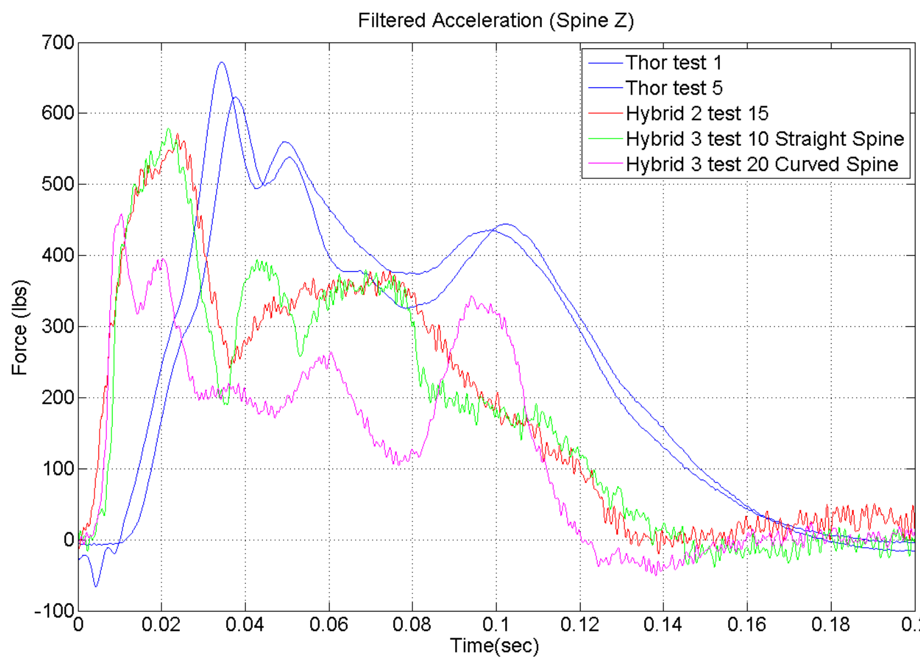
Initial Correlation Efforts:

- Analysis performed by Virginia Tech (THOR-NT FEM v. 2011)
- Evaluate sensitivity of kinematics, accelerations, and force results in the FEM prior to correlation to test results

Vertical Impulsive Testing, Comparision of Hybrid II, Hybrid III, and THOR/NT





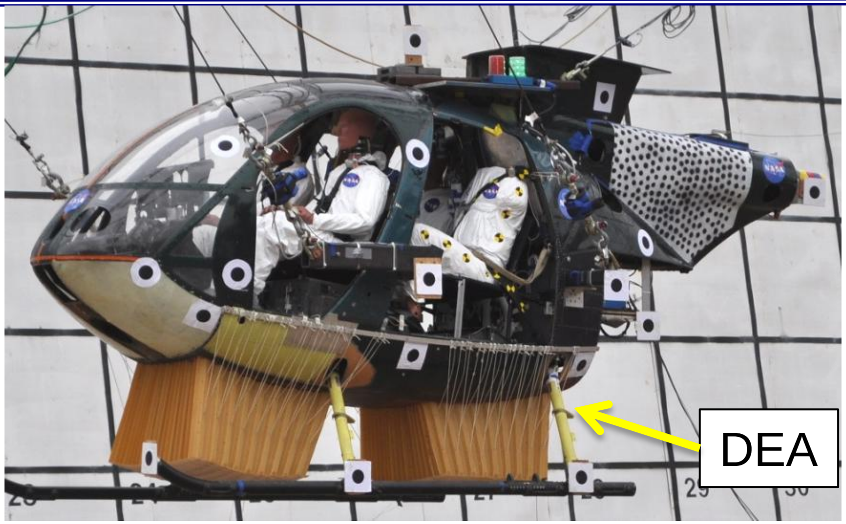


Full-Scale Crash Test Objectives

- To evaluate the performance of an external Deployable Energy Absorber (DEA) under realistic crash test conditions
- To generate test data to validate a system-integrated LS-DYNA FEM that includes accurate physical representations of all critical components
- To establish methodologies for FEM development, calibration, and validation that will ultimately lead to crash certification by analysis

MD-500 Crash Test with DEA

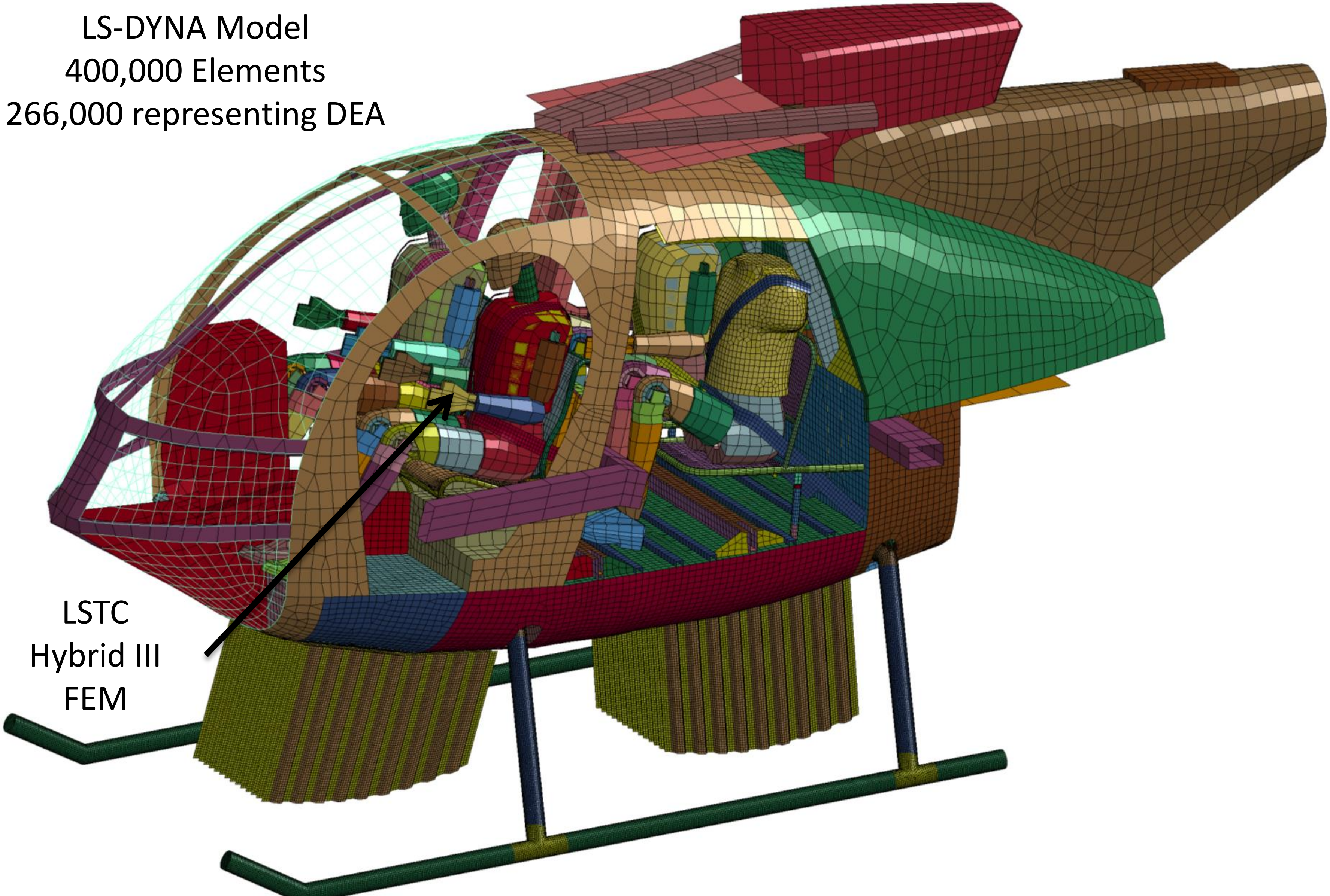
Test Parameters		Nominal Conditions	MD-500 with DEA
Vehicle Weight (lb)		2,900	2,940
Linear Velocity (ft/sec)	Forward	40.	38.8
	Vertical	26.	25.6
	Lateral	0	0.5
Attitude (deg)	Pitch	0	-5.7
	Roll	0	7.0
	Yaw	0	9.3
Angular Velocity (deg/sec)	Pitch Rate	0	0.4
	Roll Rate	0	1.1
	Yaw Rate	0	4.8



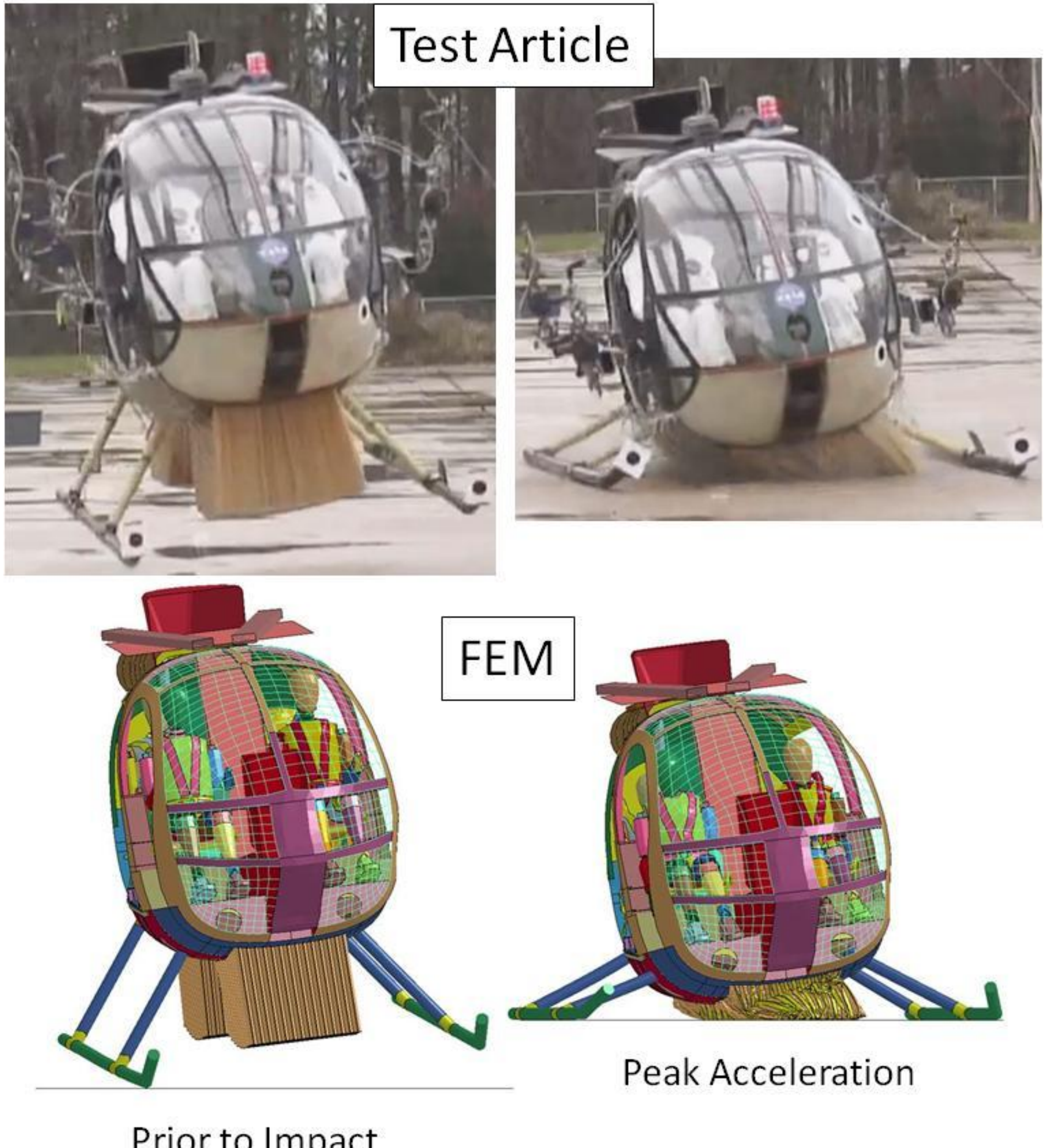
Test with DEA

Baseline LS-DYNA FEM

LS-DYNA Model
400,000 Elements
266,000 representing DEA

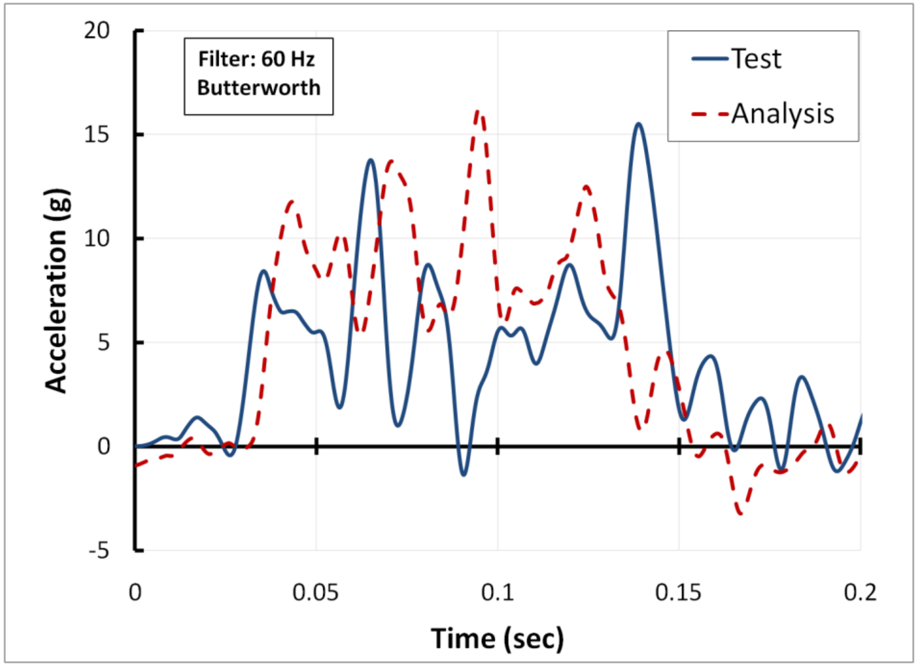


Comparison-Crash Test with DEA

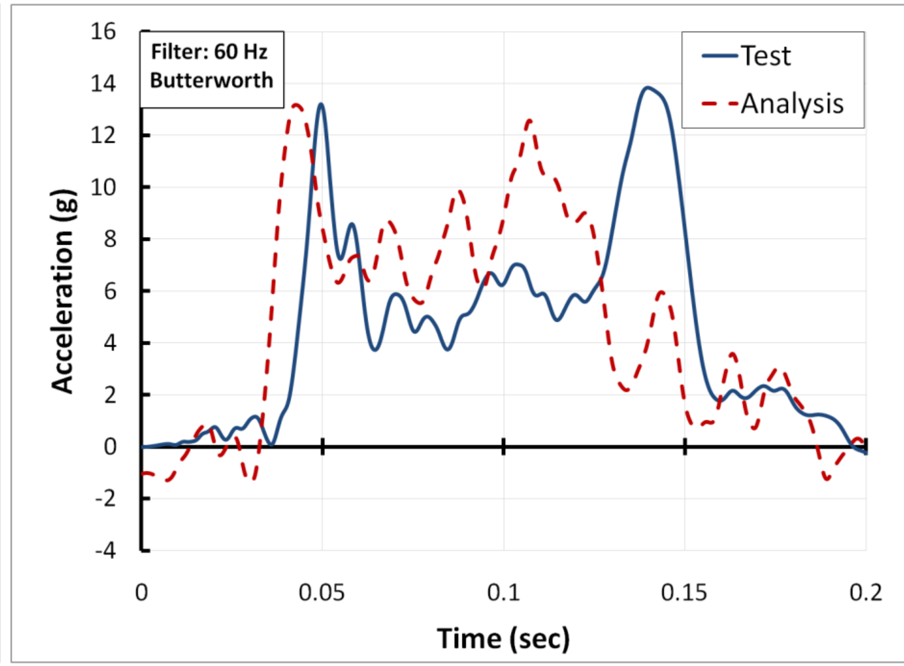


Comparison-Crash Test with DEA

Pilot Seat Box Vertical Acceleration



Passenger Floor Vertical Acceleration



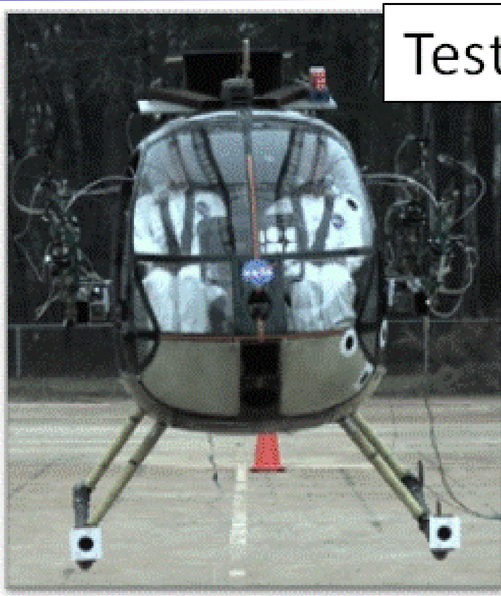
Acceptable Test/Analysis Correlation for Airframe Response

MD-500 Crash Test without DEA

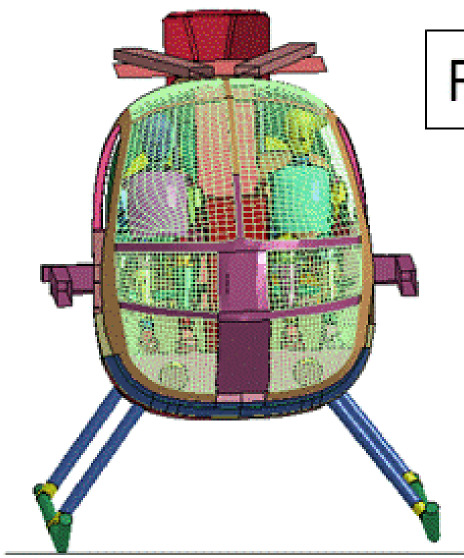
Test Parameters		Nominal Conditions	MD-500 Without DEA
Vehicle Weight (lb)		2,900	2,906
Linear Velocity (ft/sec)	Forward	40.	39.1
	Vertical	26.	24.1
	Lateral	0	0.6
Attitude (deg)	Pitch	0	-6.2
	Roll	0	1.9
	Yaw	0	2.1
Angular Velocity (deg/sec)	Pitch Rate	0	0.5
	Roll Rate	0	0.7
	Yaw Rate	0	1.7

Comparison-Crash Test without DEA

Test Article



FEM



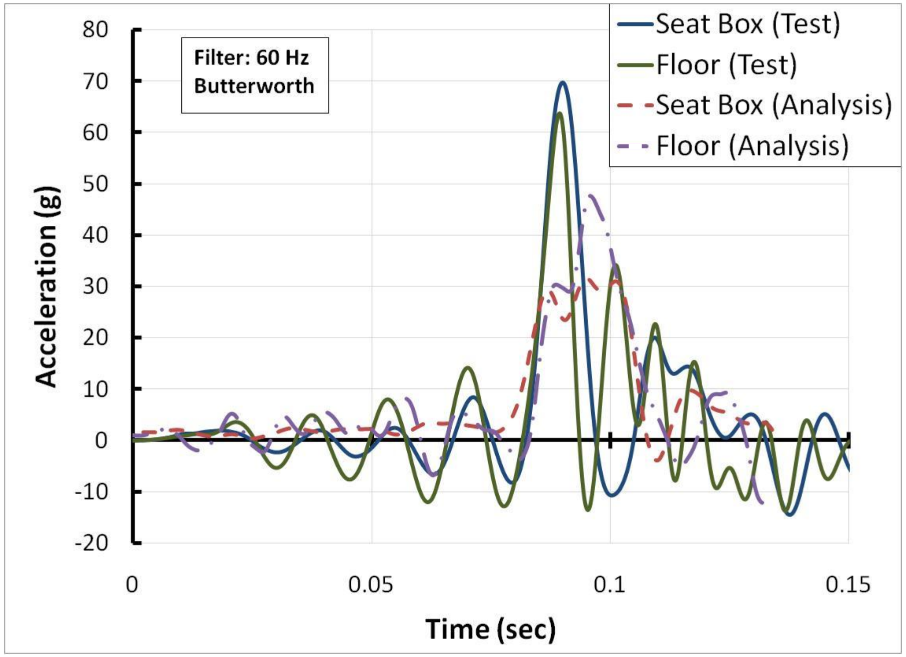
Prior to Impact

Peak Acceleration

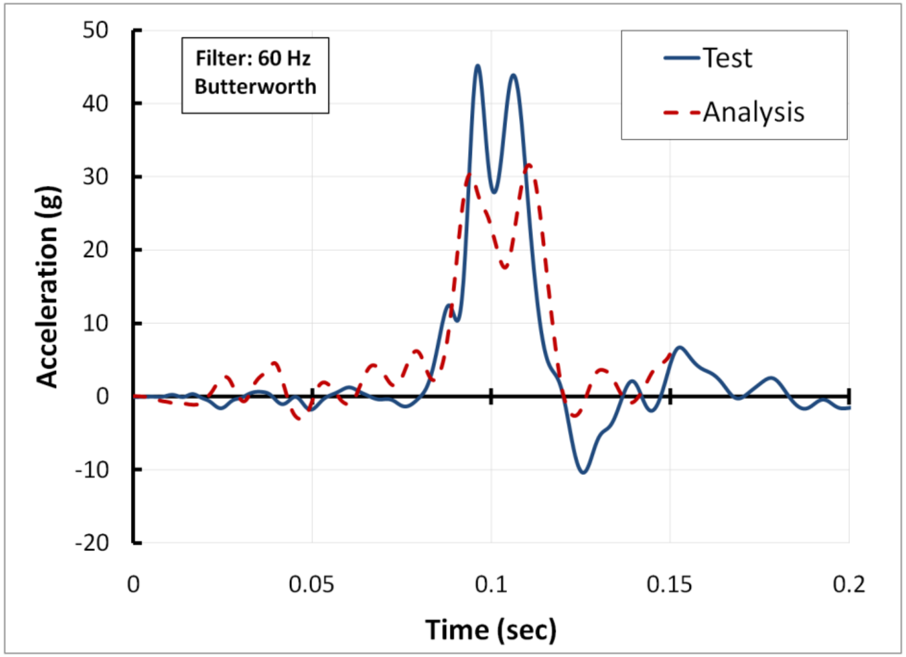
Increased number of airframe elements from 134,000 to 250,000

Comparison-Crash Test without DEA

Pilot Region Vertical Acceleration



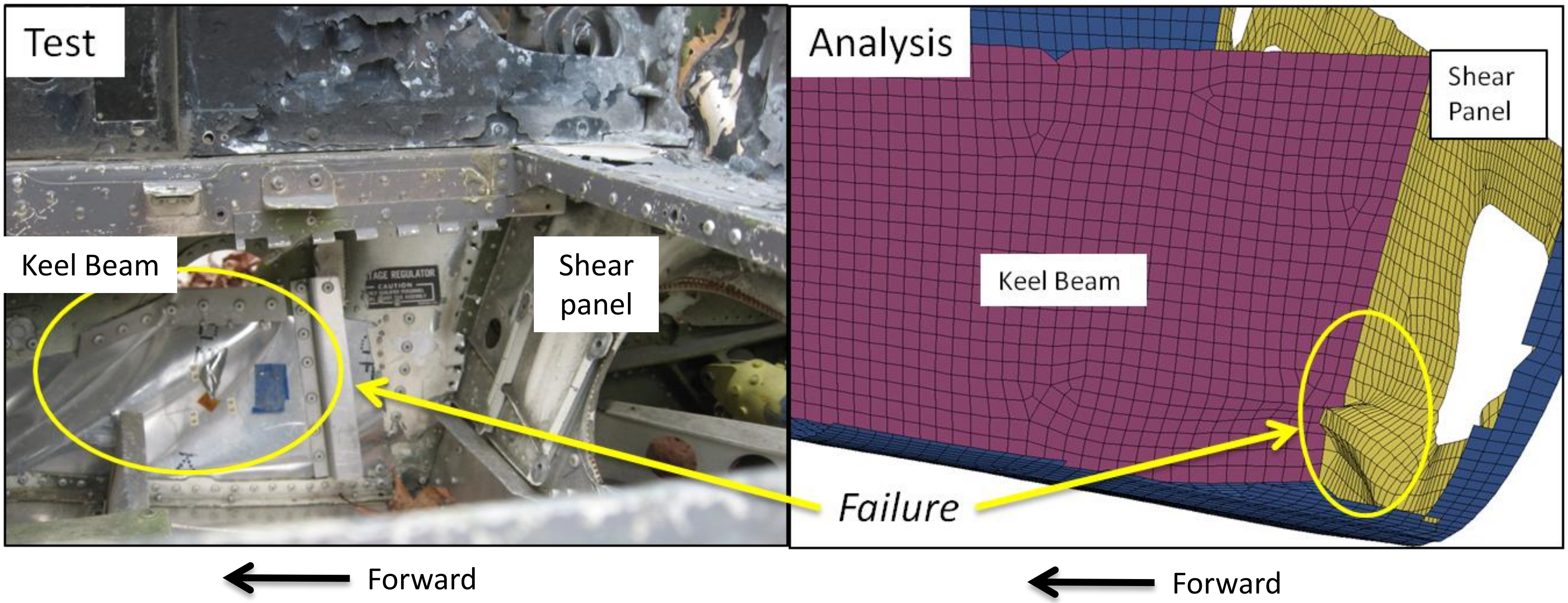
Passenger Floor Vertical Acceleration



Inconsistencies in Acceleration Time Histories

Comparison-Crash Test without DEA

Pilot Subfloor Deformation



Inconsistencies in Deformation Patterns

Rationale -Multi-Dimensional Calibration

- FEM deficiencies became apparent when severe loads and highly nonlinear responses were introduced for the test without the DEA

- A comprehensive and systematic calibration was conducted
  - Is modification of existing parameters sufficient?
  - Is more physical detail required in the model?

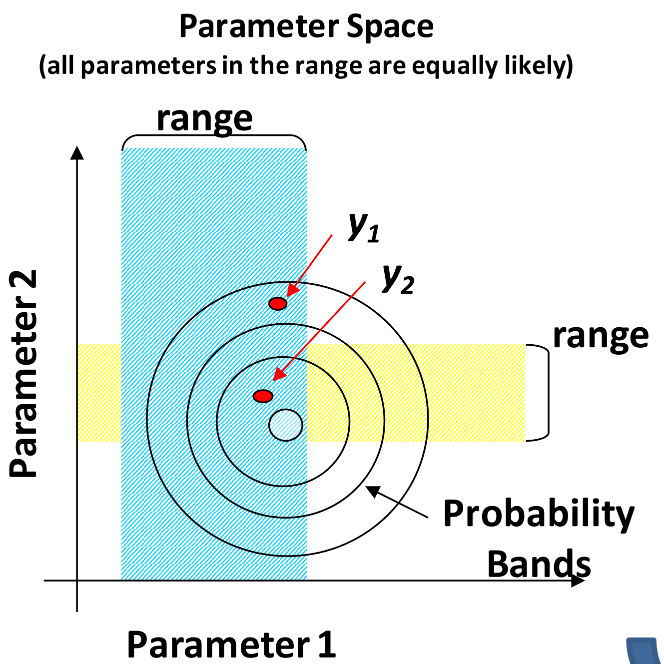
- Process implemented is divided into several steps:
  1. Metric definition
  2. Selection of candidate parameter set
  3. Definition of parameter uncertainty model
  4. Estimation of variance-based sensitivity
  5. Model parameter calibration

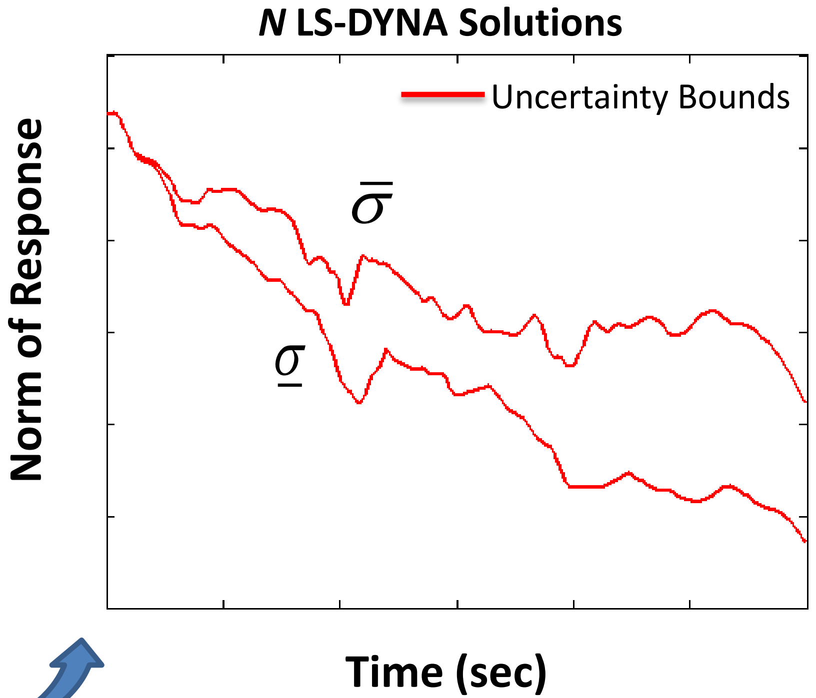
Multi-dimensional Calibration FEM

Calibration Metrics

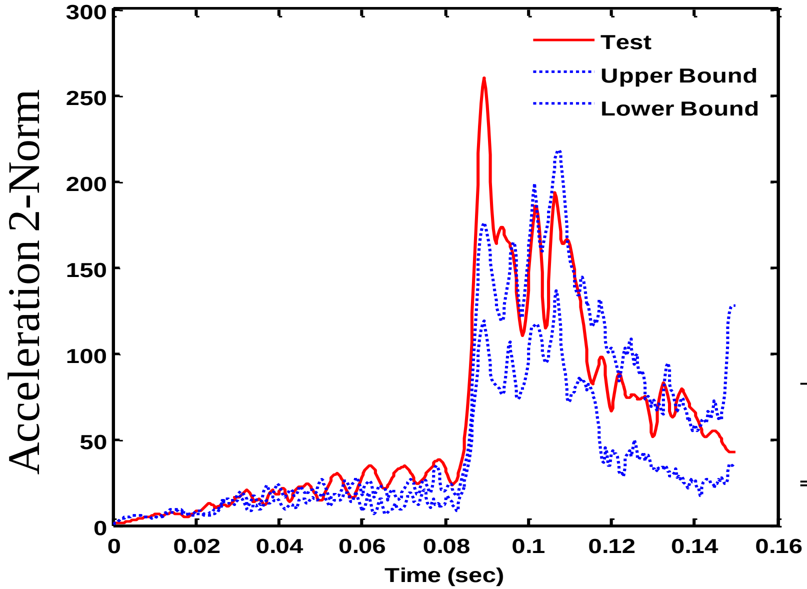
Metric 1: Let $Q(t,p) = \|v\|_2$ be the 2-norm of a response vector *v* and let $\bar{\sigma} = \max_{\forall p} Q(t,p)$ and $\underline{\sigma} = \min_{\forall p} Q(t,p)$. The probability to reconcile test with analysis given *N* model realizations is bounded by:

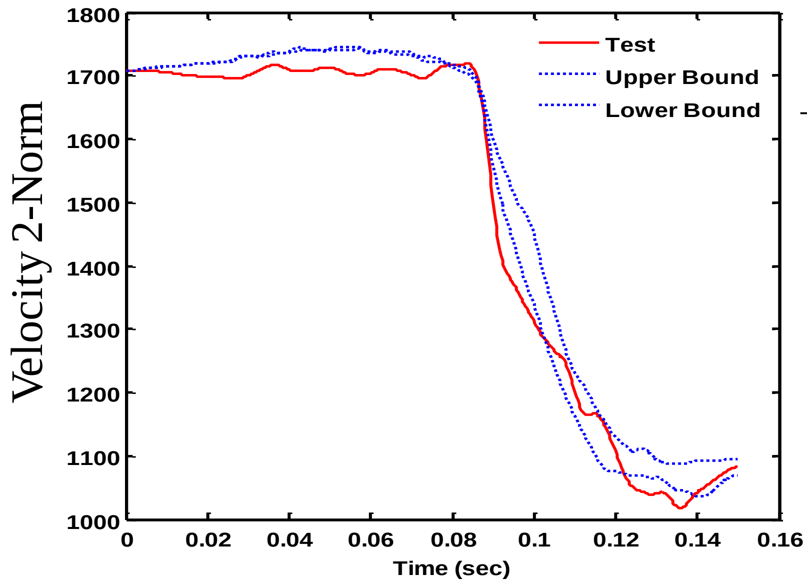
$$M_1 = Prob(\underline{\sigma} \leq Q_e(t) \vee Q_e(t) \geq \bar{\sigma}) << 1/N$$





Calibration Metric 1: Uncertainty Bounds



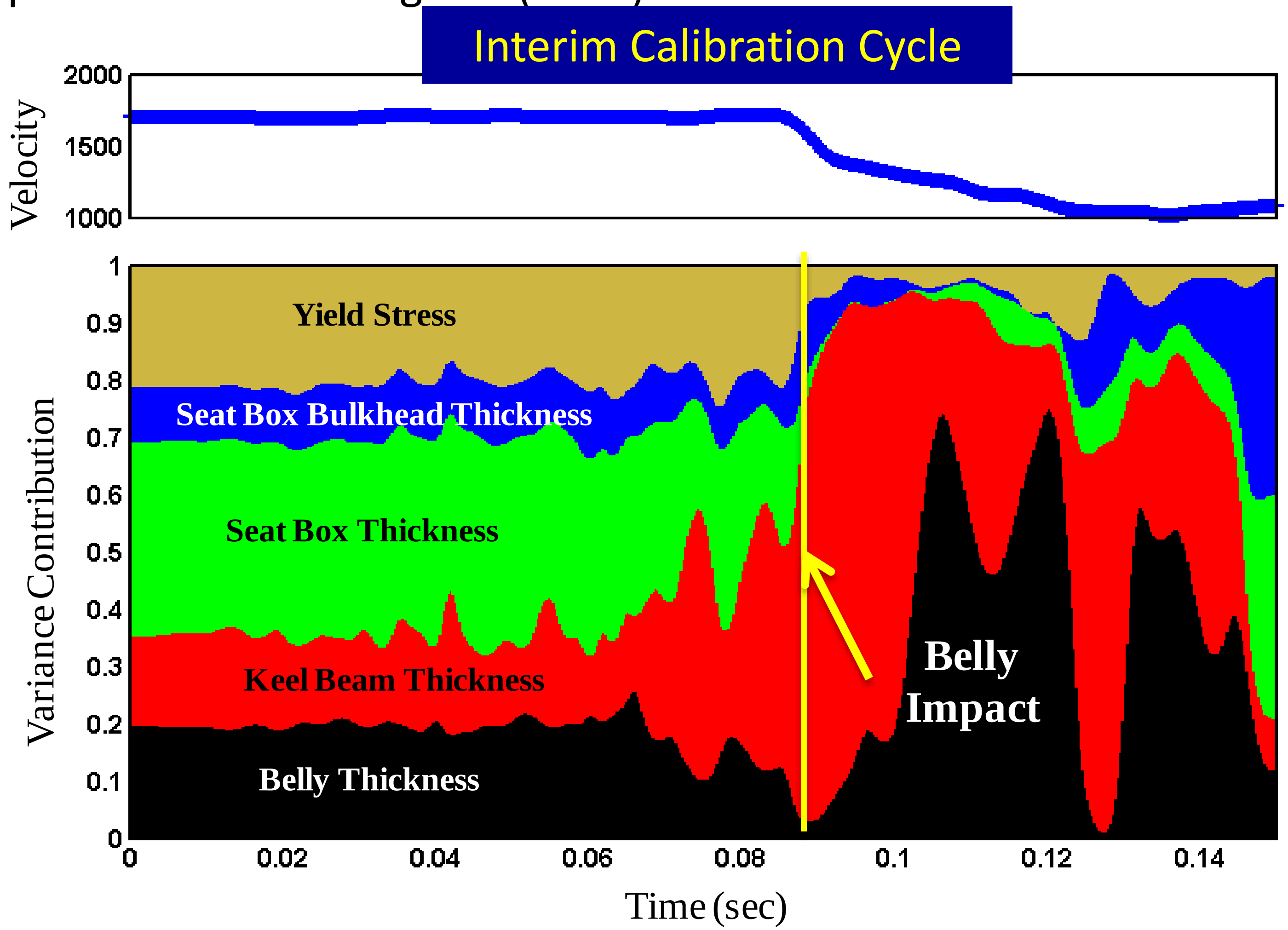


Interim Calibration Cycle

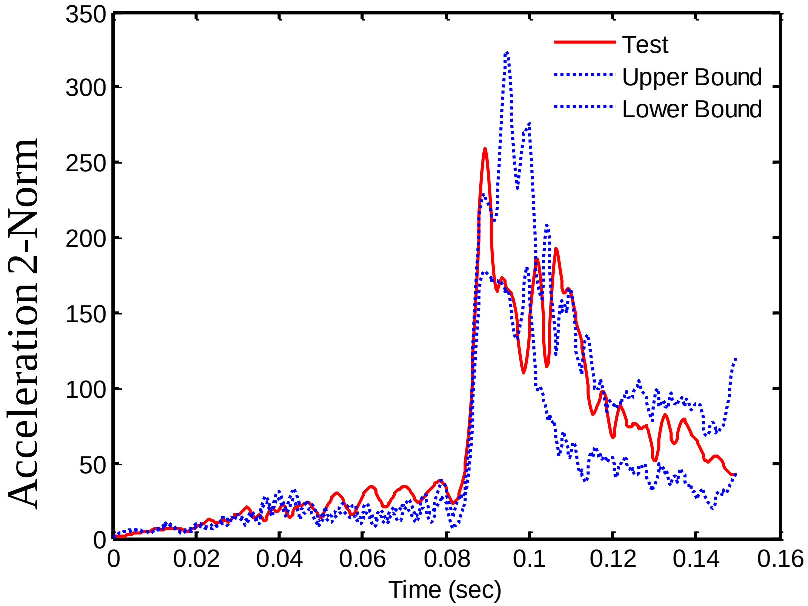
No.	Parameter Description	Nominal	Upper Bound	Lower Bound
1	belly thickness (in)	0.09	0.12	0.08
2	keel beam thickness (in)	0.04	0.07	0.03
3	seat box thickness (in)	0.1	0.12	0.08
4	seat box bulkhead thickness (in)	0.05	0.07	0.03
5	yield stress (psi)	40,000	45,000	35,000

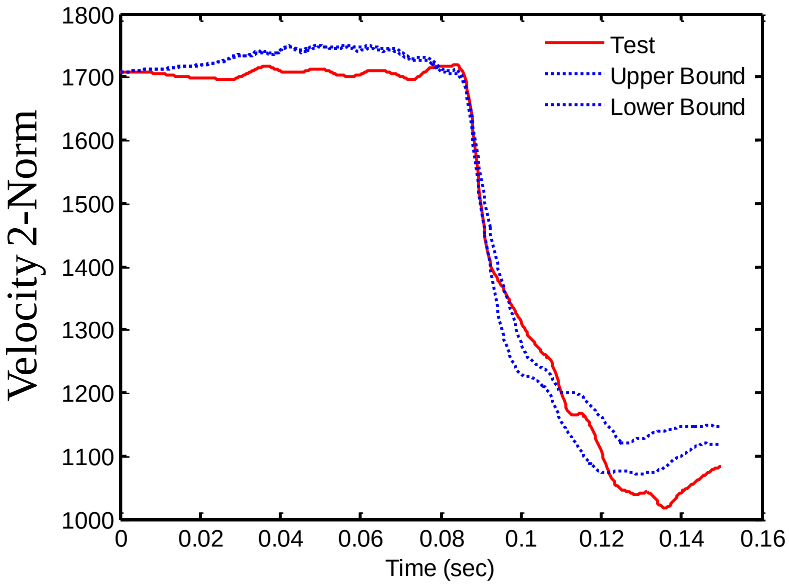
Variance Based Global Sensitivity Analysis

- Analysis of variance (ANOVA) is used for parameter sensitivity
- LS-DYNA simulations limited compared to number of solutions required
- Response surface surrogates (ERBF) are used to estimate additional solutions



Calibration Metric 1: Uncertainty Bounds



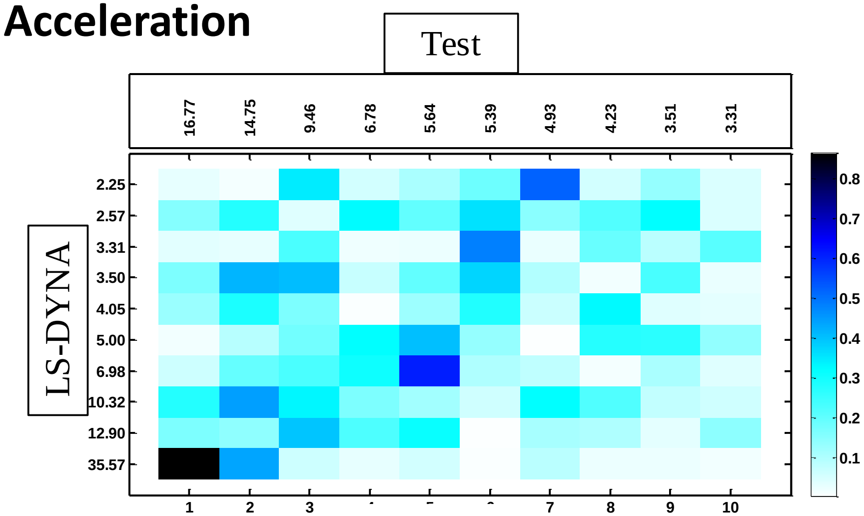


Final Calibration Cycle:
Keel Beam & Seat Pan Thicknesses Increased

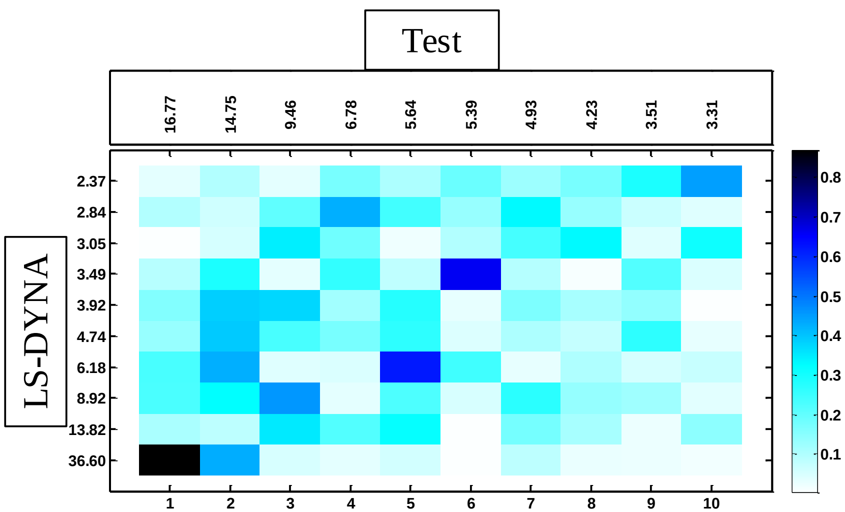
No.	Parameter Description	Nominal	Upper Bound	Lower Bound
1	belly thickness (in)	0.09	0.12	0.08
2	keel beam thickness (in)	0.12	0.15	0.10
3	seat box thickness (in)	0.1	0.12	0.08
4	seat box bulkhead thickness (in)	0.05	0.07	0.03
5	yield stress (psi)	40,000	45,000	35,000

Calibration Metric 2: Impact Shapes

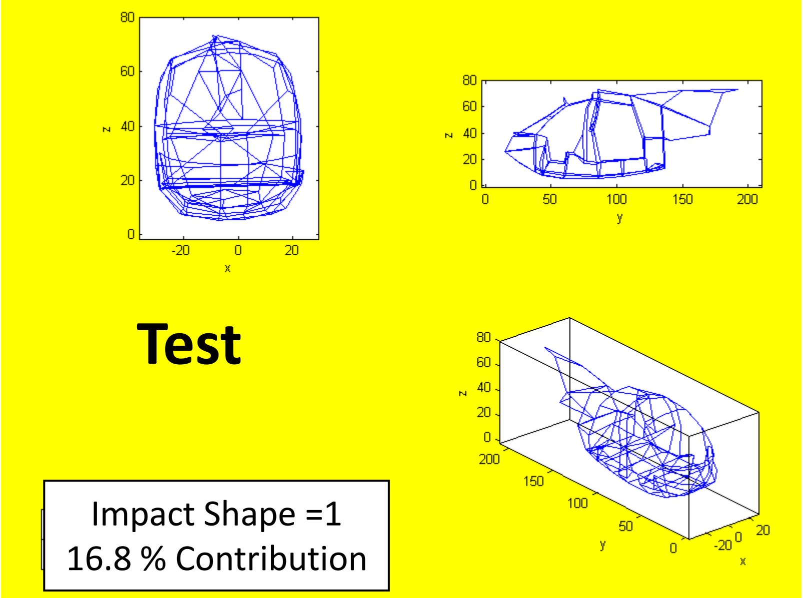
Acceleration

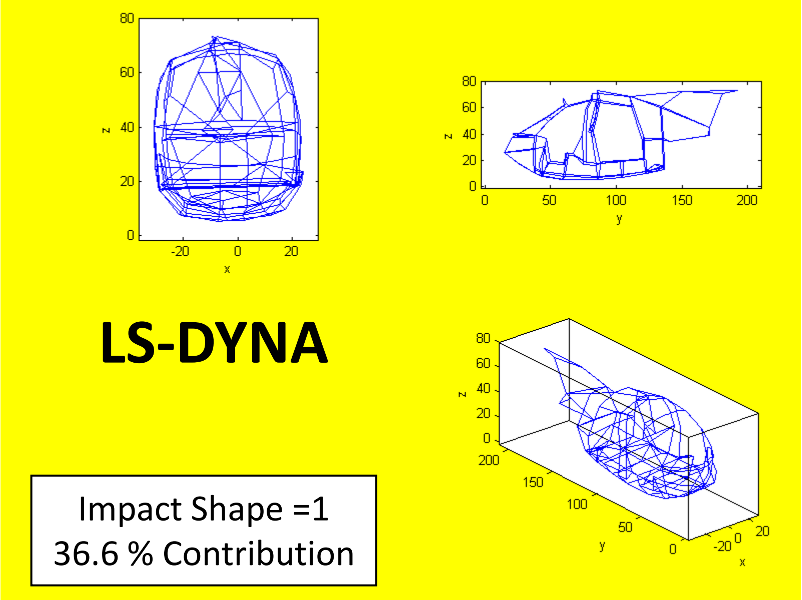


Baseline



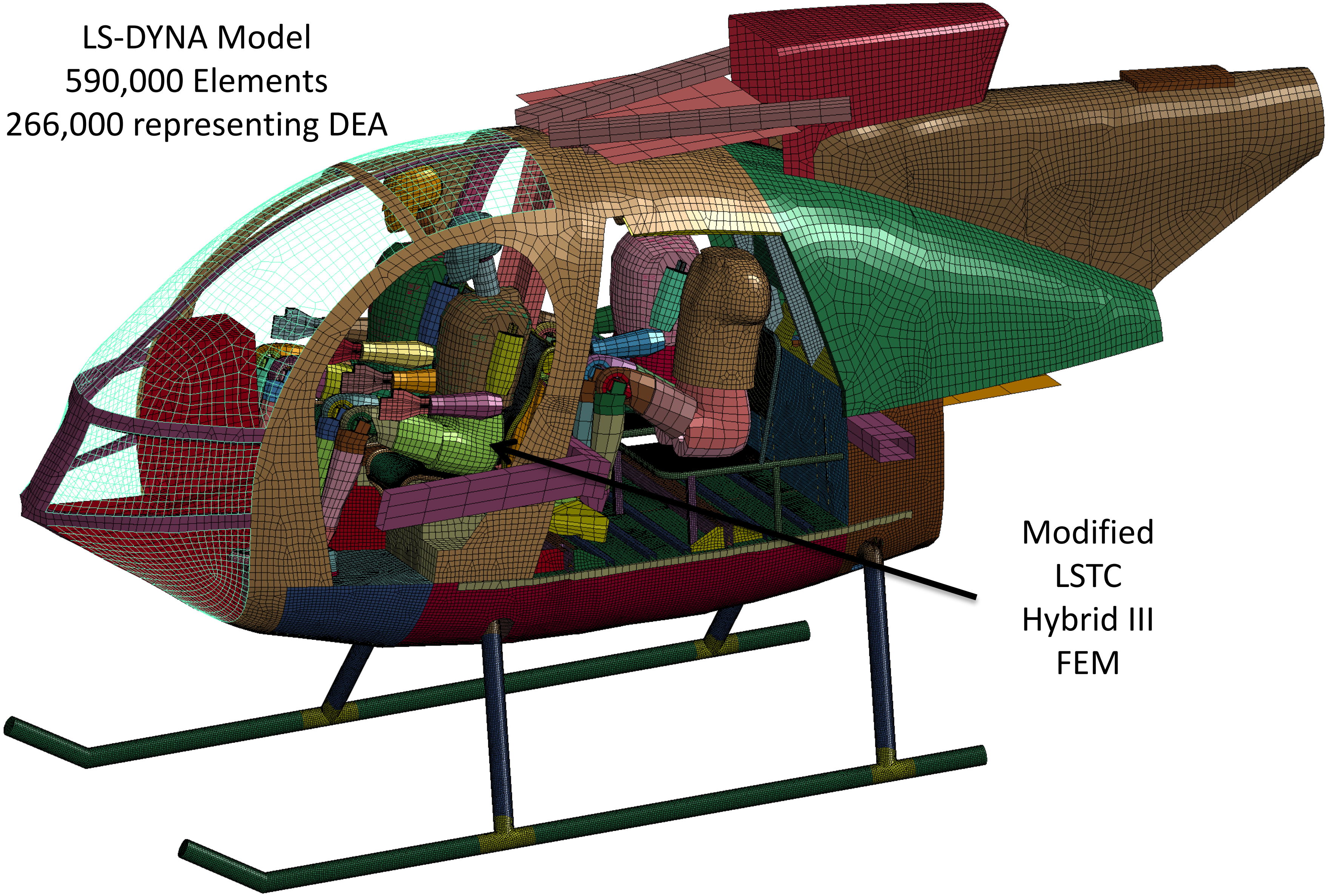
Final Calibration Cycle





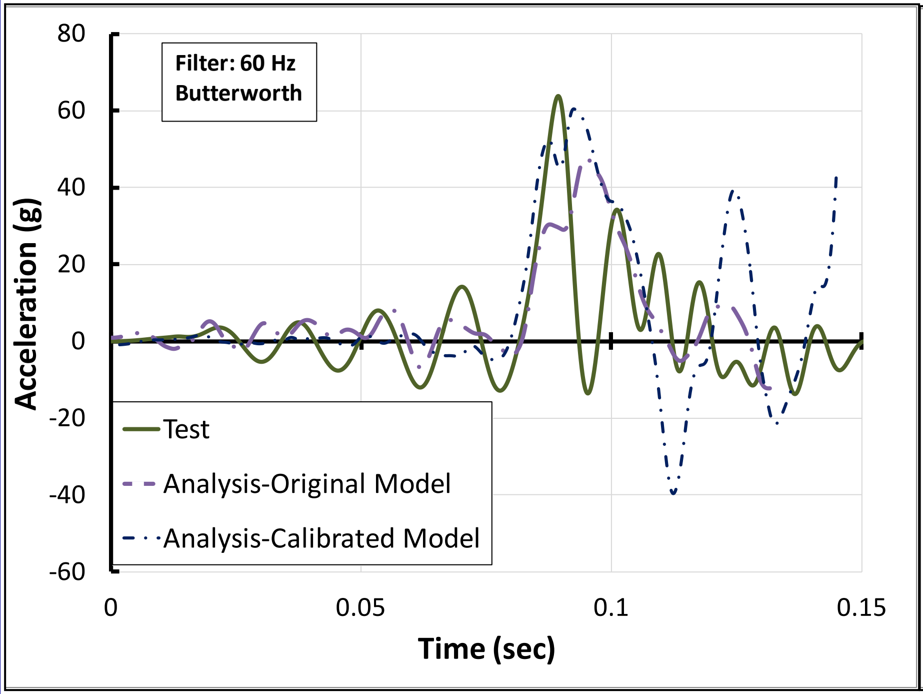
Final Calibrated FEM

LS-DYNA Model
590,000 Elements
266,000 representing DEA

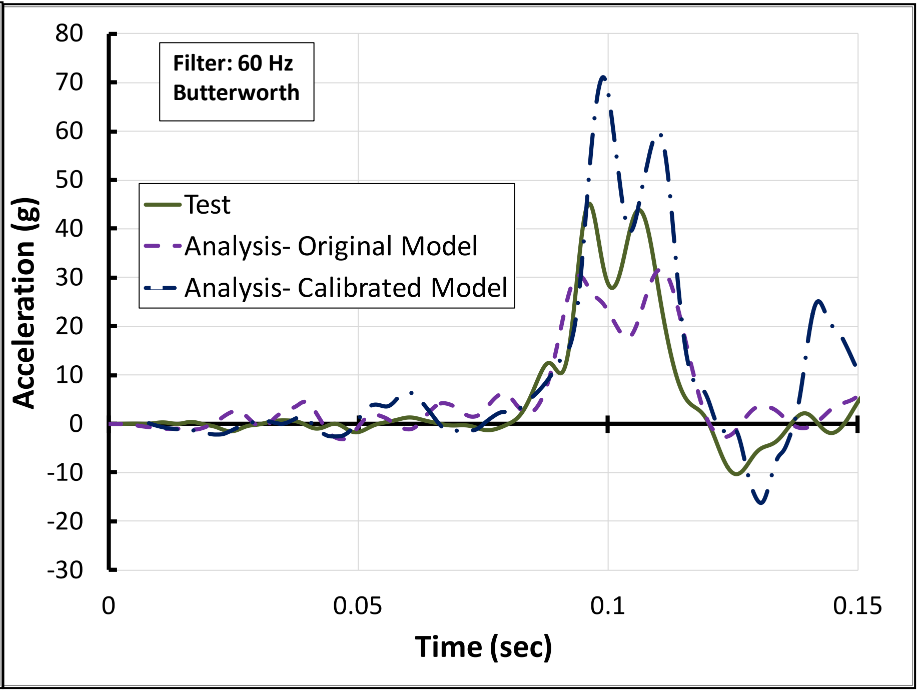


Calibrated FEM-Crash Test without DEA

Pilot Region Vertical Acceleration



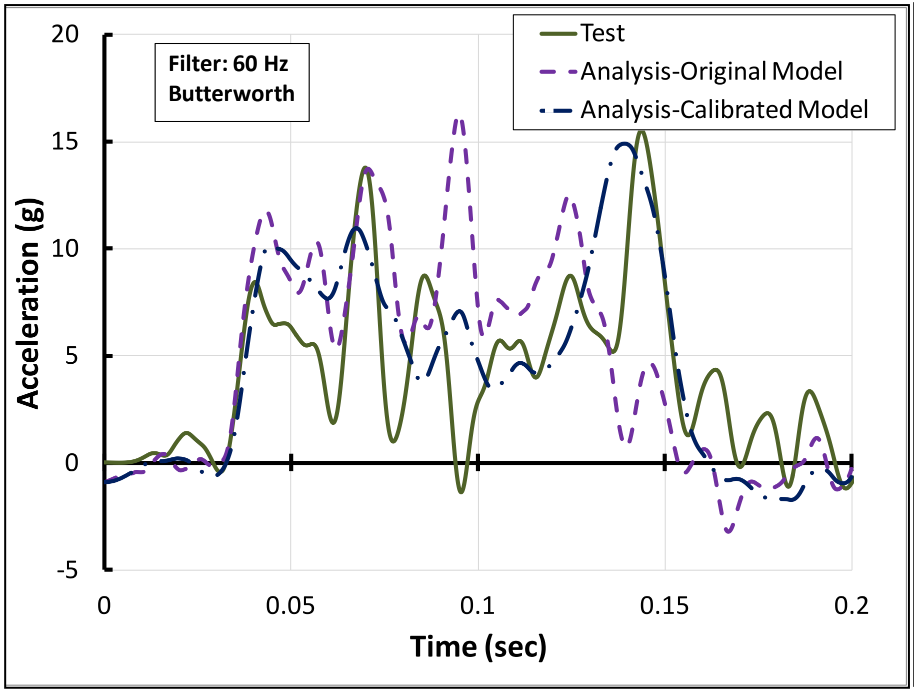
Passenger Floor Vertical Acceleration



No.	Parameter Description	Nominal	Upper Bound	Lower Bound	Calibrated
1	belly thickness (in)	0.09	0.12	0.08	0.089
2	keel beam thickness (in)	0.12	0.15	0.10	0.12
3	seat box thickness (in)	0.1	0.12	0.08	0.11
4	seat box bulkhead thickness (in)	0.05	0.07	0.03	0.065
5	Yield Stress (psi)	40,000	45,000	35,000	35,210

Calibrated FEM-Crash Test with DEA

Pilot Region Vertical Acceleration



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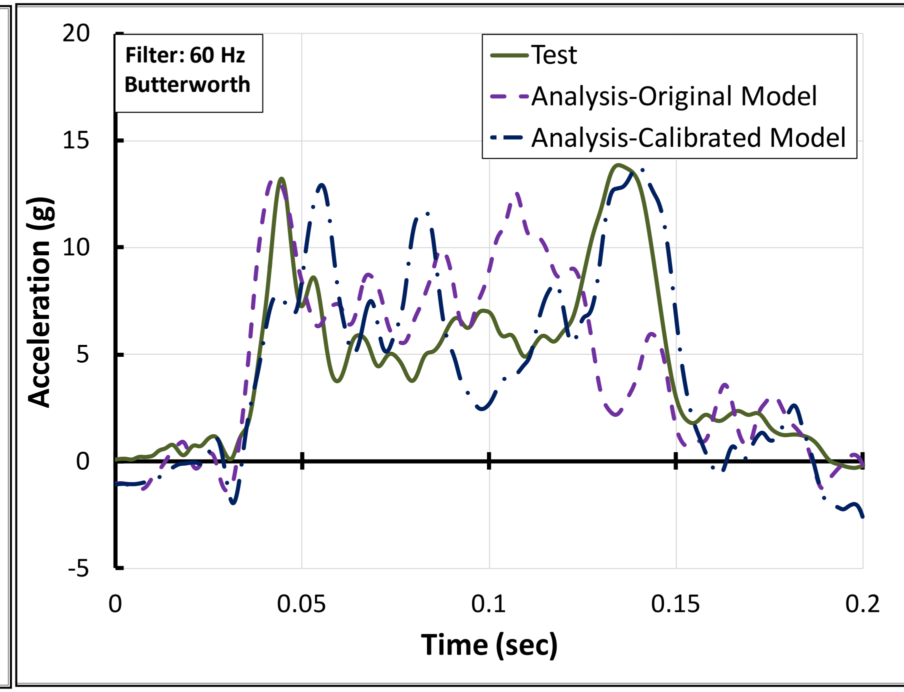

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5	Yield Stress (psi)	40,000	45,000	35,000	35,210

Conclusions

- Multiple parameters required to calibrate ATD response, mostly relegated to pelvic/lumbar region
- For crash test of full-scale airframe, multi-dimensional model calibration was performed based on two new calibration metrics:
  - (1) 2-norm acceleration and velocity bound metric (Time variation)
  - (2) Orthogonality of test and analysis impact shapes (Spatial variation)
- Response surfaces generated from a subset of DYNA simulations for variance analyses
- Calibration cycles identified critical parameters and provided effective guidance to improve model responses for both tests, with and without DEA

Remarks

- Important considerations when conducting severe crash tests for the purpose of validating analytical models
  - Sensor suite must cover all critical components, and should be located to avoid high-frequency saturation of the acceleration output.
  - Accelerometers should be chosen to ensure their velocity integration is accurate (limit drift)
  - Multiple validation metrics should be applied between test and analysis which comprehensively identify modeling deficiencies, evaluate parameter importance, and propose required model changes.
  - Building block approach to model calibration breaks up the problem into more manageable subsystems

The objective of crash certification by analysis achievable using similar methodologies