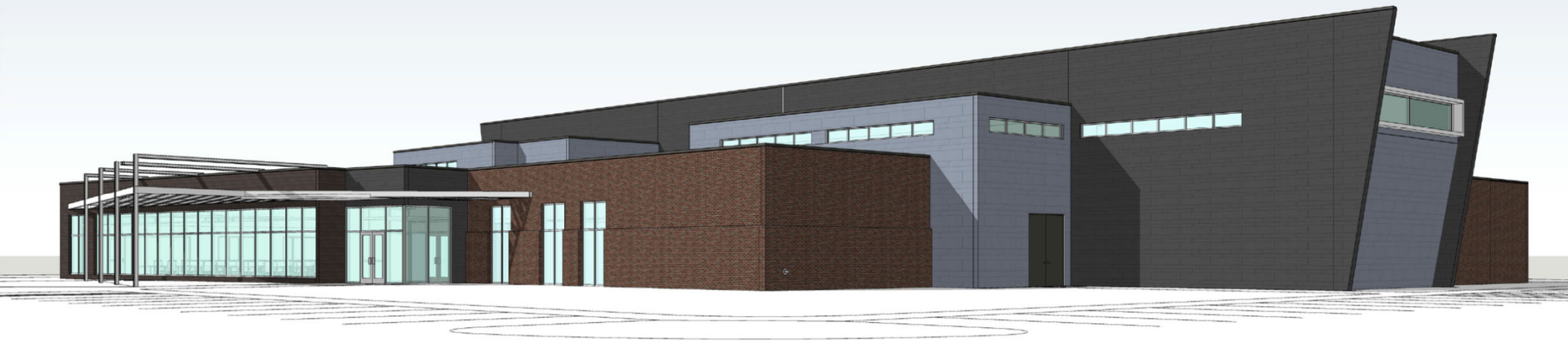
# Aerospace Impact Dynamics Simulation Methods: Verification and Validation Process

NIAR Advanced Virtual Engineering and Testing Laboratories



Gerardo Olivares Ph.D. | Gerardo.Olivares@wichita.edu | Workshop: Use of Dynamic Analysis Methods in Aircraft Certification| Cologne August 29-30th 2019

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# Agenda

## Aerospace Impact Dynamics Simulation

- Introduction Aerospace Structural Impact Dynamics Simulation
- Current Challenges
- Method Development: Verification and Validation
- Example A: sUAS Airborne Collision
- Example B: Dynamic Seat Modeling
- Conclusion and Recommendations

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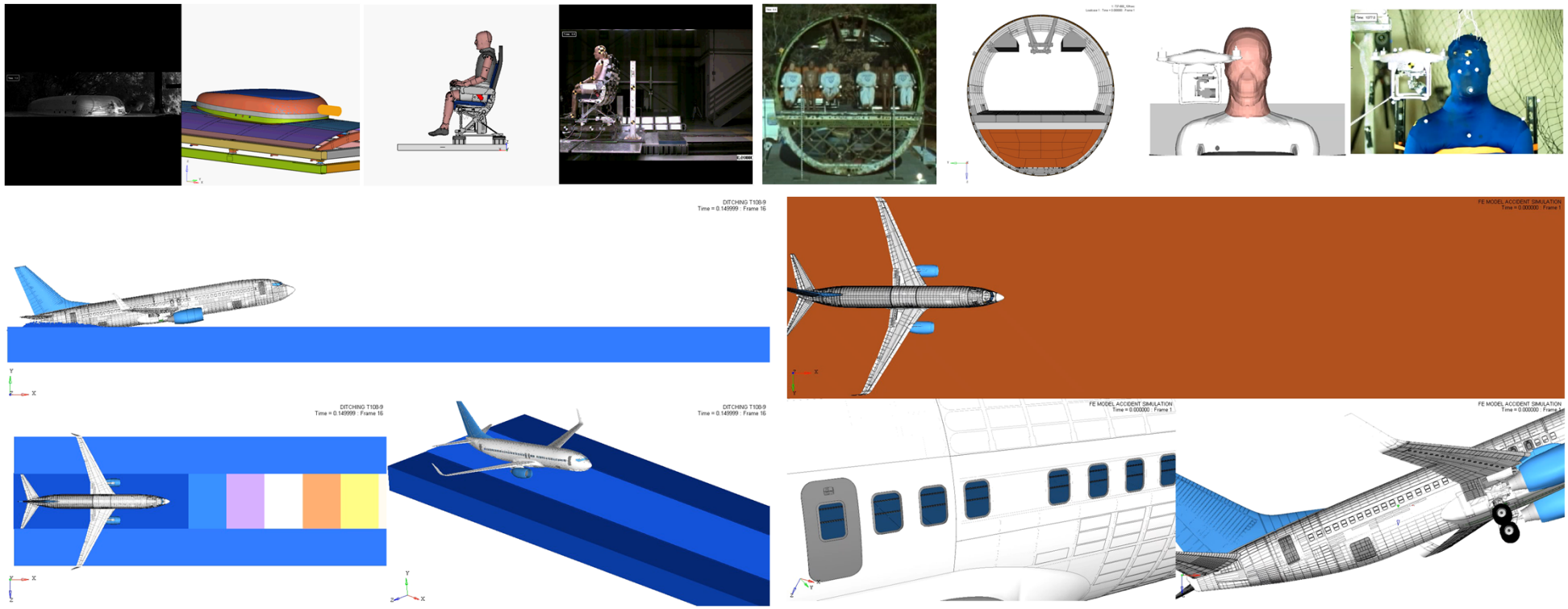
# Aerospace Impact Dynamics Applications

## Introduction Aerospace Structural Impact Dynamics Simulation



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# Current Challenges

## Aerospace Impact Dynamics Simulation

- Regulators:
  - Standardized Industry Wide Methods
- Industry:
  - Standardized Industry Wide Methods
  - Verification and Validation Data
  - Test/Simulation Errors and Uncertainty (For full scale dynamic tests we only conduct one test per condition)
  - Physical Test to Test Variability – HIC Compliance Row to Row
  - Robustness of Seat Designs- Most seat designs are not driven by simulation\structural analysis. Hence moving the problem from the physical to the virtual world.
  - Method\Process Repeatability -Robustness
  - Documentation
  - Qualified Personnel
  - Cost of Entry: Method Development, Experimental, Computational, Personnel..etc.

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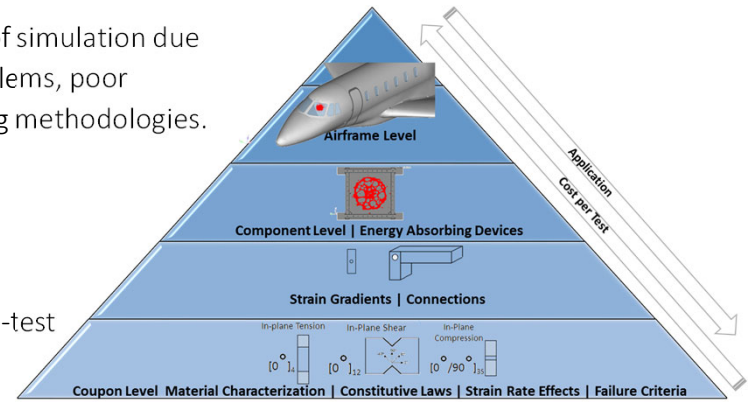
# Method Development, Verification and Validation

Example Dynamic Seat Modelling

# Modeling Methods

## Method Development, Verification and Validation

- Non-Physics Based Modeling:
  - This approach has been used by the aerospace industry since the introduction of simulation due to limitations in computing power and computational tools, complexity of the problems, poor understanding of the physics, lack of test-to-test variability data, and poor modeling methodologies.
  - Simulation follows system level testing. Hence models are **not predictable**.
  - Testing results are used to **calibrate** the model [non-physics based].
  - Models are evaluated by the **calibration-validation methods**.
  - The **validation criteria** is always unreasonable (5 to 10 %) and vague (peak, shape, **subjective**) due to the lack of research and understanding of the real test-to-test variability.




- Physics Based Modeling:
  - This approach used by NIAR takes advantage of the advances in computational power, the latest computational tools, years of research to understand the physics, generated test-to-test variability data, and verified & validated (V&V) modelling methodologies.
  - Defined modelling methodologies using the building block approach. Understanding of the physics and testing variability from the coupon to the system level. Taking a conservative modeling approach based on data derived from R&D and the Building Block Approach to define simplified models when required. <u>The definition of the numerical model is not driven by system level test results, is driven by a predefined V&V building block modeling methodology.</u>
  - Simulation **predicts** system level test results within the scope and scatter of the physical test results.
  - **Objective validation** criteria based on an understanding of the test-to-test variability. Defined objective validation metrics (i.e. Sprague and Gears). The correlation level between simulation and testing is driven by an understanding of the test-to-test variability.

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# Methods Evaluation Criteria

## Method Development, Verification and Validation

- Subject Matter Expert Evaluation: Does the team conducting the analysis have the methods and the experience (computational and experimental) required to solve this type of problem. The SMEE Technique is a systematic way of gathering information from experts on a specific subject, and ranking the importance of the information, in order to meet some decision-making objective .
- Verification of the tools used for analysis: The process of determining that a computational model accurately represents the underlying mathematical model and its solution .
- Validation of the methods used for analysis: 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.

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# Subject Matter Expert Evaluation

## Method Development, Verification and Validation

- The Subject Matter Expert Evaluation (SMEE) is a systematic way of gathering information from experts on a specific subject, and ranking the importance of the information, in order to meet some decision-making objective.
- The SMEE process results in lists of phenomena which are germane to a particular subject (a very specific figure-of-merit). The process proceeds by ranking these phenomena using a scoring criterion in order to help determine what is most important. That ranking, as well as the rationale for the ranking along with the information obtained to explain the ranking, can assist in decision making.
- The SMEE methodology brings into focus the phenomena that dominate an issue, while identifying all plausible effects to demonstrate completeness. An important part of the process is to also identify the uncertainty in the ranking, usually by scoring the knowledge base for the phenomenon. Again the rationale for the scoring is an important product of the elicitation. When a phenomenon is identified as being important but the corresponding knowledge level is low it is an indication that more effort must be applied, e.g., more research support.

| | | **Importance** | | |
|---|---|---|---|---|
| | | H (High) | M (Medium) | L (Low) |
| **Knowledge Level** | K (Known) | | | |
| | P (Partially) | Add. R&D Suggested. | | |
| | U (Unknown) | Add. R&D Suggested. | Add. R&D Suggested. | |

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# Method Verification and Validation Process

## Method Development, Verification and Validation

- Verification and Validation (V&V) are the processes by which evidence is generated, and credibility is thereby established that the computer models have adequate accuracy and level of detail for their intended use. The following are key principles in the V&V process:
  - Verification must precede validation.
  - The need for validation experiments and the associated accuracy requirements for computational model predictions are based on the intended use of the model and should be established as part of V&V activities.
  - Validation of a complex system should be pursued in a hierarchical fashion from the coupon-component level to the system level.
  - Validation is specific to a particular computational model for a particular intended use.
  - Validation must assess the predictive capability of the model in the physical realm of interest, and it must address uncertainties that arise from both simulation results and experimental data.
- The three key elements of the V&V Plan that will help in estimating the resource allocations are:
  - System Response Features – the features of interest to be compared and how they are to be compared (metrics).
  - Validation Testing – set of experiments for which the model's predictive capability is to be demonstrated for the model to be accepted for its intended use.
  - Accuracy Requirements - specification of accuracy requirements allows the "acceptable agreement" question to be answered quantitatively.


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# Verification

## Method Development, Verification and Validation

- Code Verification is the domain of software developers who are expected to use modern Software Quality Assurance techniques along with testing of each released version of the software. Users of software also share in the responsibility of code verification, even though they typically do not have access to the software source. The large number of software users, typical of most commercial codes, provides a powerful potential code verification capability, if it is used wisely by the code developers.
- Calculation Verification, or estimating the errors in the numerical solution due to discretization. Calculation verification, of necessity, is performed after code verification, so that the two error types are not confounded. However, any comparison of the numerical and analytical results will contain some error, as the discrete solution, by definition, is only an approximation of the analytical solution. Consequently the goal of calculation verification is to estimate the amount of error in the comparison that can be attributed to the discretization.

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# Validation

## Method Development, Verification and Validation

- The validation process has the goal of assessing the predictive capability of the model. This assessment is made by comparing the predictive results of the model with validation experiments.
- The key components of the validation process are the:
  - Validation Experiments – experiments performed expressly for the purpose of validating the model.
  - Accuracy Assessment – quantifying how well the experimental and simulation outcomes compare.
- The important qualities of a validation experiment include:
  - Redundancy of the Data – repeat experiments to establish experimental variation.
  - Supporting Measurements - not only are measurements of the important system response quantities of interest recorded, but other supporting measurements are recorded. An example would be to record the curvature of a beam to support a strain gauge measurement.
  - Uncertainty Quantification - errors are usually classified as being either random error (precision) or systematic error (bias).

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**NIAR Dynamic Modeling Methodology**

# Example Application of Dynamic Modelling: sUAS Airborne Collision

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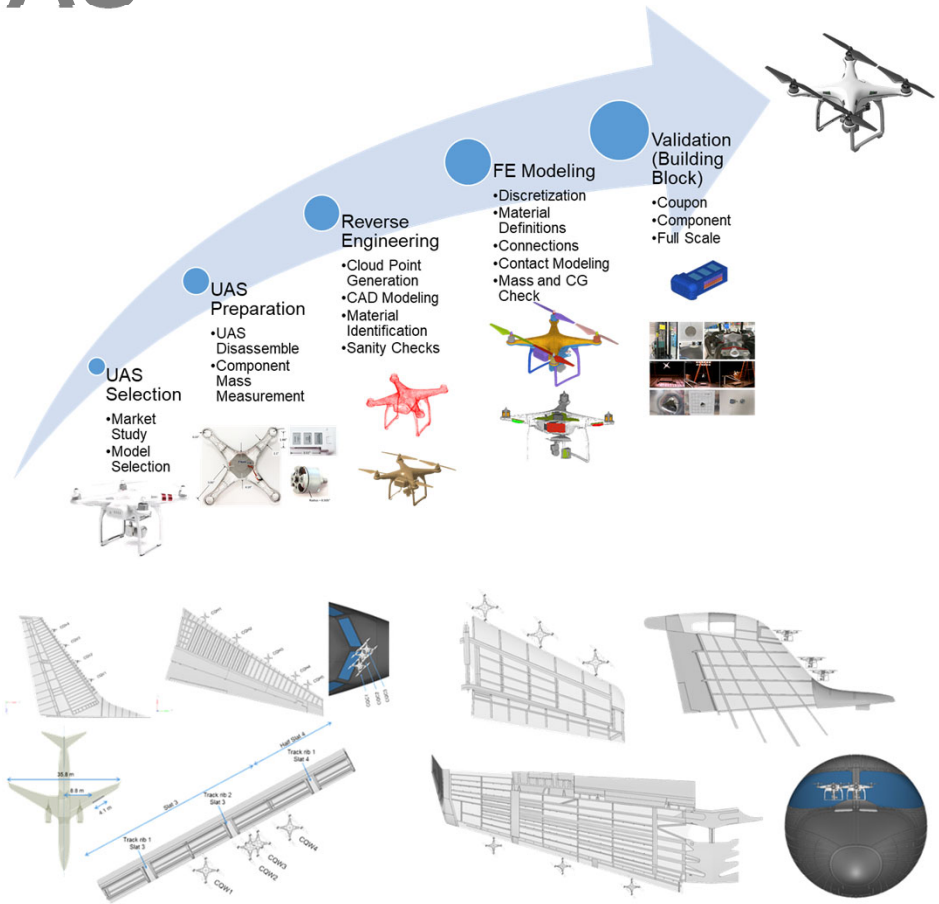
# Airborne Collision sUAS

## Example sUAS Dynamic Impact

- 14 month research effort plus a 3 month peer review process.
- Over 140 scenarios were analyzed:
  - Two different sUAS configurations(QuadCopter and Fixed-Wing)
  - Two different Airplane Targets (Single Aisle Commercial and Business Jet) with eight different impact locations (Wing leading edge, Horizontal Stabilizer, Vertical Stabilizer, and Windshield).
  - Impact velocities from 100 knots to 365 knots.
  - Comparison with 2.68, 4, and 8 lb bird strike impacts. sUAS masses 2.68, 4, and 8 lb. configurations.
  - Engine ingestion configurations: Take-off, Cruise, Landing
- This will have not been possible through Full Scale Physical Testing [Prohibitive costs and time, sourcing of test articles, control of accurate impact conditions, etc.]
- Simulation allows for quick changes on impact conditions (Orientation, Velocity, Impact location, Mass)
- Simulation allows for repeatability between tests and appropriated comparisons between impact scenarios.
- Simulation allows for further evaluations with minimal costs.





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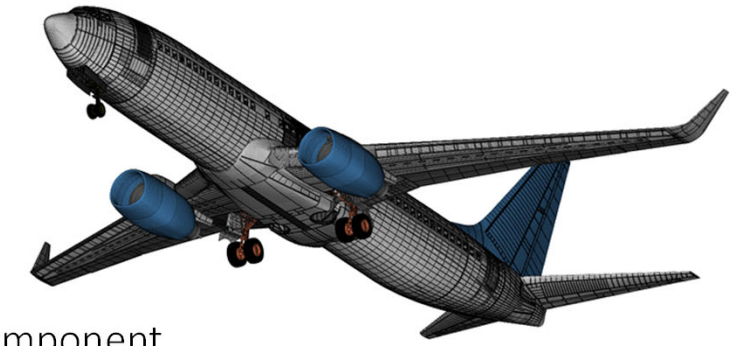
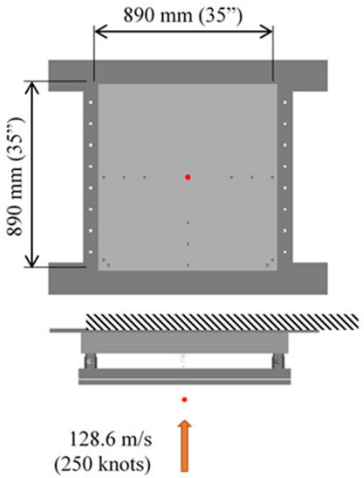
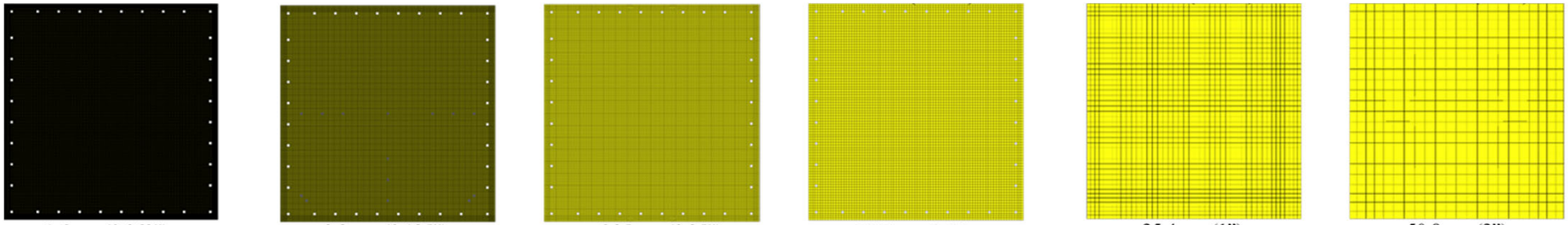
# Discretization Evaluation

## Methods Evaluation Criteria

- Target: AL2024-T3 Plate (same as component level tests)
- Projectiles:
  - UAS Quadrotor Motor
  - UAS Quadrotor Battery
- Mesh Sensitivity 1.6 to 50 mm
- Impact Velocity 250 knots (128.6 m/s)
- Final mesh selection was validated with component level test.





1.6mm (0.063") 3.2mm (0.125") 6.35mm (0.25") 12.7mm (0.5") 25.4mm (1") 50.8mm (2")

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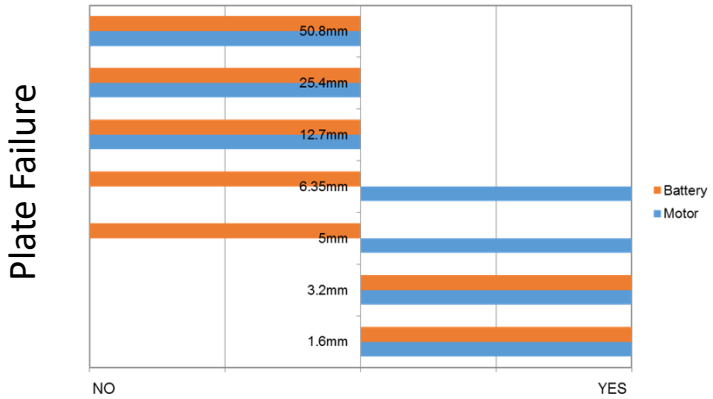
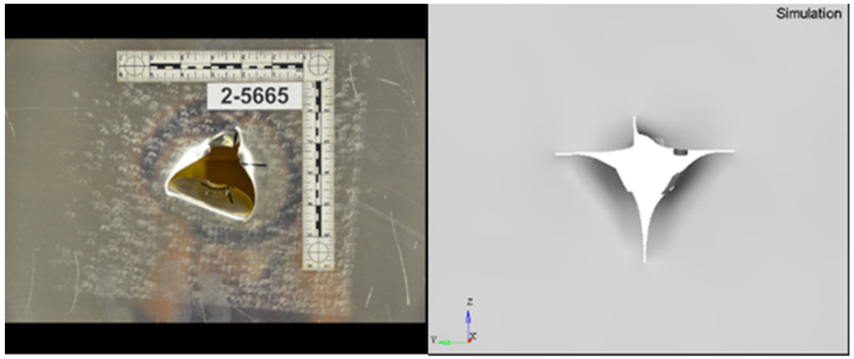
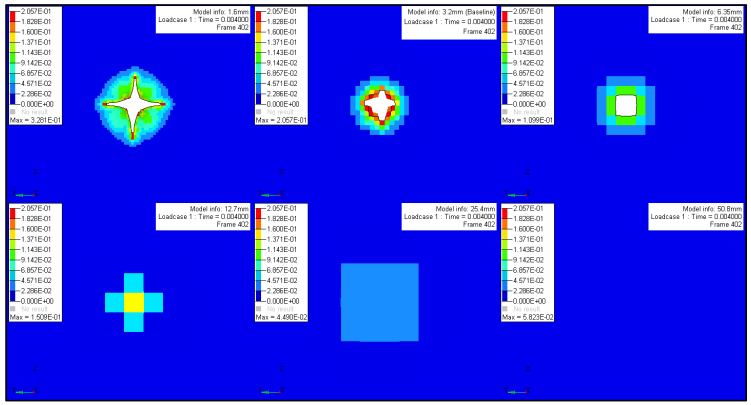
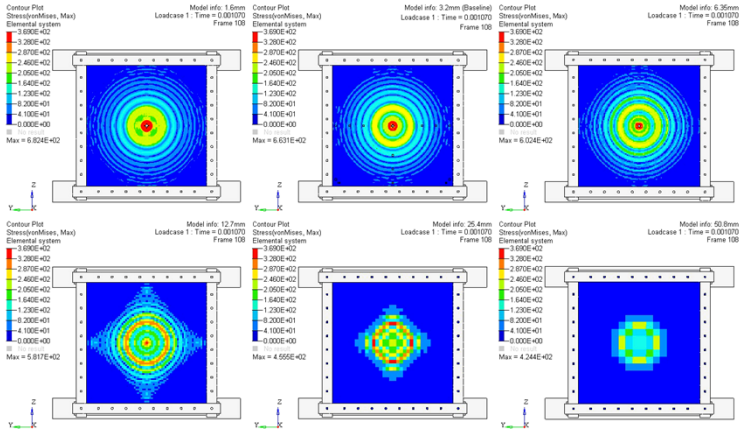
# Discretization Evaluation

## Methods Evaluation Criteria



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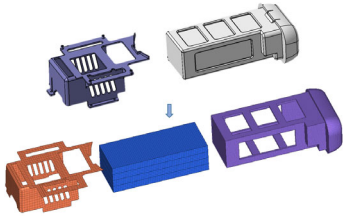
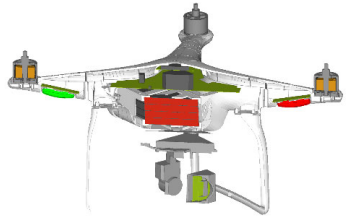
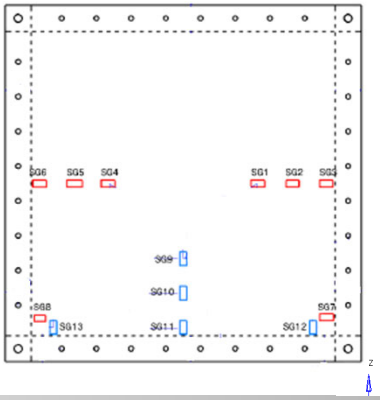
# Validation Example – Building Block

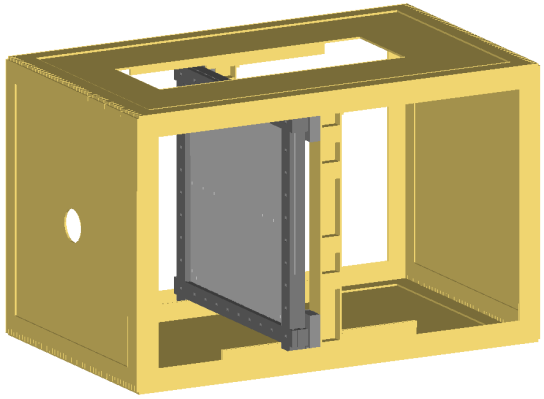
## Methods Evaluation Criteria

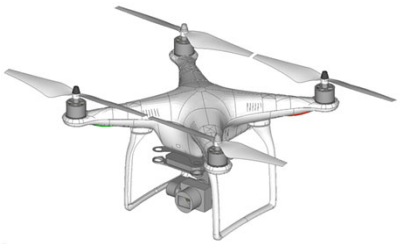
| Test Number | Shot Number | Panel Type | Projectile Type | Projectile Weight (g) | Pitch (Deg.) | Yaw (Deg.) | Impact Velocity (knot) | Impact Velocity (m/sec) | Impact Energy (J) | Penetrate Panel (Y/N) | Rebound Velocity (m/sec) | Residual Velocity (m/sec) | Peak load (lb) | Permanent Deformation (in) | Max Deflection (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2-5660 | 0.063" Al | Battery (discharged) | 344.28 | 0.2° D | 9.9° L | **258.92** | 133.20 | 3054.43 | N | n/a | n/a | **23,090** | 1.26 | 1.91 |
| | 2-5669 | 0.063" Al | Battery (discharged) | 348.86 | 0.2° D | 13.8° L | **251.21** | 129.24 | 2913.66 | N | n/a | n/a | **20,575** | 1.204 | 1.95 |
| | **2-5670** | 0.063" Al | Battery (discharged) | 343.07 | 0.8° D | 0.8° L | **248.25** | 127.71 | 2798.12 | N | n/a | n/a | **20,791** | 1.337 | 1.88 |
| 2 | **2-5661** | 0.25" Al | Battery (discharged) | 350.06 | 1.7° D | 2.1° L | **255.95** | 131.67 | 3035.05 | N | n/a | n/a | **27,852** | 0.285 | 0.77 |
| | 2-5662 | 0.25" Al | Battery (charged) | 351.62 | 0.2° U | 10.4° L | **250.03** | 128.63 | 2909.07 | N | n/a | n/a | **27,468** | 0.358 | 0.79 |
| | 2-5671 | 0.25" Al | Battery (discharged) | 344.71 | 3.5° D | 5.7° L | **251.81** | 129.54 | 2892.59 | N | n/a | n/a | **30,286** | 0.23 | 0.75 |
| | 2-5672 | 0.25" Al | Battery (charged + ON) | 346.6 | 0.4° D | 3.8° L | **250.62** | 128.93 | 28791.65 | N | n/a | n/a | **29,567** | 0.256 | 0.75 |
| 3 | **2-5675** | 0.125" Al | Battery (discharged) | 344.1 | 2.0° U | 1.5° L | **96.57** | 49.68 | 424.73 | N | 7.62 | n/a | **10,829** | 0.218 | 0.57 |
| | 2-5676 | 0.125" Al | Battery (discharged) | 344.08 | 17.1° U | 11.7° R | **90.65** | 46.63 | 374.19 | N | 6.40 | n/a | **8,729** | 0.177 | 0.5 |
| | 2-5679 | 0.125" Al | Battery (charged) | 351.45 | 2.8° D | 10.4° R | **99.54** | 51.21 | 460.83 | N | 6.40 | n/a | **9,987** | 0.207 | 0.61 |









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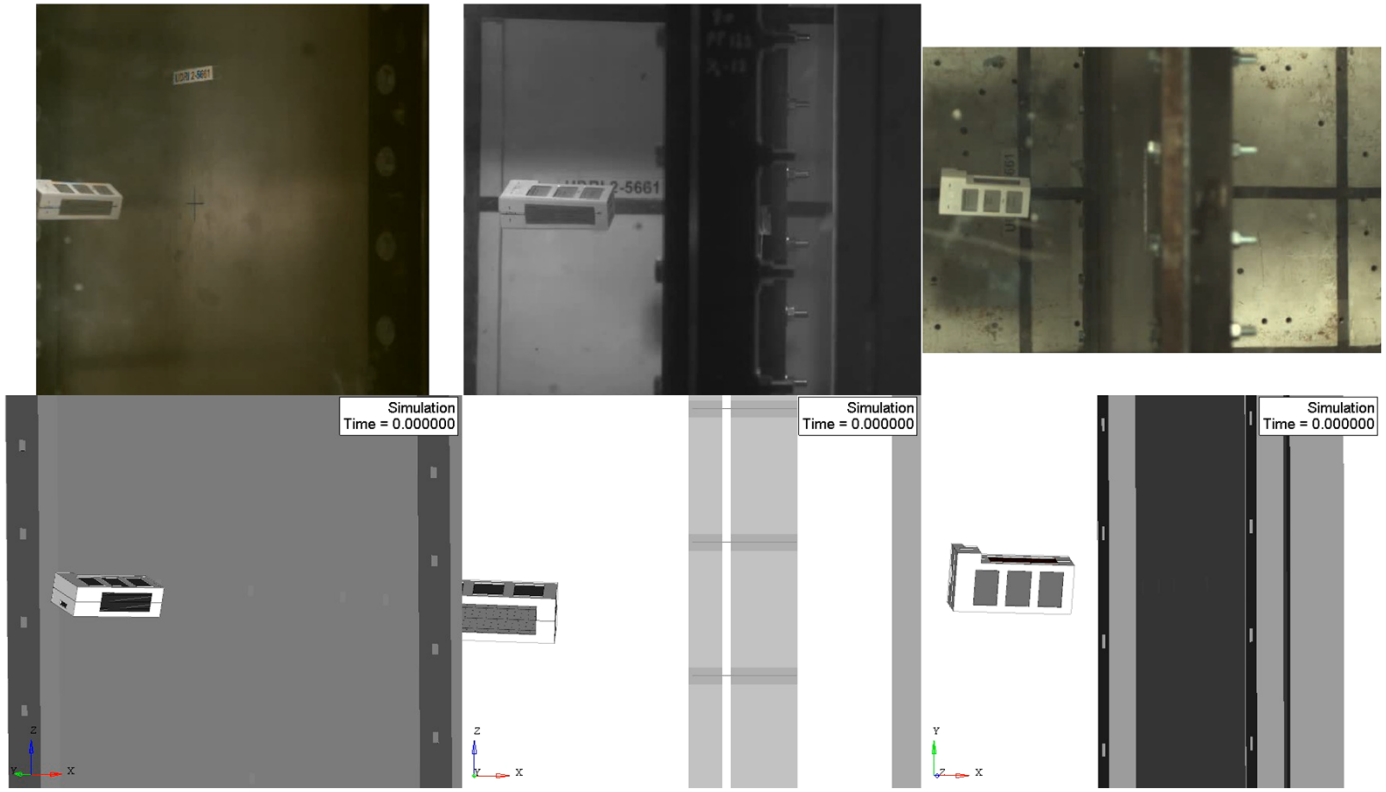
# Method Verification Process – Building Block

## Methods Evaluation Criteria

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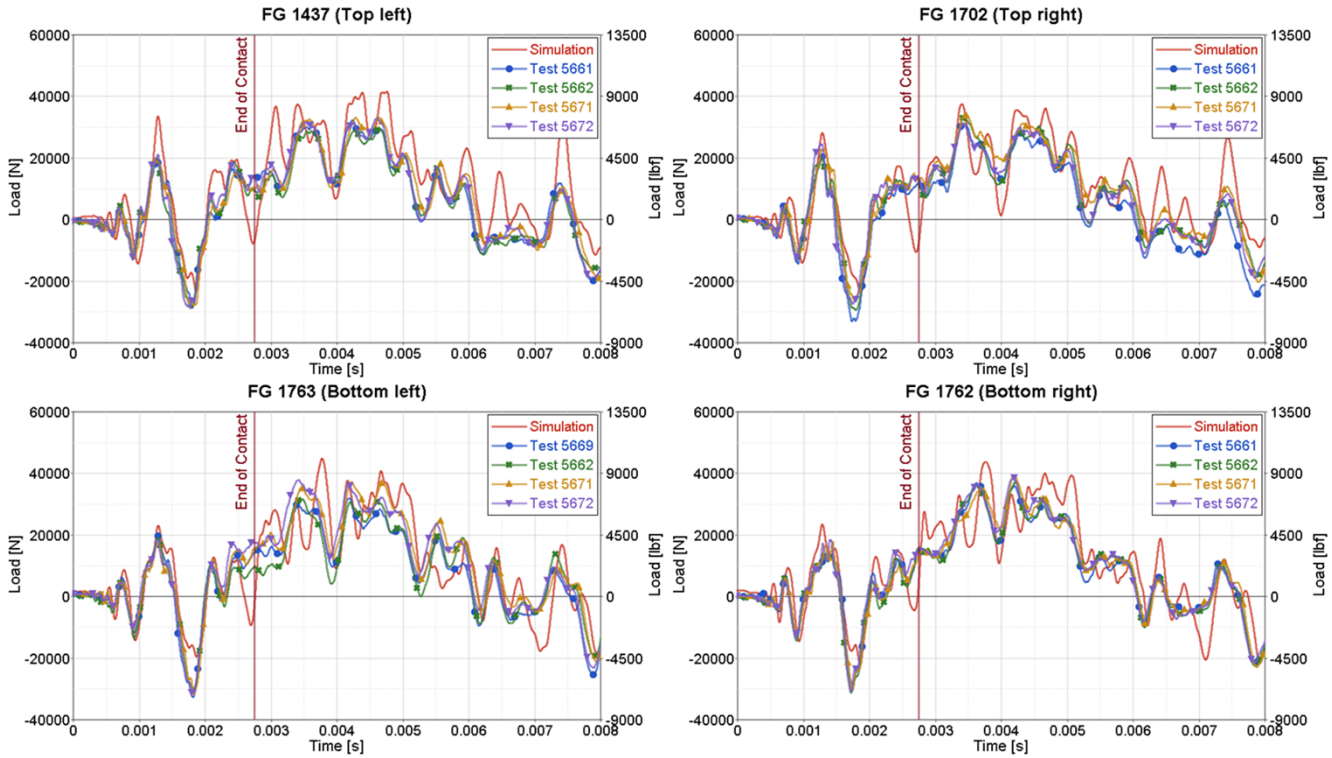
# Method Verification Process – Loads

## Methods Evaluation Criteria





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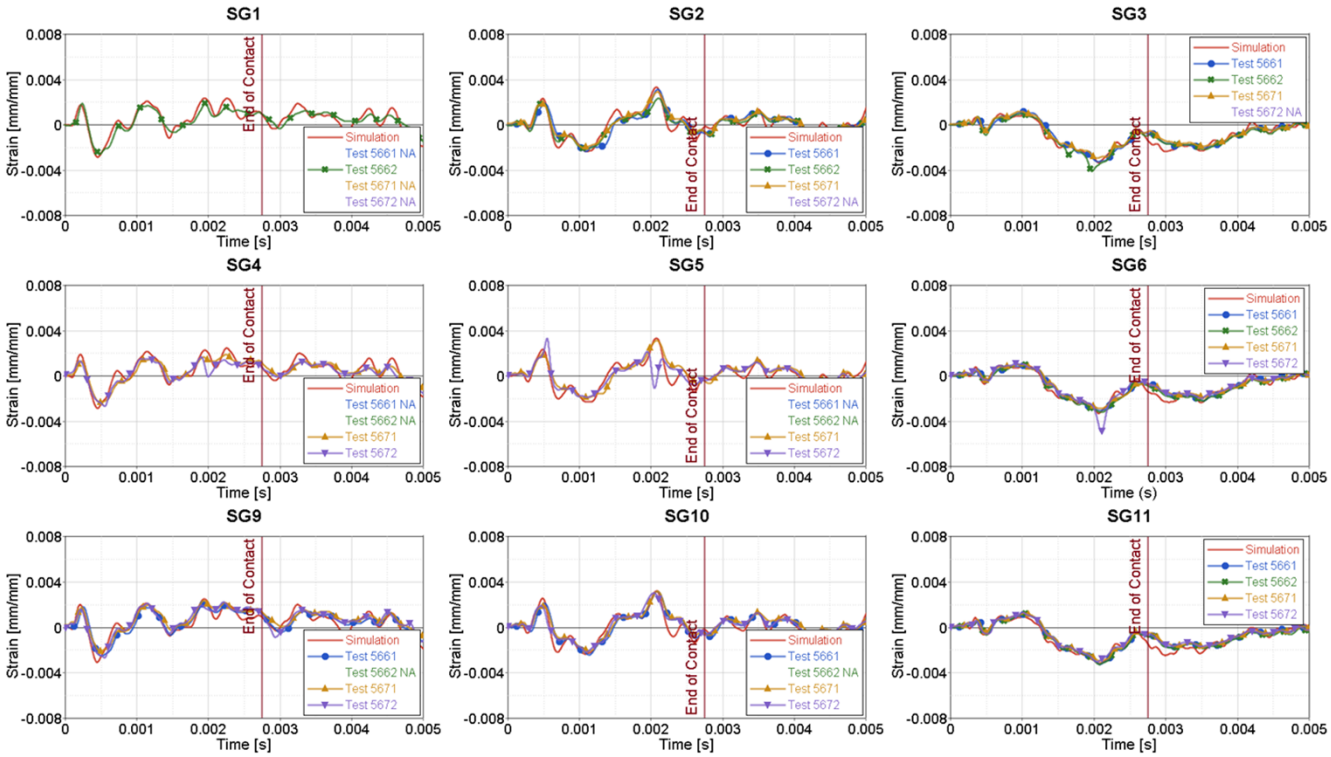


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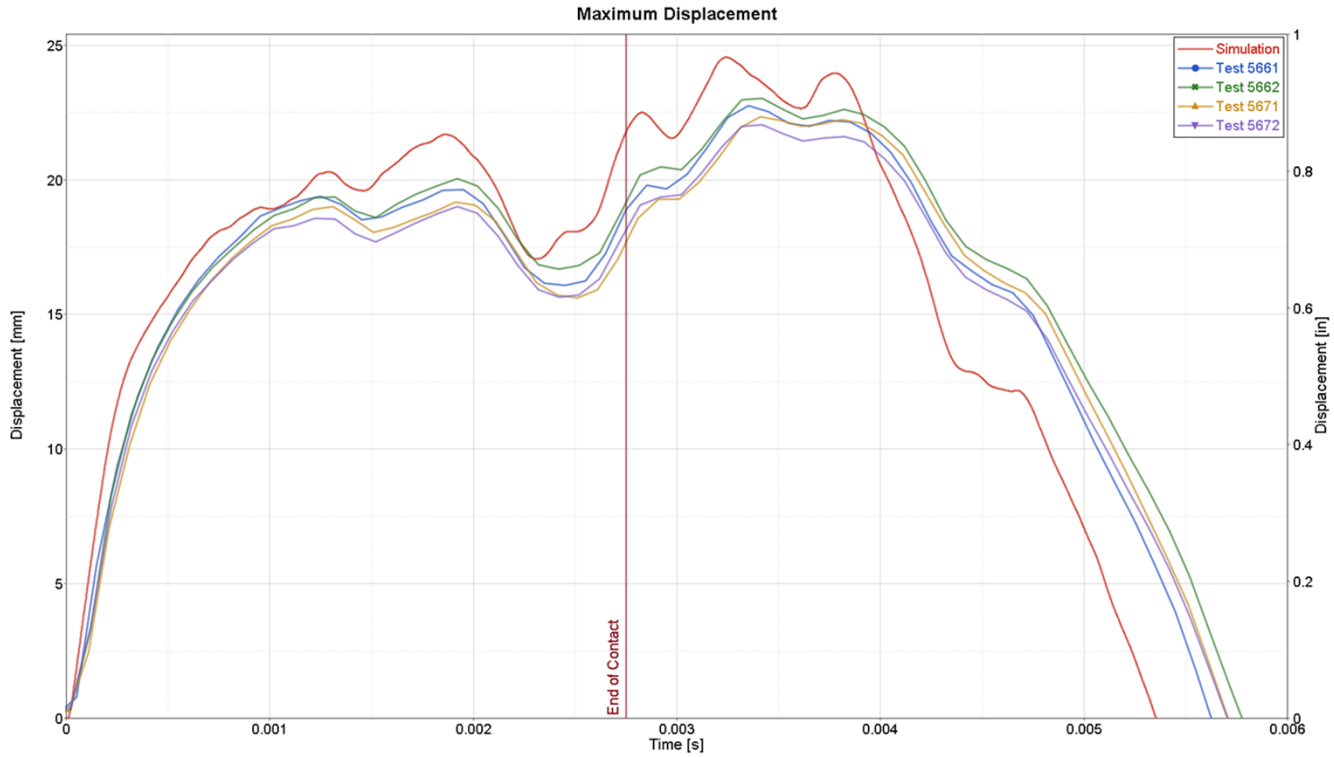


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# Method Verification Process – Building Block

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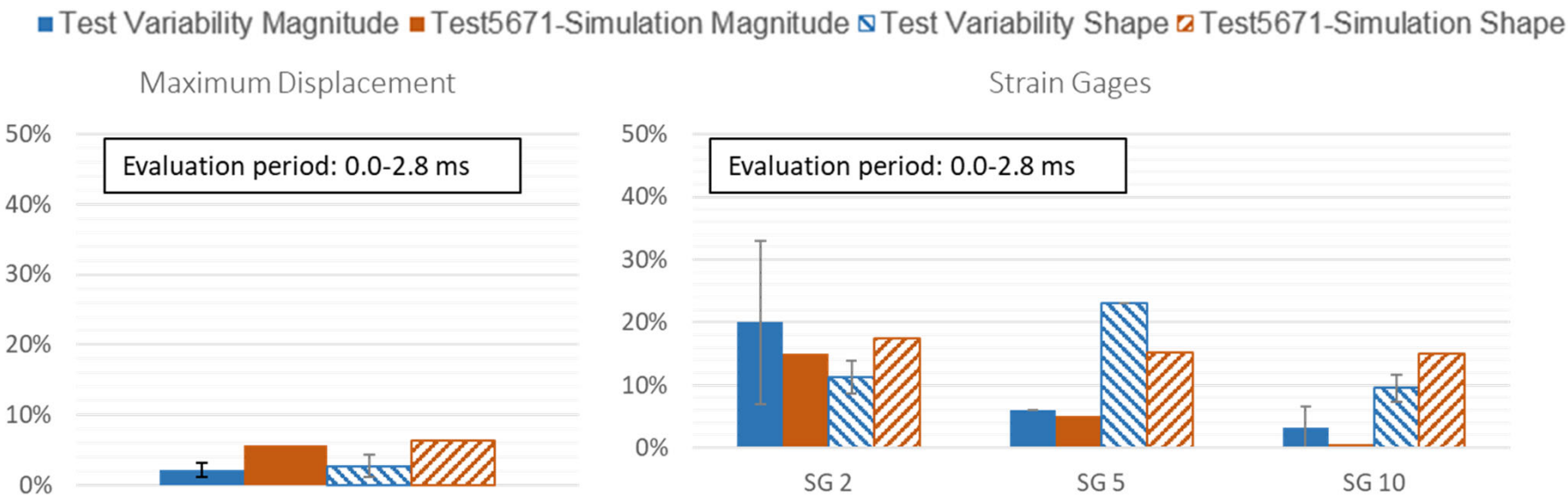


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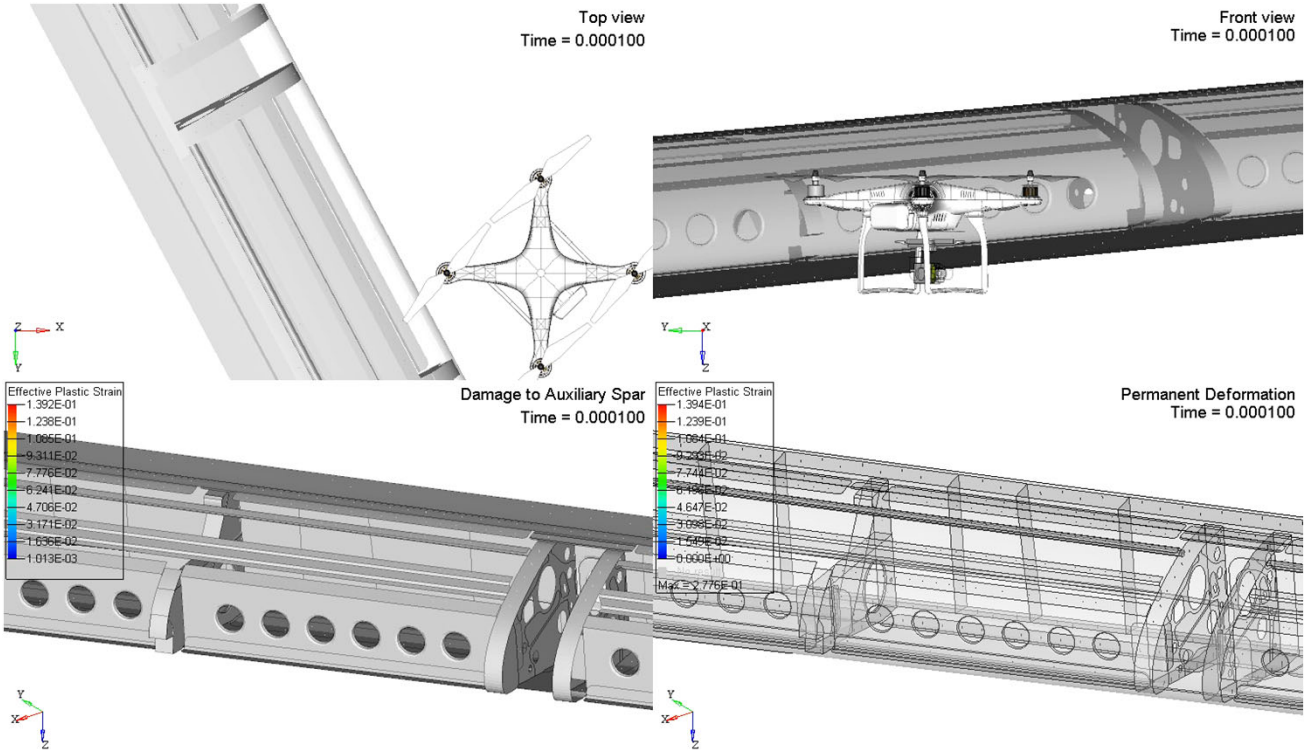


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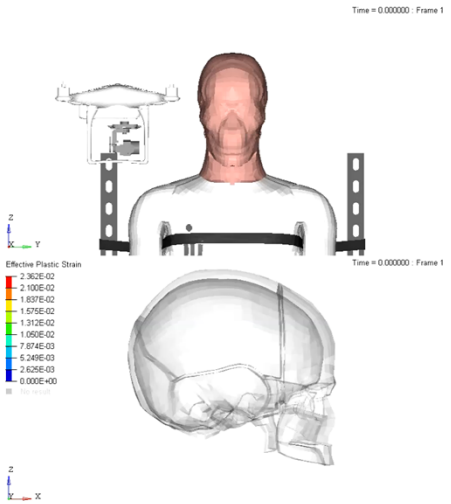
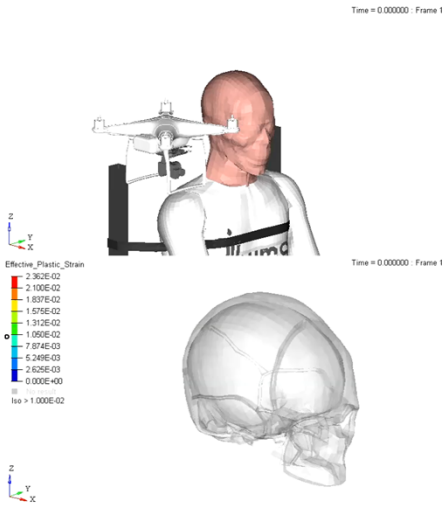
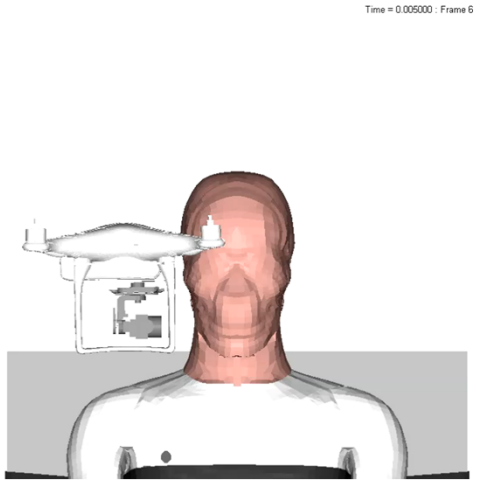
# Can I use the sUAS validated model for other applications?

## Methodology Verification and Validation Examples



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**NIAR Methodology**

# Example Aerospace Seat Dynamic Modeling Applications

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# Evolution of Dynamic Seat Simulation

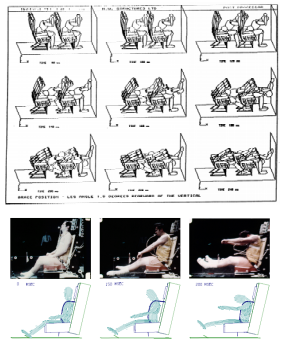
## Dynamic Seat Analysis Methods

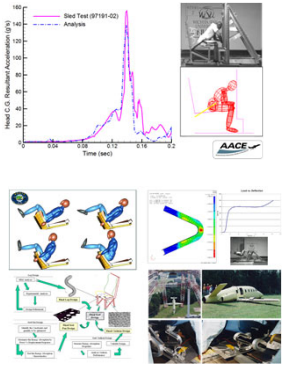
2005-Present

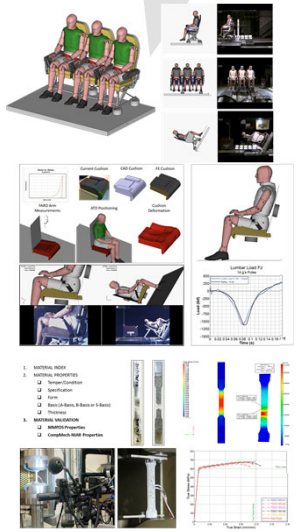
NIAR-FAA (JAMS CBA R&D Projects), NASA, Industry SAE

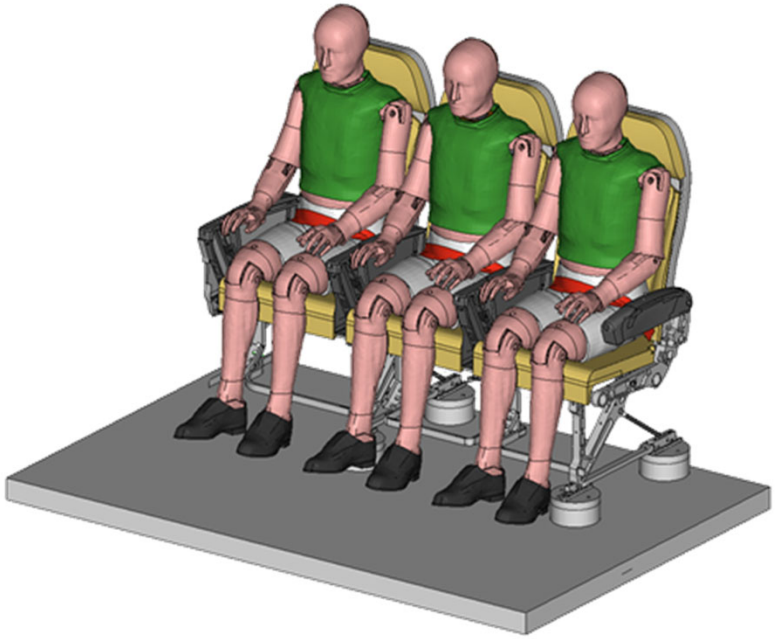
1990 – 2004
NIAR,FAA[CAMI],NASA,INDUSTRY,TNO , AGATE and ADMARC R&D Projects

1975 – 1997 FAA Sponsors the Development of SOMLA and SOMTA. Air Force sponsors CVS [70's] and ATB [80's]









**Further Reading:**


- Soltis S. , "Overview of Usage of Crash Dynamic Analytical Methods in Civil Aircraft Research and Certification Programs " , FAA Cabin Safety Conference, 2007.
- Olivares, G., Lankarani,., "A Virtual Multibody and Finite Element Analysis Environment in the Field of Aerospace Crashworthiness", Chapter in the book, Virtual Nonlinear Multibody Systems, Schiehlen and Valasek (Eds.), NATO Science Series, II, Vol. 103, pp. 187-212, ISBN 1-4020-1339-6, Kluwer Academic Publishers, 2003.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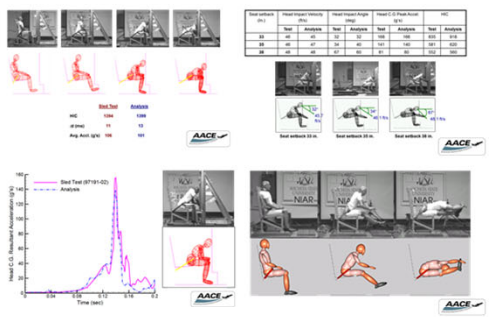
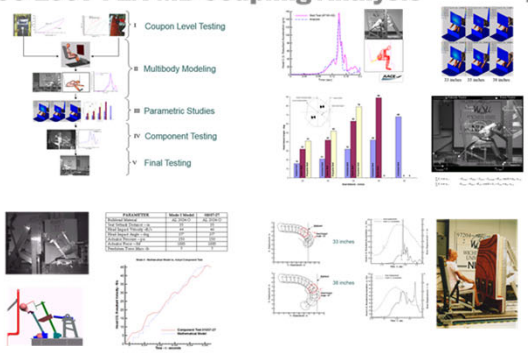
# Evolution of Dynamic Seat Simulation

## Dynamic Seat Analysis Methods

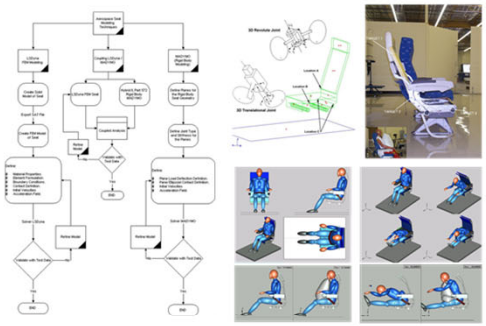
### 1994-1997 Multibody Analysis



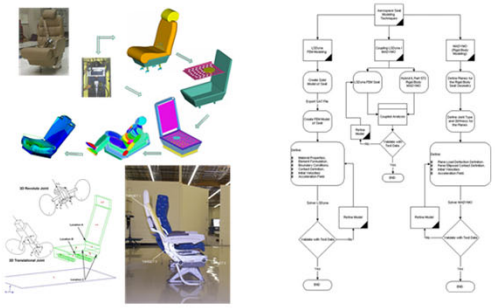
### 1995-1997 FEA-MB Coupling Analysis



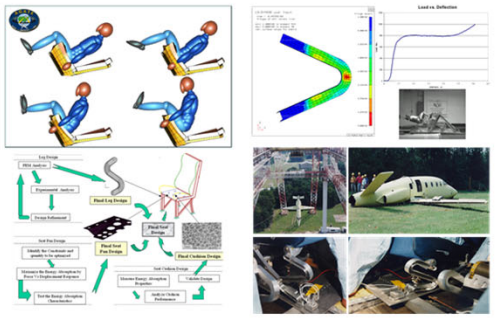

### 1995-1998 FEA-MB Coupling Analysis - Airbags



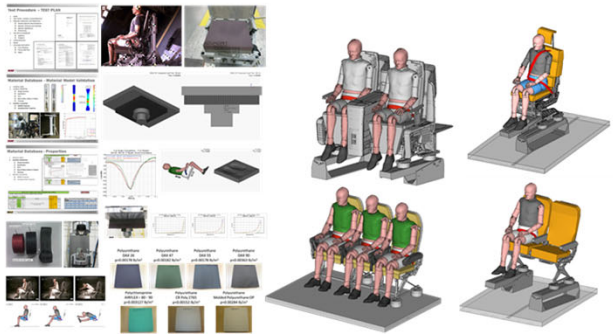
### 1998-2000 FEA-MB Coupling Analysis



### 1998-2001 FEA-MB Coupling Analysis



### 2005-Present FEA Conceptual to Certification



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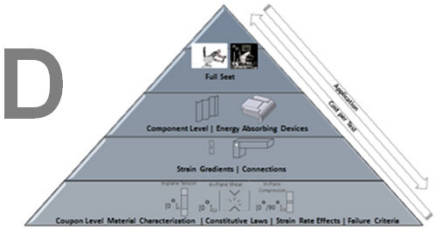
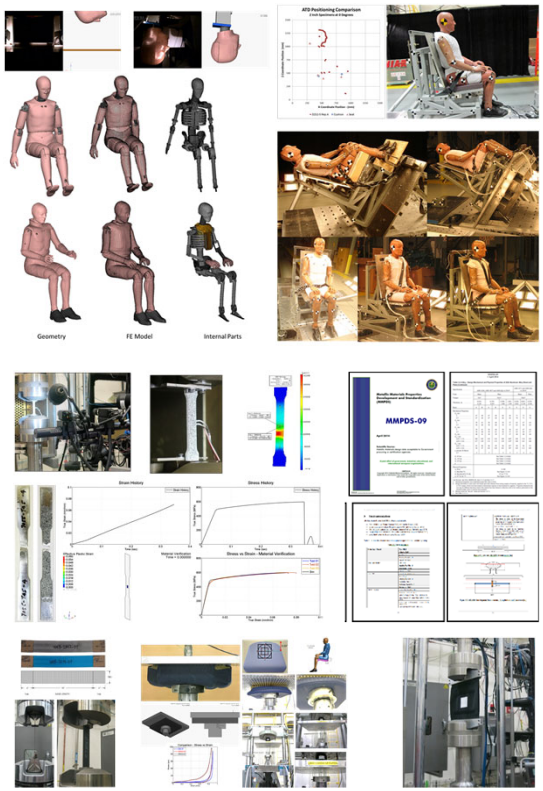
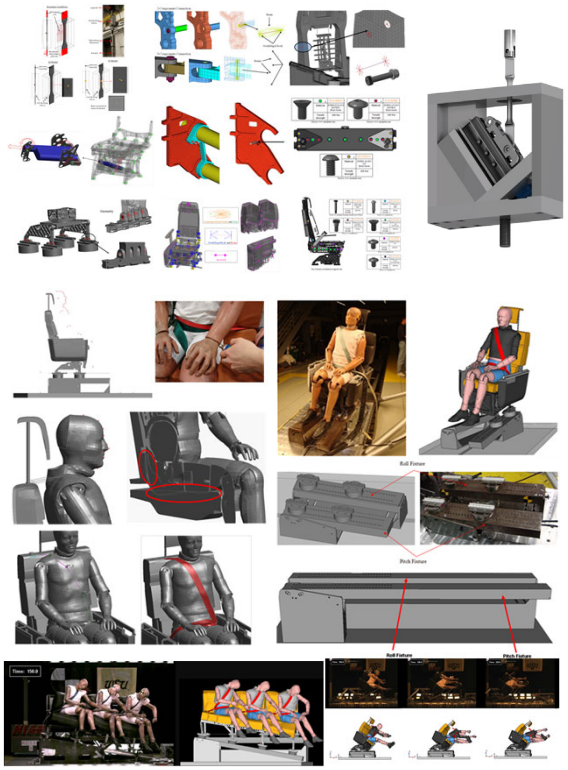
# Methodology Development R&D

## Dynamic Seat Analysis Methods







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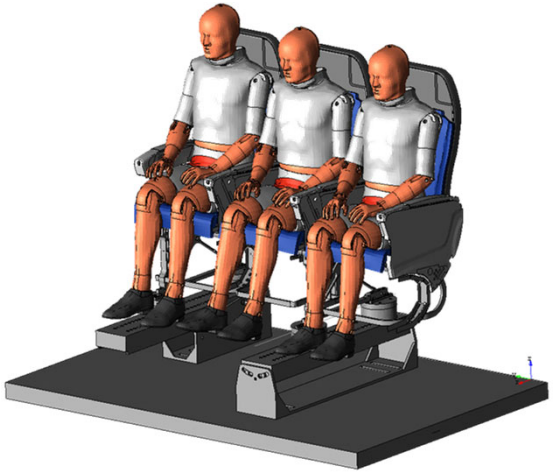
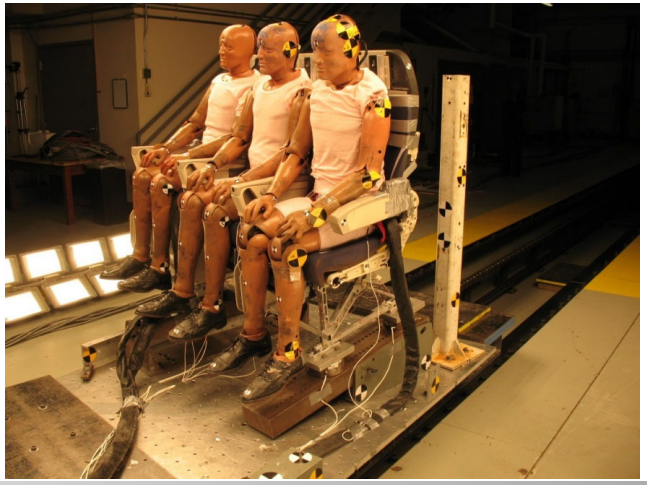
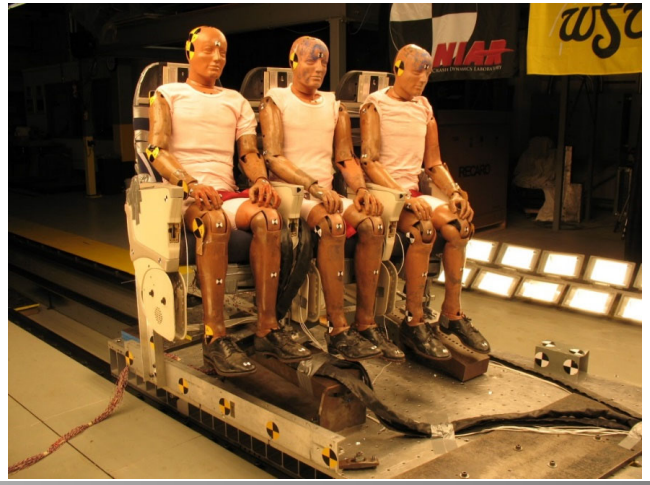
# Methodology V&V Multiple Users

## NIAR-Vimotech Methodology

- Test Condition
  - Three Passengers Economy Aircraft Seat
  - Standard 2-pt Belt
  - FAA 25.562 - Pitch - 10 deg. Down - Roll - 10 deg. CW - Yaw 10 deg. CW
- The methodology was independently followed by two analysts with different experience levels (Novice and 3 years of experience) to evaluate its robustness (Seat Mesh is common to both modelers).
- Objective to study the variability within the process due to the analyst experience level







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# Occupant Kinematics – Multiple Users

## NIAR-Vimotech Methodology

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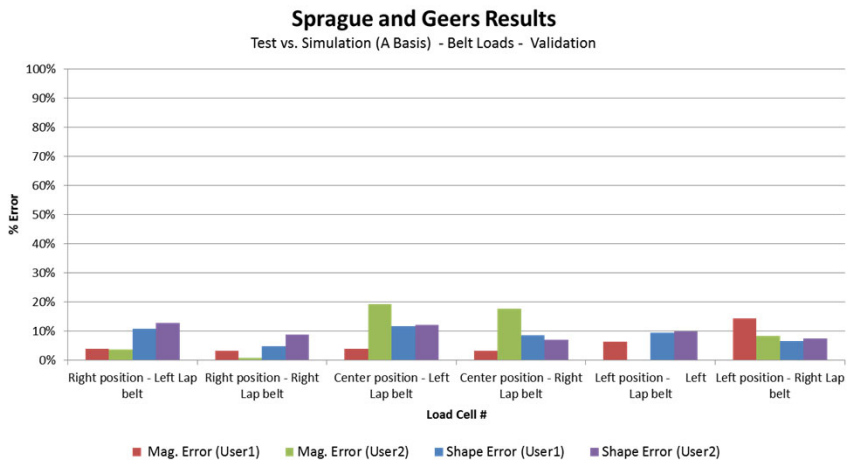
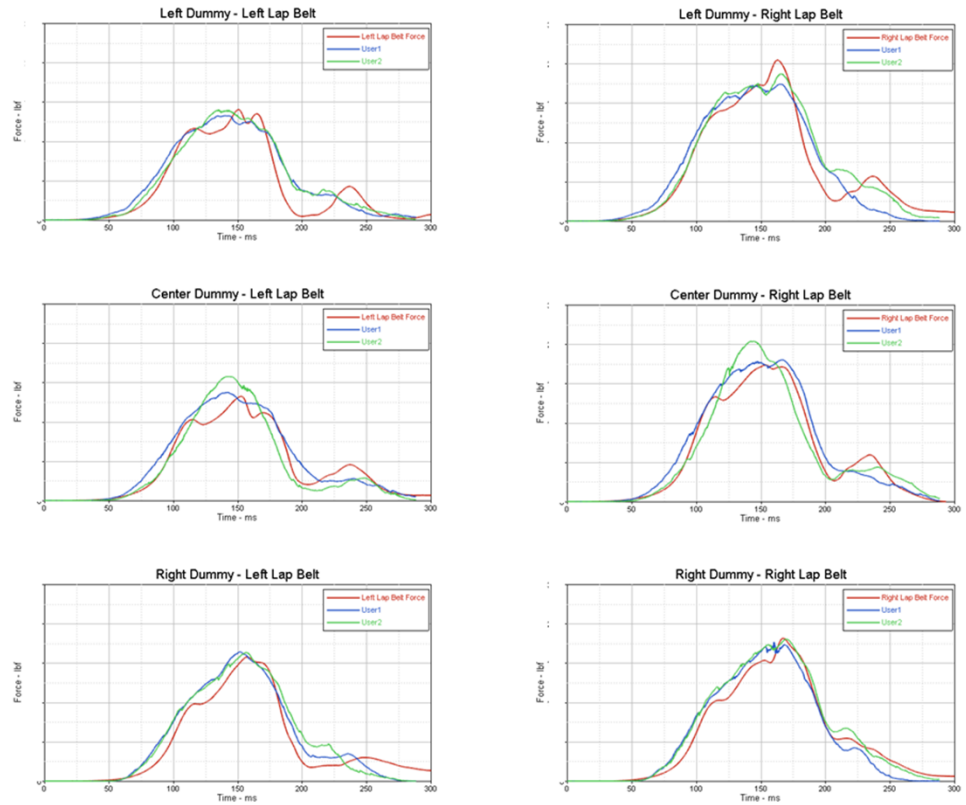
# Belt Loads – Test vs. Simulations

## NIAR-Vimotech Methodology

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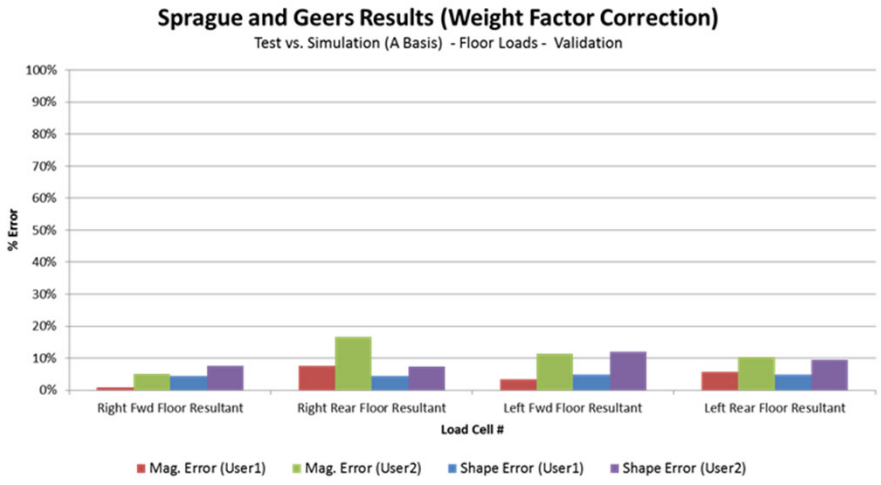
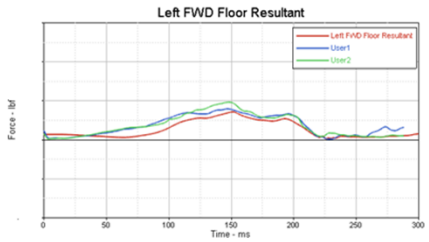
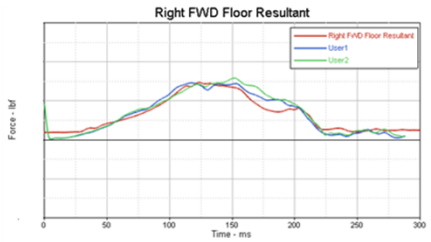
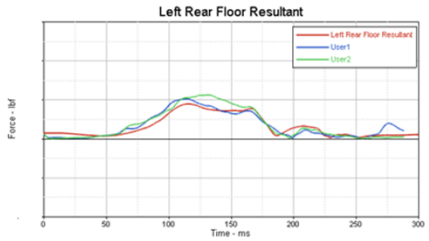
# Floor Loads – Test vs. Simulations

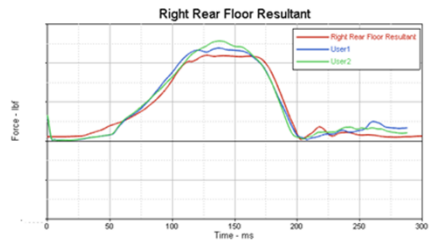
## NIAR-Vimotech Methodology

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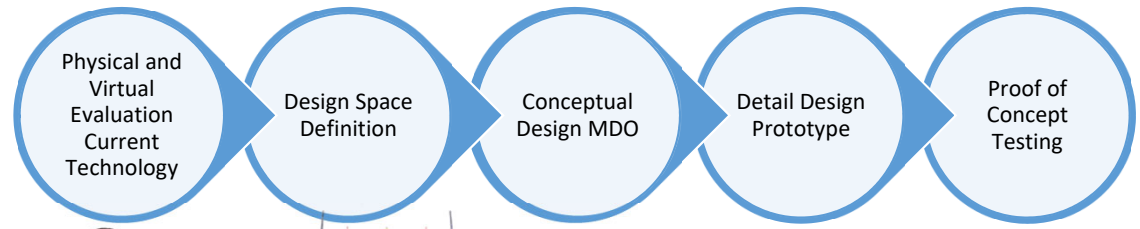
# Dynamic Seat Analysis Methods

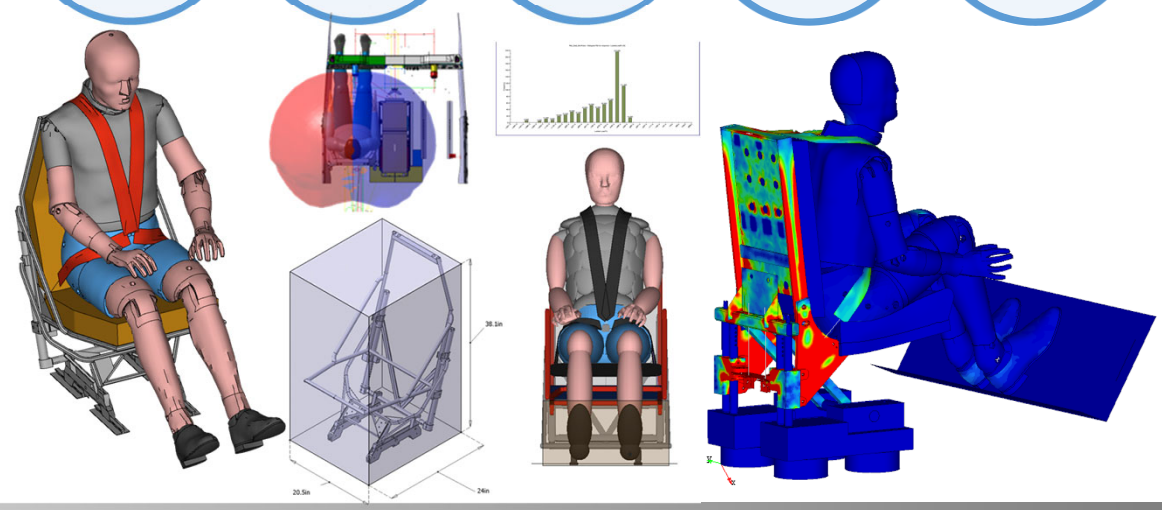
Example: Virtual Dynamic Seat Design

# Project Scope

## High G Seat Design

- Since the stall speed of the aircraft (77 knots) is higher than 61 knots a feasibility study is required to define and identify aircraft seating technologies capable of meeting additional FAR 23.562 dynamic test requirements:
  - For conventional 14 CFR 23.562 pilot seats the stall velocity is 61 knots and the maximum deceleration level experience by pilots during emergency landing conditions is 19 g's.
  - For the pilot seat ("First row") for a stall speed of 77 knots the g level should be 30.27 g's [ =19*(77/61)^2] ≈ 31 g's

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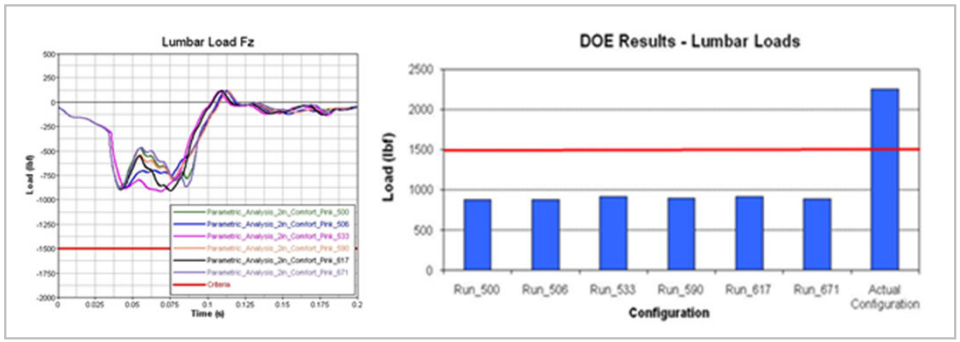
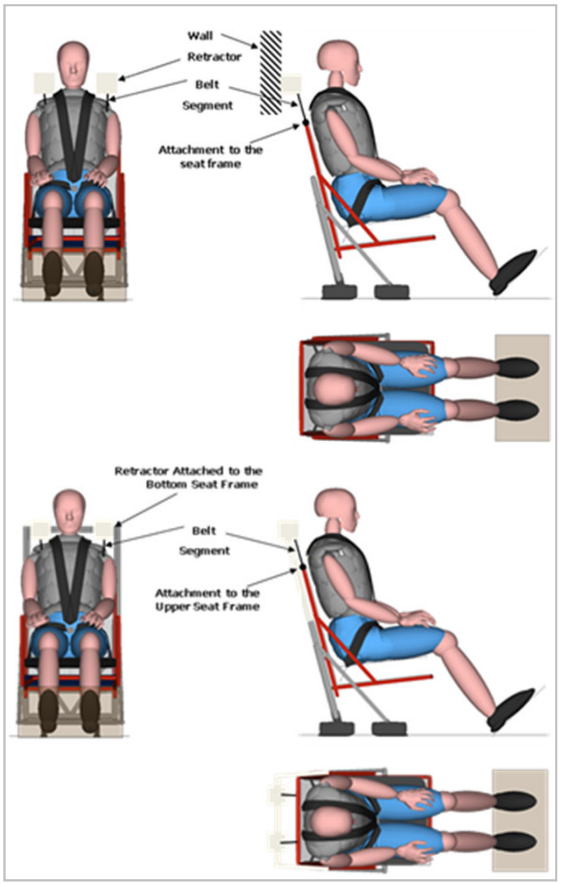
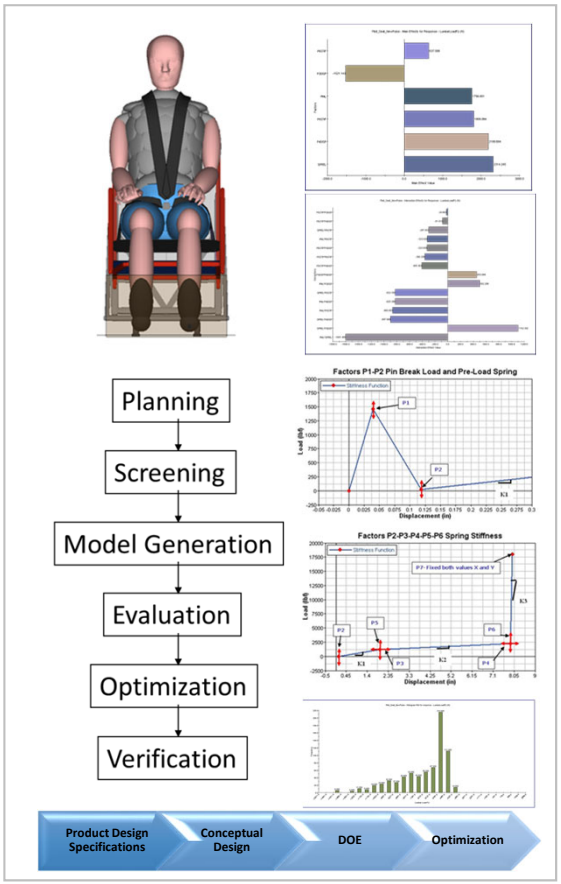
# Conceptual Design MDO

## High G Seat Design

- Over 5000 Simulations Evaluated
- Parameters:
  - Seat Architecture
  - Energy Absorber
  - Seat Cushion
  - Restraint Configuration
- Objective Function:
  - Minimize Lumbar Load





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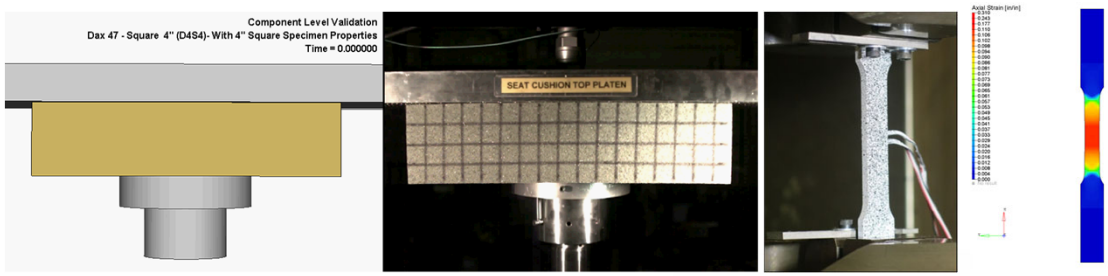
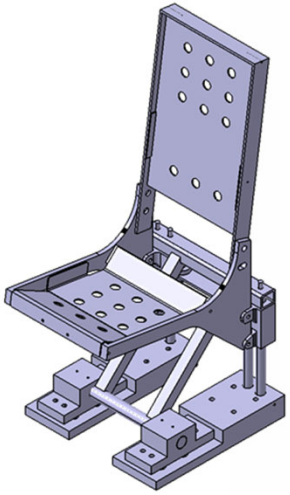
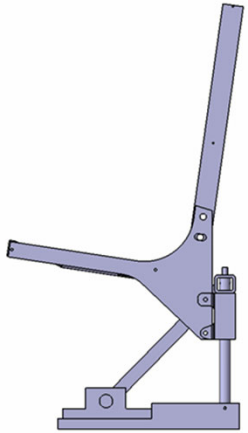
# Detail Design

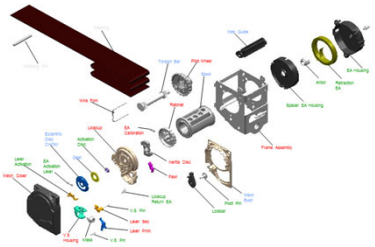
## High G Seat Design

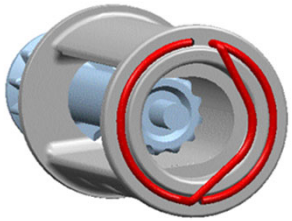
- Detail Design CAD
- Virtual Engineering Building Block Approach: Coupon and Component Level Testing

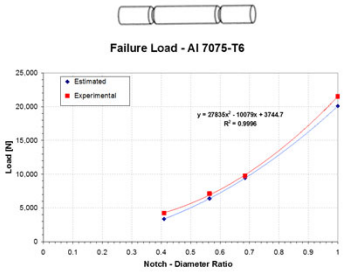


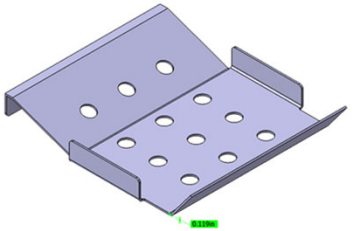


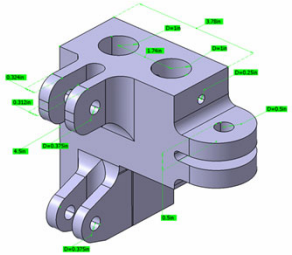








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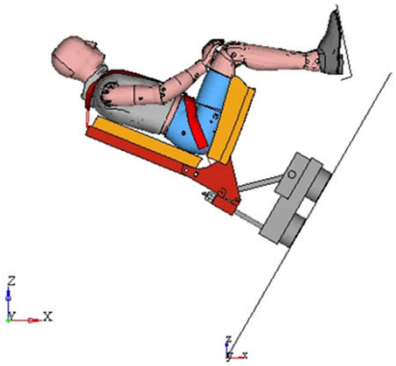
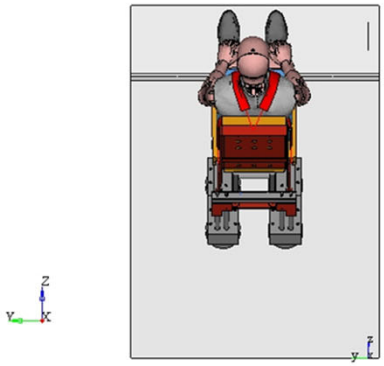
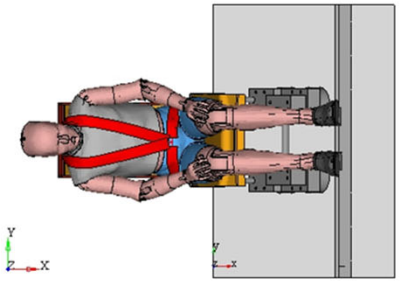
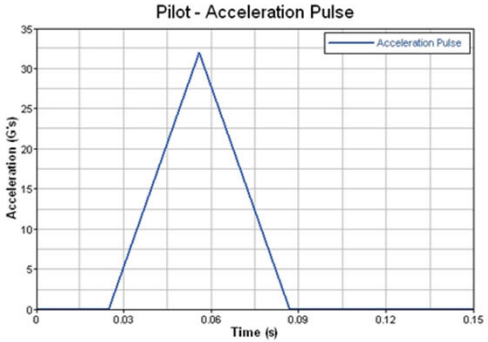
# Detail Design – Virtual System Prediction

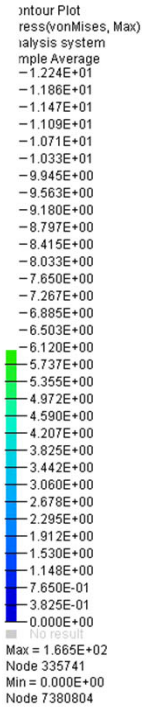
## High G Seat Design

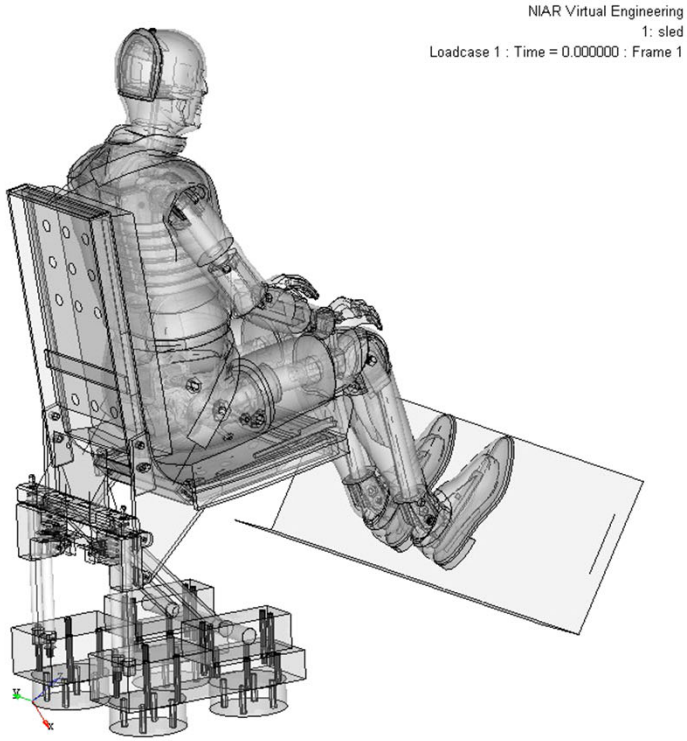






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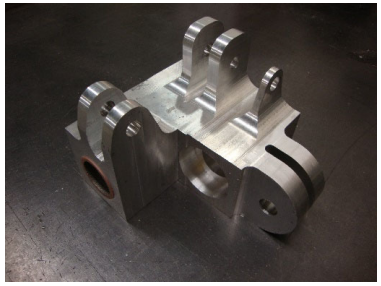
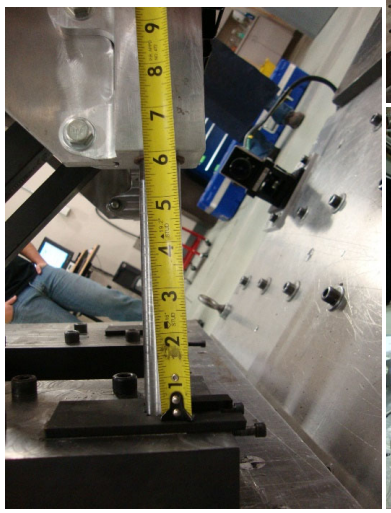
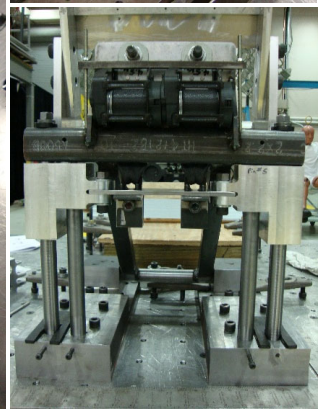
# Prototype Manufacturing

## High G Seat Design







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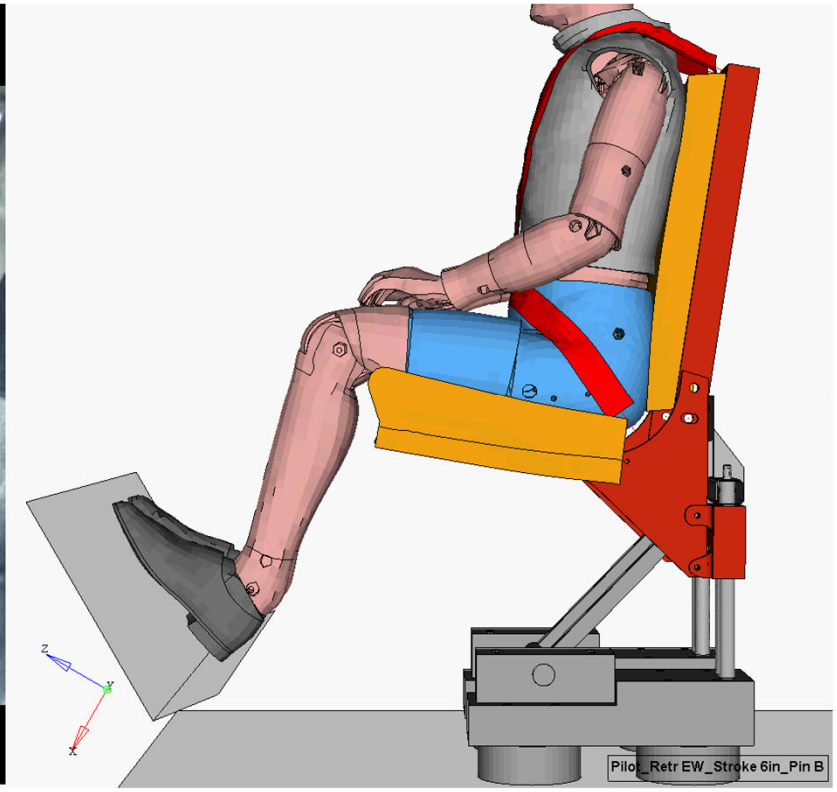
# Virtual Development Prediction

## High G Seat Design

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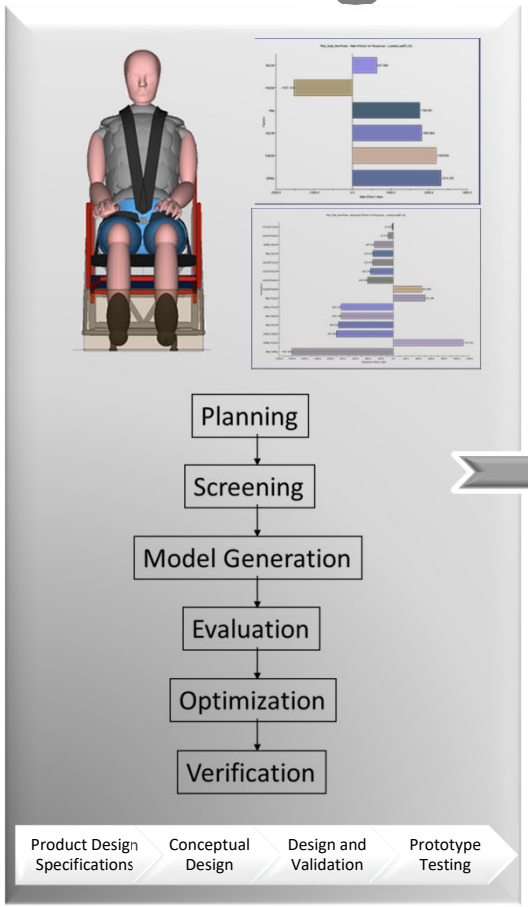
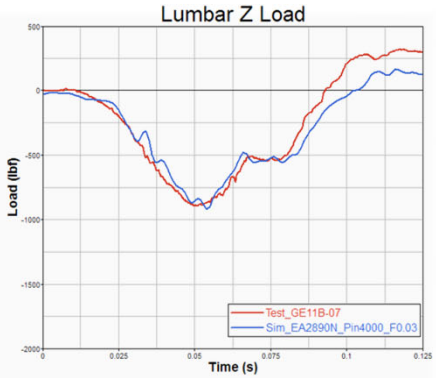
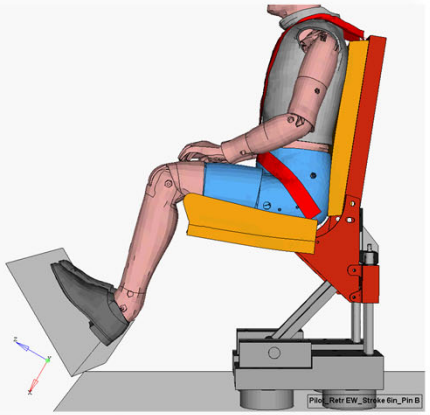
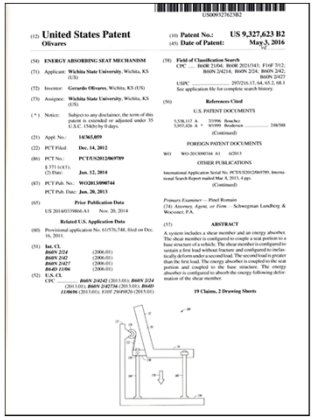
# Virtual Engineering Process




- 6 Month Virtual Development
- Concept to Proof Test
- Optimization Methods to cover 5th through 95th Percentile Occupants
- Over 5000 Simulations
- New EA Technology Development - US Patent 9,327,623
- 1st Prototype test meets the Design Requirements
- Lumbar Load Reduction from 2300 lbf down to 895 lbf









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# Conclusions

## Aerospace Impact Dynamics Simulation

- The advances in simulation methods allow for the reduction or elimination of full scale tests. On the other hand an increase in Coupon and Component level tests programs are required to support predictable full scale simulations.
- For simulation to be predictable at the full scale level it needs to:
  - V&V Building Block Methodology
    - Standardized coupon and component level testing protocols
    - Standardized experimental to computational data transfer protocols
    - Standardized V&V Material Databases
  - Drive the design from conceptual design – Robust Design
  - Robust methods to cover the range of experience within the workforce available
- Industry is placing too much emphasis on using analytical models to reduce (or eliminate) the number of certification tests. The real value of simulation is to drive the design and minimize development testing\time\cost.


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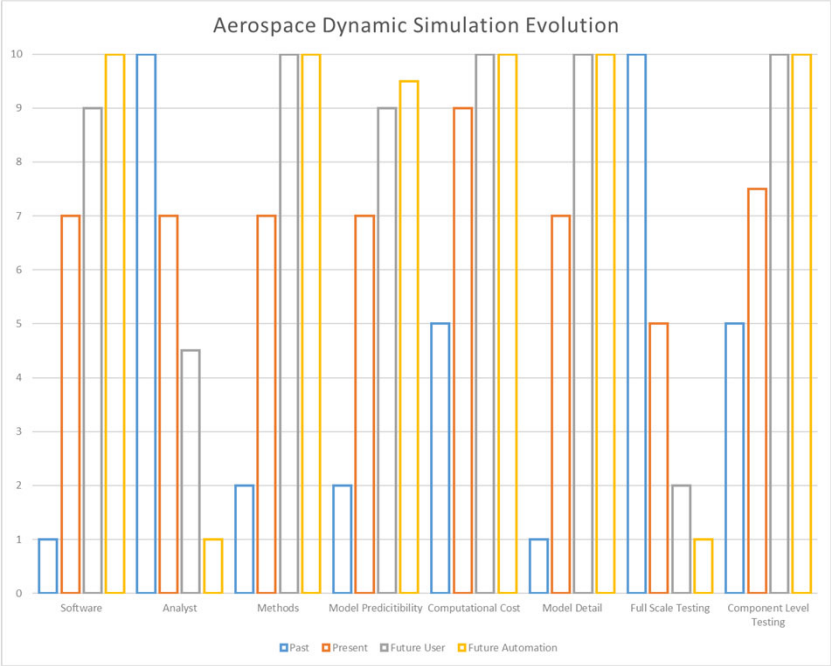
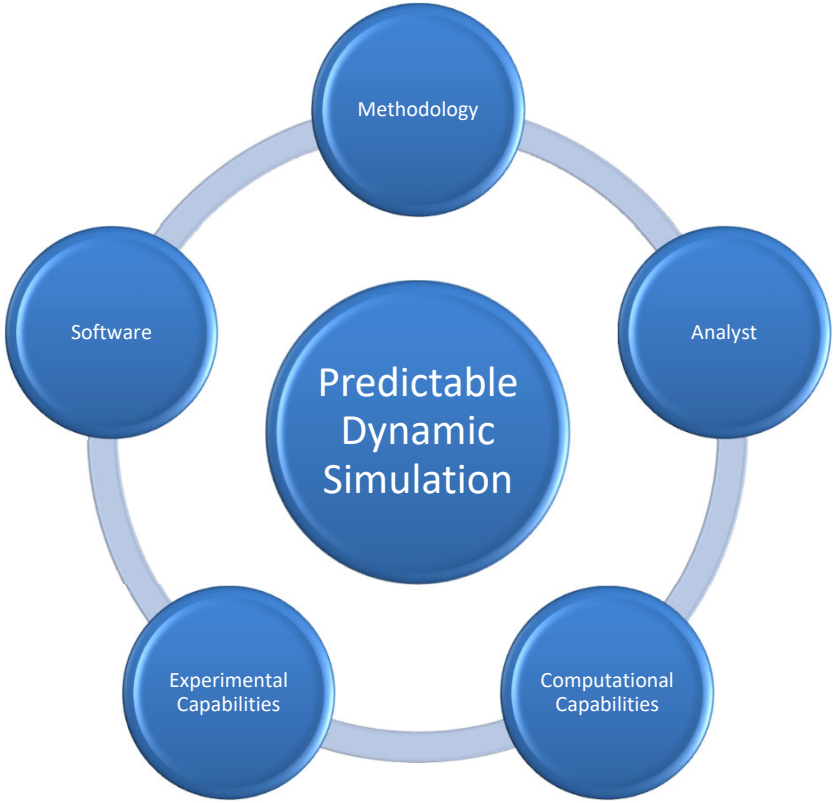
# Can we have predictable simulations today?

## NIAR Virtual Engineering and Testing Group

Yes if….

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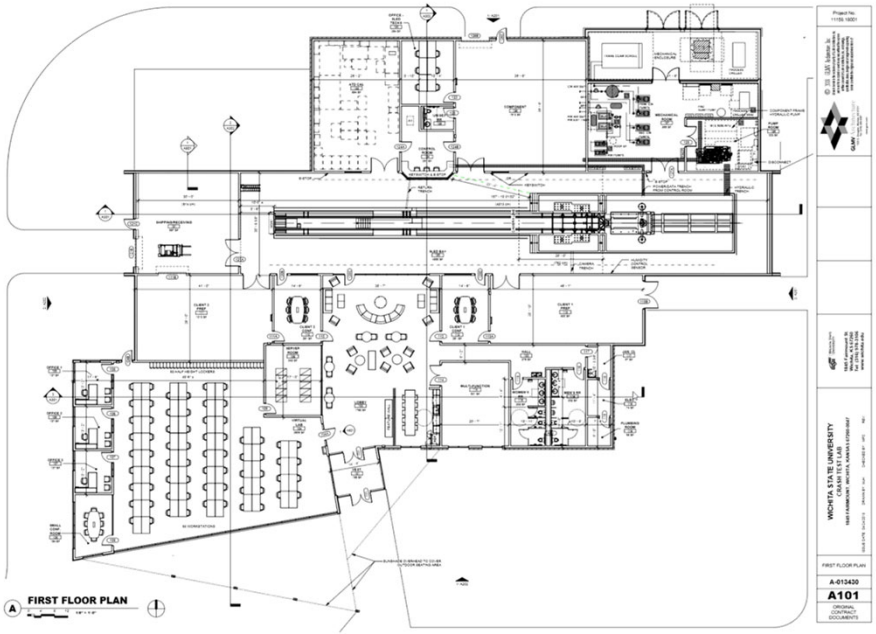
# Advanced Virtual Engineering and Testing Laboratories (AVET) – October 2019

## NIAR 4.0 and vNIAR 5.0

- Coupon to Full Scale – Virtual and Physical Testing



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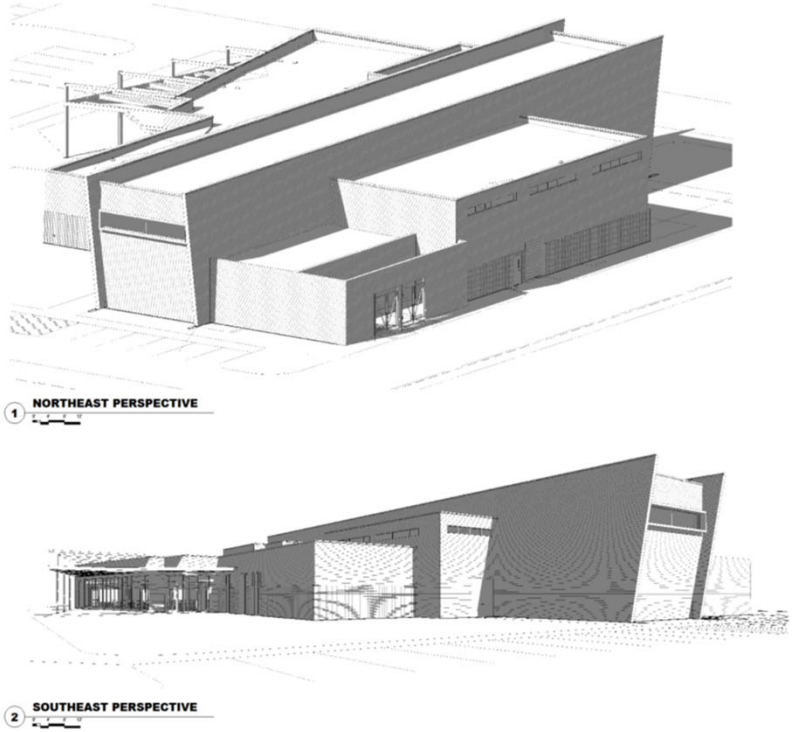
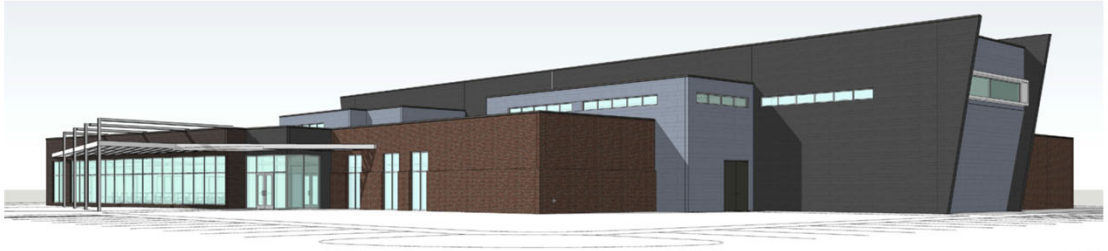
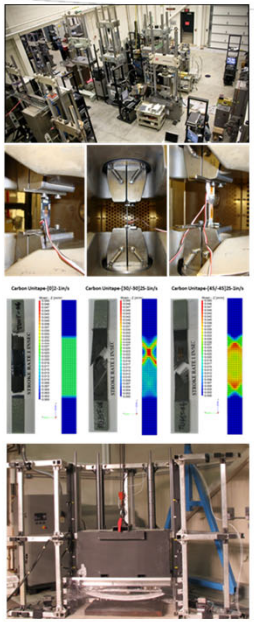
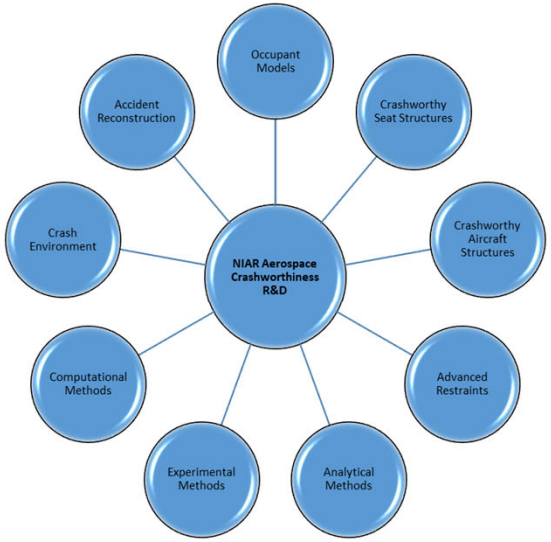
# NIAR AVET Laboratories – October 2019

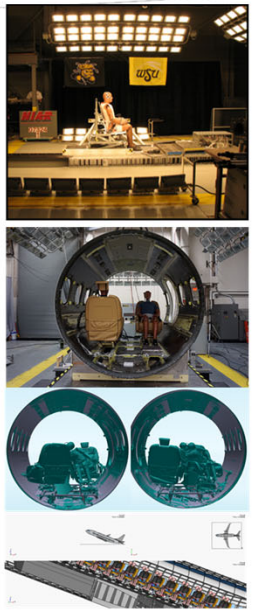
## NIAR 4.0 and vNIAR 5.0





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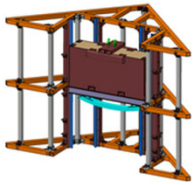
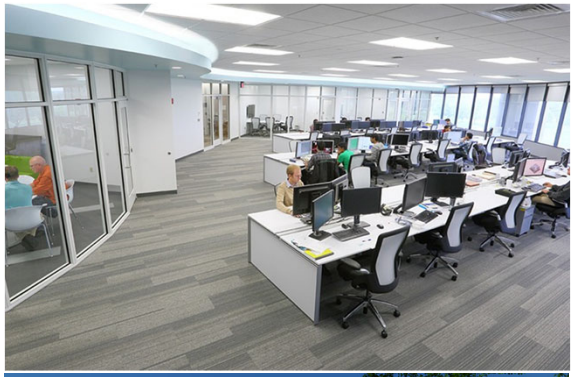
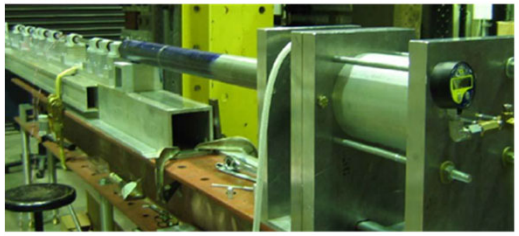
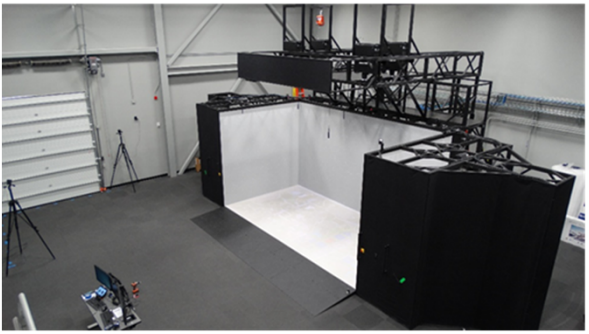
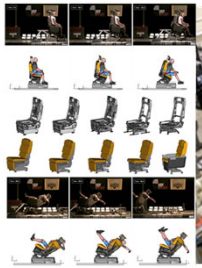
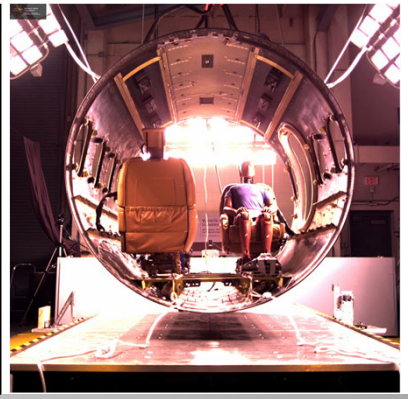
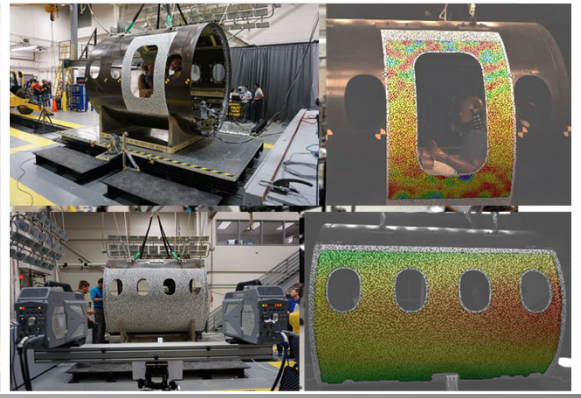
# AVET LABORATORIES



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