Experimental Methods in Crash and Impact for Simulation Validation

FAA Workshop on Use of Dynamic Analysis Methods in Aircraft Certification

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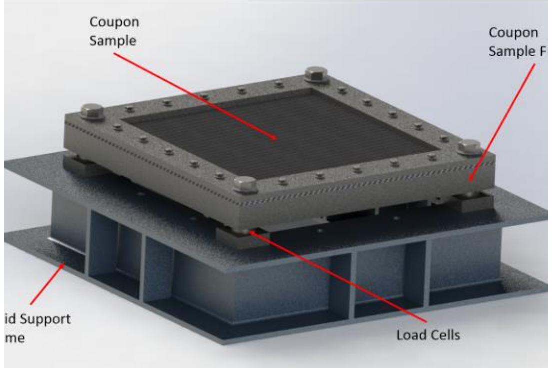
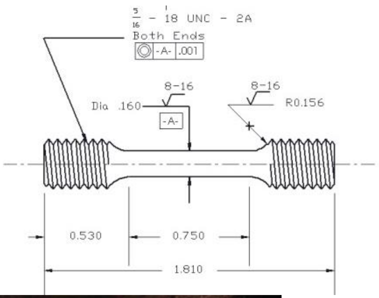


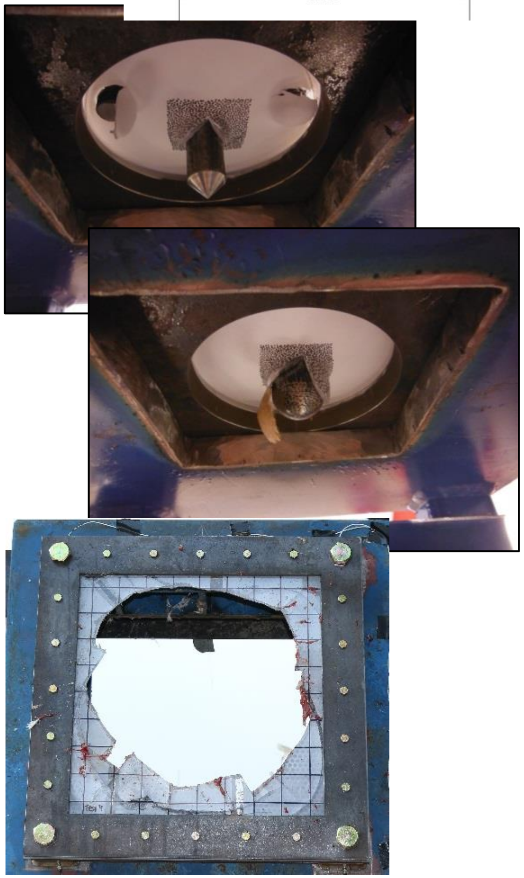
Intro: Experiments for V&V of Certification by Analysis

- Full-scale crash and impact experiments are expensive and time-consuming: we want to use a set of full-scale test data to verify and validate our dynamic simulation analyses so that we can do fewer tests and rely on our analysis in the future – certification by analysis
- Critical that experimentalists and analysts are coupled: need to understand each others requirements and methods so as to achieve goals – simulation validation

Types of Experiments for V&V

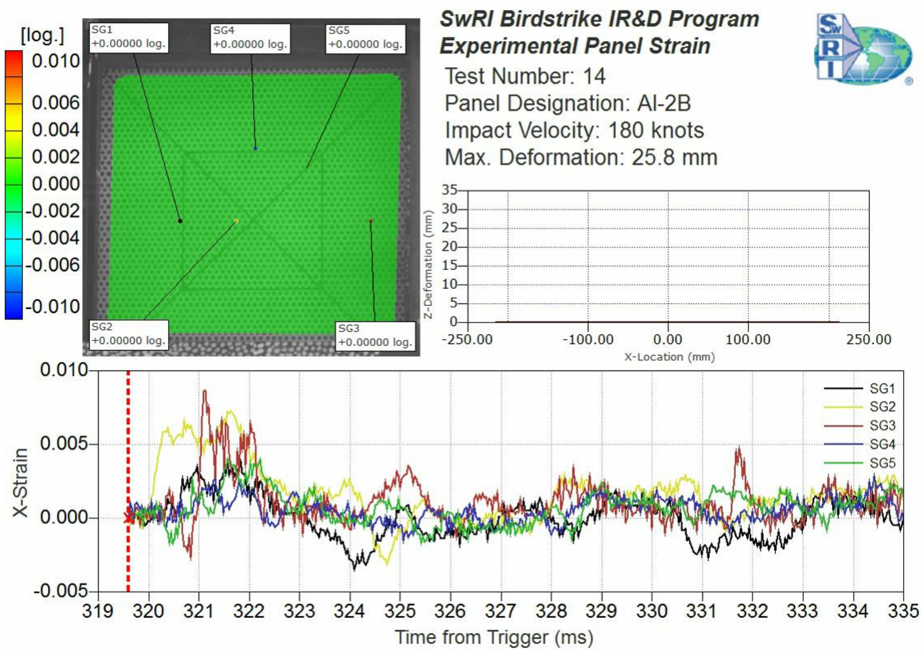


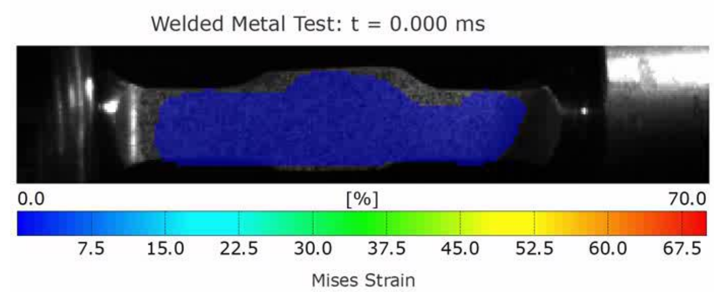
- Laboratory scale to full scale; single effects to multiple full-scale effects experiments
- Similar data collection techniques applied at all scales: but the data we gather may be used differently
  - Lab-scale experiments (UTM, Split-Hopkinson Bar, and Drop-Tower) are used to determine material constants used in models (data inputs) and for insights/data on single effect response (validation of decoupled software models)
  - Full-scale single-material panel tests used to validate material dynamic response models, simulating the test
  - Full-scale component tests used to validate systems of models or fully coupled response models, simulating the test
- Focus of this presentation is on full-scale, single-material tests, but the methods used are also relevant for system-level testing

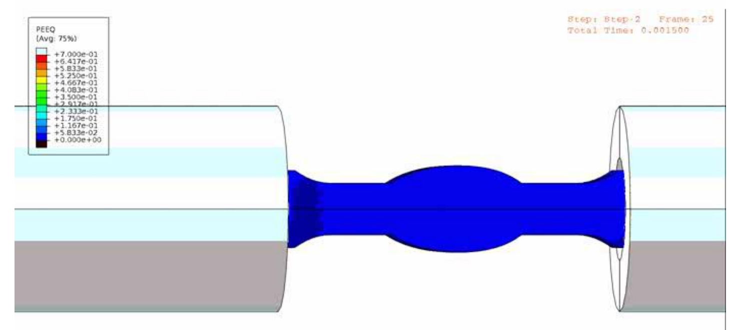


What Data Do We Want to Capture for V&V?

- Repeat experiments – necessary to determine variability of data in experiments for the same apparent initial/boundary conditions - to more fully quantify experiment uncertainty
- Dynamic analysis simulates the stress-strain response of the materials subjected to impact: so strain data from experiments is critical
- The strain response is coupled to the deformation of the impacted part/structure: measurement of deformation is also useful – DIC
- Projectile and target characteristic quantities such as failure/fracture of impactor and target (location and time of failure, type of failure, pattern of failure) and projectile deformation shape as a function of time
- Accurately measure impact velocity and impact location as these will provide inputs to the simulation to insure a proper replication of the validation test

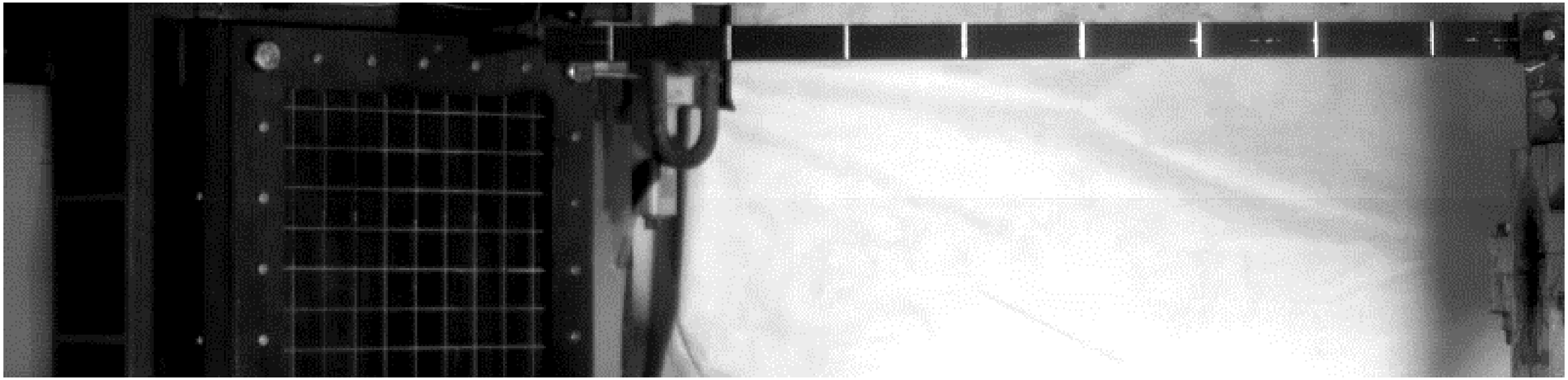






Full-Scale Bird Strike Experiments

- Dynamic simulations of material response to a full-size bird strike must be ultimately validated
- Code verification is assumed in this presentation to be completed (by vendor or code developer, confirmed by user through relevant benchmark simulations)
- Solution verification is done through a grid refinement or convergence study – GCI (Grid Convergence Index) – establishes numerical uncertainty and addresses input uncertainty – (ASME V&V 20-2009 Standard)
- The material models in the simulation require input parameters, these are defined in this methodology based on lab-scale experiments accounting for input parameter uncertainties
- We do a set of solution verification simulations and a simulation validation study using some data as inputs and other data for validation from these lab-scale or single effects experiments
- Scale up to System-level Response – the modeling of the actual bird and aero structure fixture introduce new variables and scales of dynamic response – methods for roll-up of single effects to full-scale processes is an active area of research, as well as methods for accessing numerical uncertainty and propagation of uncertainty and error from single effects simulations to full-scale simulations – the simulation hierarchy
- Current approach: measure the dynamic response of validated single effects models when coupled for full-scale simulations - do coupled models still resolve response within experimental & numerical uncertainties?

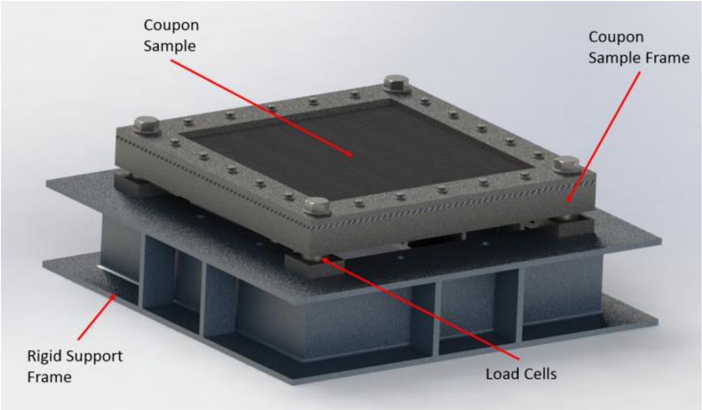


SwRI IR Project: Materials Response from Actual Bird Impact

- Example of a specific coupled simulation and testing program used for validation of material models used in full-scale simulations
- The experimental techniques used here are not unique to this example: they can be used at different facilities and at different scales to collect similar data for other models
- SwRI executed a large internal-research program with 16 impacts on flat plates of 3 different materials to provide data for simulation validation

SwRI IR Project: Materials Response from Actual Bird Impact

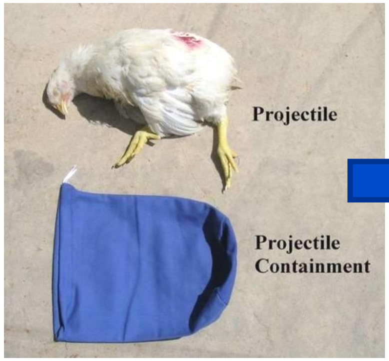
- 16 fully-instrumented bird strike tests conducted at SwRI to provide data for simulation validation
- Three panel materials
  - Composite (TORAY 48-ply P707AG-15)
  - Transparent (0.5 in (12.7mm) Makrolon PC)
  - Aluminum (0.25 in (6.35mm) 2024-T3)
- Steel "window frame" at 45° obliquity
- 2.2 and 4 lb (1.8 kg) birds, 170-310 knots (90 – 160 m/s)
- Highly Instrumented
  - 4 PCB load cells at frame corners
  - 7 strain gauges on rear surface
  - ARAMIS high-speed 3D DIC system for global displacement and strain measurements
- Simulation and test geometry coordinated

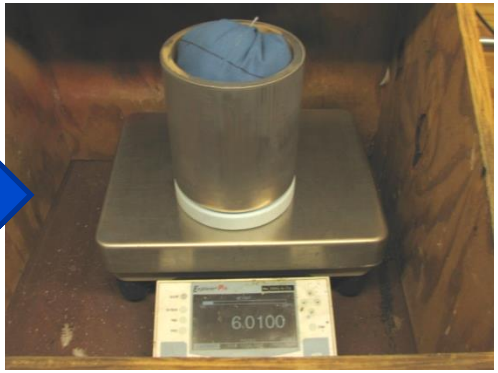


Experimental Setup: Bird Gun

- Large compressed gas gun system (LCGG)
- Pressure vessel rated to 275 psi
- Electronic control to remotely fill and operate
- 35 ft long, 6 in diameter one-piece barrel
- Laser alignment
- 2.2 and 4.0 lb birds for ASTM F330-10 testing
- Custom sabot design for high repeatability
- Recessed Pit Area for high shot lines (~19 ft.)
- Also have smaller gas guns used for hail/ice impact and gelatin ball impacts

Clearly, these are large and expensive tests: hence the drive for validated dynamic analyses – certification by analysis



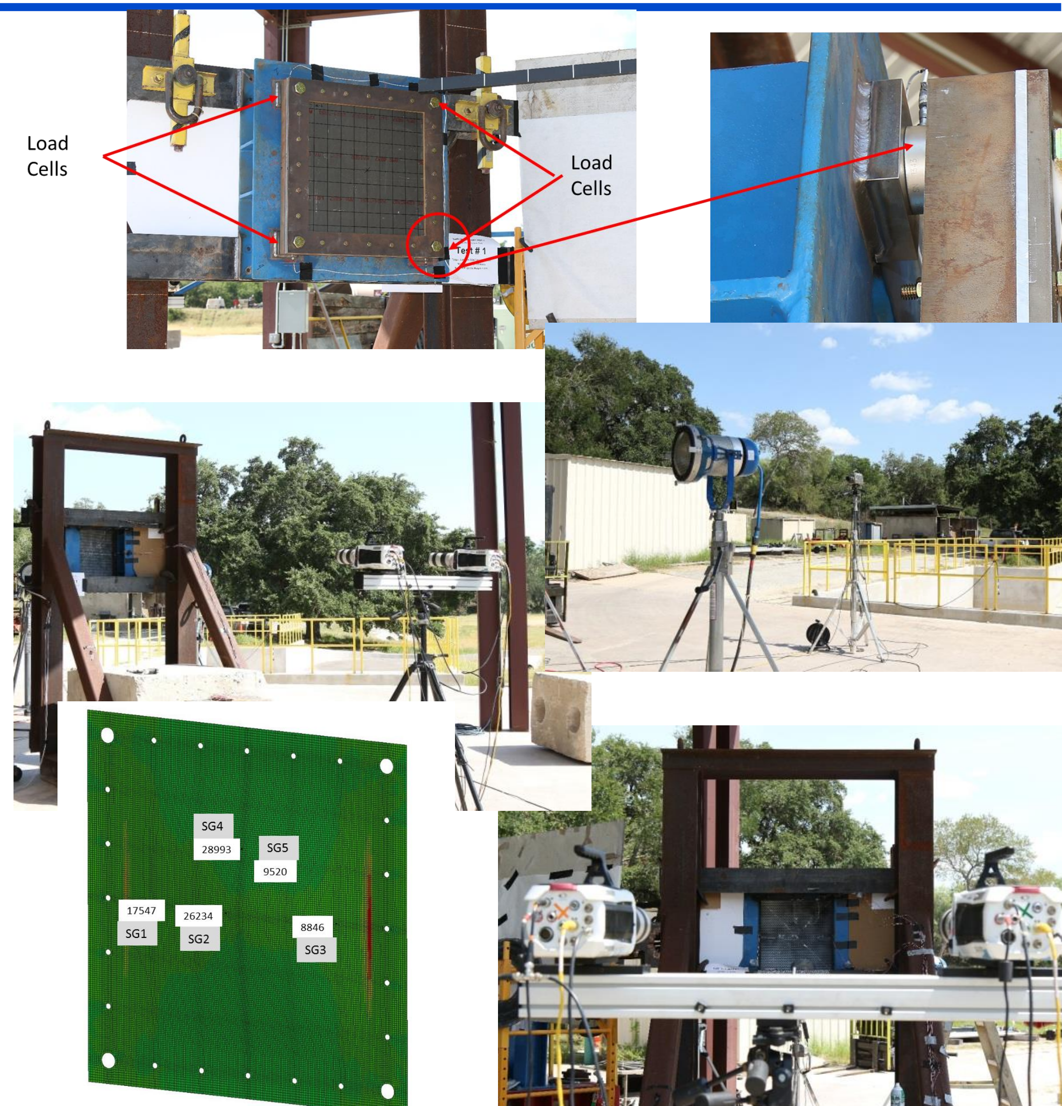


Experimental Setup: Fixture and Instrumentation

We continue to develop and refine methods to quantify the uncertainties in all measured data (speed, impact location, etc.) and then access the effects of experimental uncertainties to the simulation validation process – references ASME 19.1 Standard and the ISO GUM

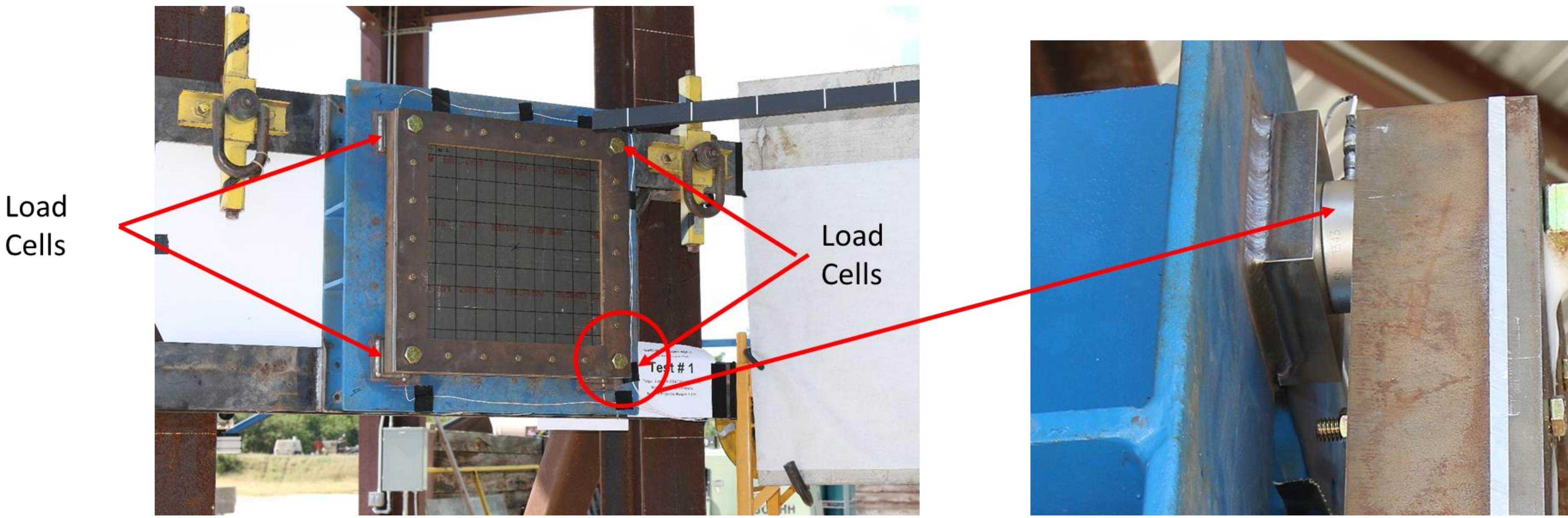
Experimental Setup: Fixture and Instrumentation

- 4 PCB load cells at corners of the target frame
- 7 strain gauges on rear surface of target
- High-speed 3D digital image correlation (DIC) for displacement and strain measurement
- Strike-face high-speed video



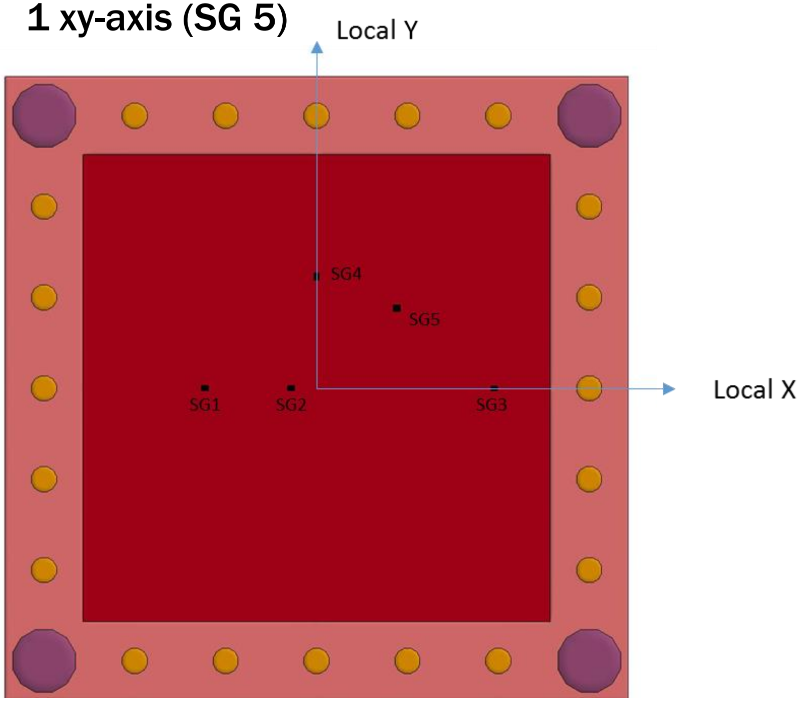
Instrumentation: Force History

- Recorded using DEWETRON high-speed DAS
- PCB 206C Load Cells
- Calibrated before and after testing at SwRI calibration lab
- In full V&V&UQ, we must determine the uncertainty and error in the load cell measurements and the DAS



Instrumentation: Strain History

- Monitored at locations shown on back face of target panel
- Recorded with DEWETRON high-speed DAS
- 4 uniaxial strain gauges
  - 3 x-axis (SG 1, 2, 3)
  - 1 y-axis (SG 4)
- 1 rosette
  - 1 x-axis (SG 5)
  - 1 y-axis (SG 5)
  - 1 xy-axis (SG 5)



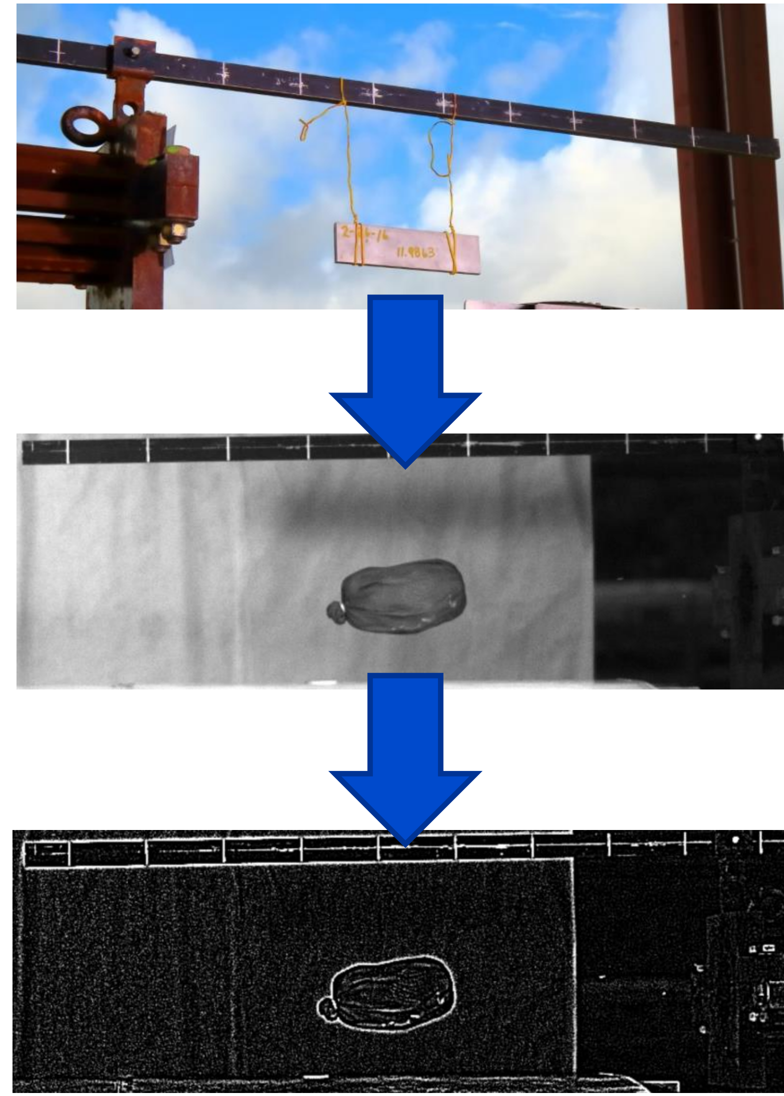
Node numbers in simulation corresponding to experiment strain gauge locations

Instrumentation: High-Speed Video

- Digital high-speed video cameras used to record projectile and impact or strike face of target at 10,000 to 20,000 Hz
- Used to calculate impact speed
- Capture overall system response data: qualitative data comparison – does the simulated target respond in the same way as in the experiment
- Quantitative data: distance of actual impact from center, time to deform and rebound, radius of deformation, mode of dynamic failure and number of cracks in the target material in the case of material failure, etc.

Speed Measurement

- Use high speed video (HSV) of projectile in flight with motion analysis software to calculate projectile speed
- Parameters of interest are distance and time
  - Distance is confirmed using a measured length standard traceable to NIST
  - Timing is confirmed by verifying camera frame rate via comparison to frequency counter traceable to NIST
  - Length standard used to calibrate motion analysis software distance/pixel relationship
- Software filter used to identify edges of projectile (front and rear)
  - Projectile speed measured by advancing through frames of the HSV, and measuring the position of the front and rear of the projectile
  - This procedure gives speed at the center or mass
  - Since the projectile changes shape during flight, this method has proven to be the most consistent at obtaining accurate speed measurements

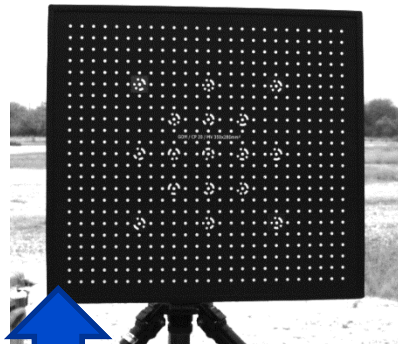


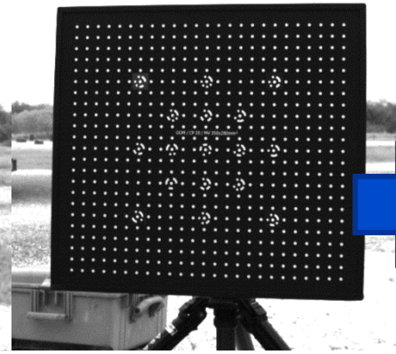
Instrumentation: 3D DIC

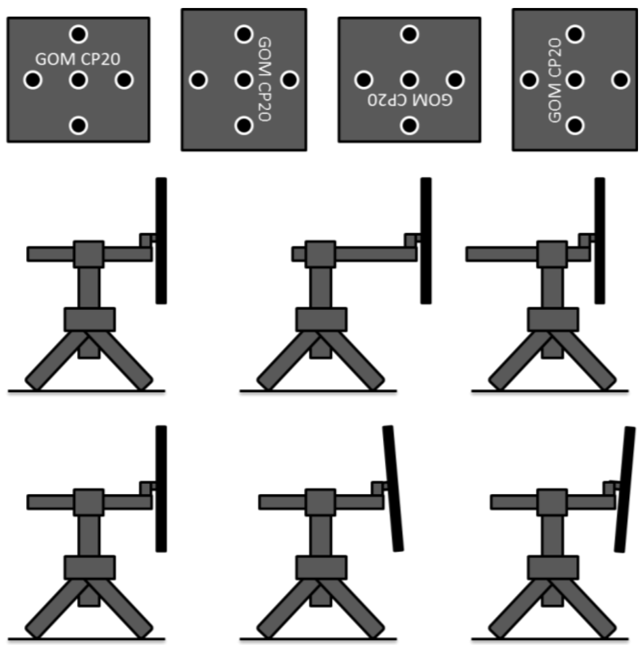
- Uses a stereo pair of digital high-speed cameras
- Deflection and strain time histories at 10,000+ Hz over full target face
- DIC Software Analysis: SwRI has developed and applied code verification methods to GOM ARAMIS software – in-house development of UQ methodology is in-progress for DIC data
- Front of target quickly obscured by projectile debris, so collect data on back face
- Calibrated using a series of images of NIST-traceable calibration panels
- Back of target prepared with a dot-pattern applied with grid and spray paint

DIC Calibration Methodology

Images of a calibration panel are turned into a calibration file by the ARAMIS software



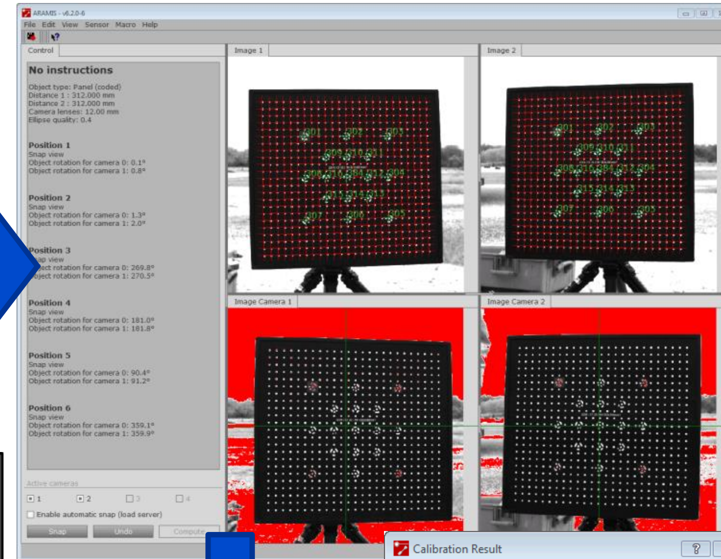


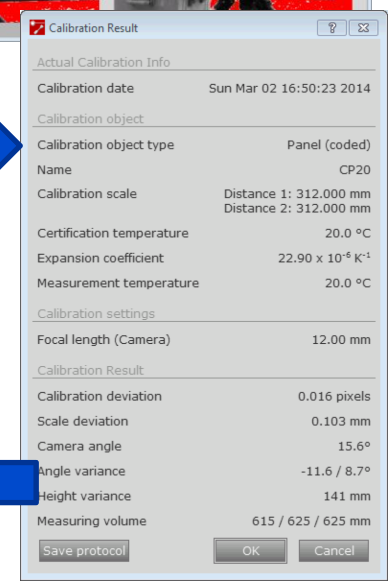


Rotation

Distance

Tilt





Once cameras are locked in place on bar, they can be moved and keep same calibration file

Full Test Matrix

Target	Bird Mass (lb)	Acutual Speed (knots)	Result	Test #
Aluminum	2.2	136	PASS	10
Aluminum	2.2	174	PASS	14
Carbon Fiber	2.2	145.4	PASS	13
Carbon Fiber	2.2	177.3	PASS	16
Polycarbonate	2.2	145.3	PASS	11
Polycarbonate	2.2	145.5	PASS	12
Polycarbonate	2.2	177.2	PASS	16
Aluminum	4.0	253.6	PASS	1
Aluminum	4.0	304.1	PASS	3
Aluminum	4.0	309.3	PASS	2
Carbon Fiber	4.0	207.1	PASS	7
Carbon Fiber	4.0	246.5	FAIL	8
Carbon Fiber	4.0	250.3	FAIL	9
Polycarbonate	4.0	177.8	FAIL	6
Polycarbonate	4.0	205	FAIL	5
Polycarbonate	4.0	249.5	FAIL	4

Repeat (tests 11 and 12)

Repeat (tests 3 and 2)

Repeat (tests 8 and 9)

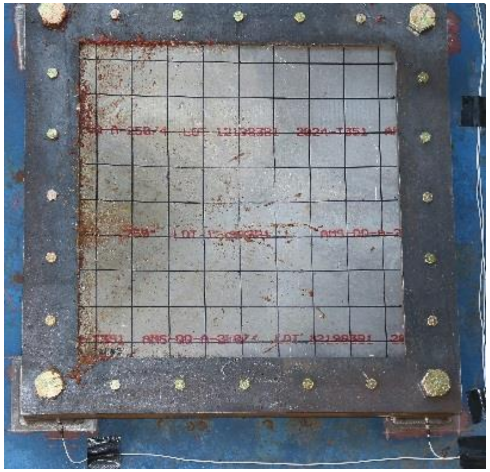
Mixtures of passes and fails important for validating failure mechanisms in simulations

Repeats useful for variability assessment and for UQ in experimental data

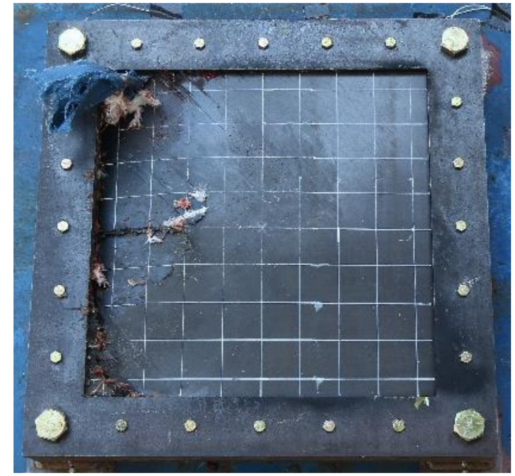
No strain gauges used on 2.2 lb. bird tests

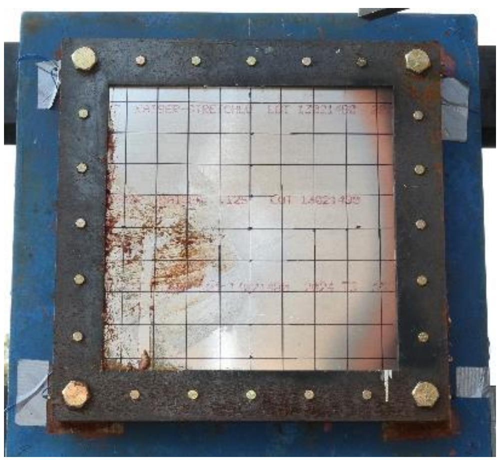
All tests at 45° Obliquity

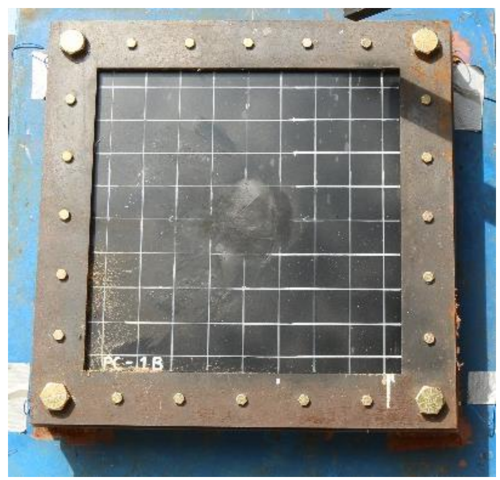
Typical Post-Test Results: First Simulation Assessment is “Do Pass/Fail Results Match Sims?” – a Qualitative Comparison

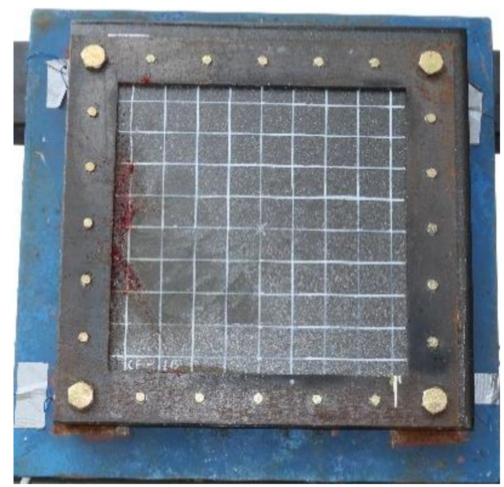

Aluminum


Polycarbonate

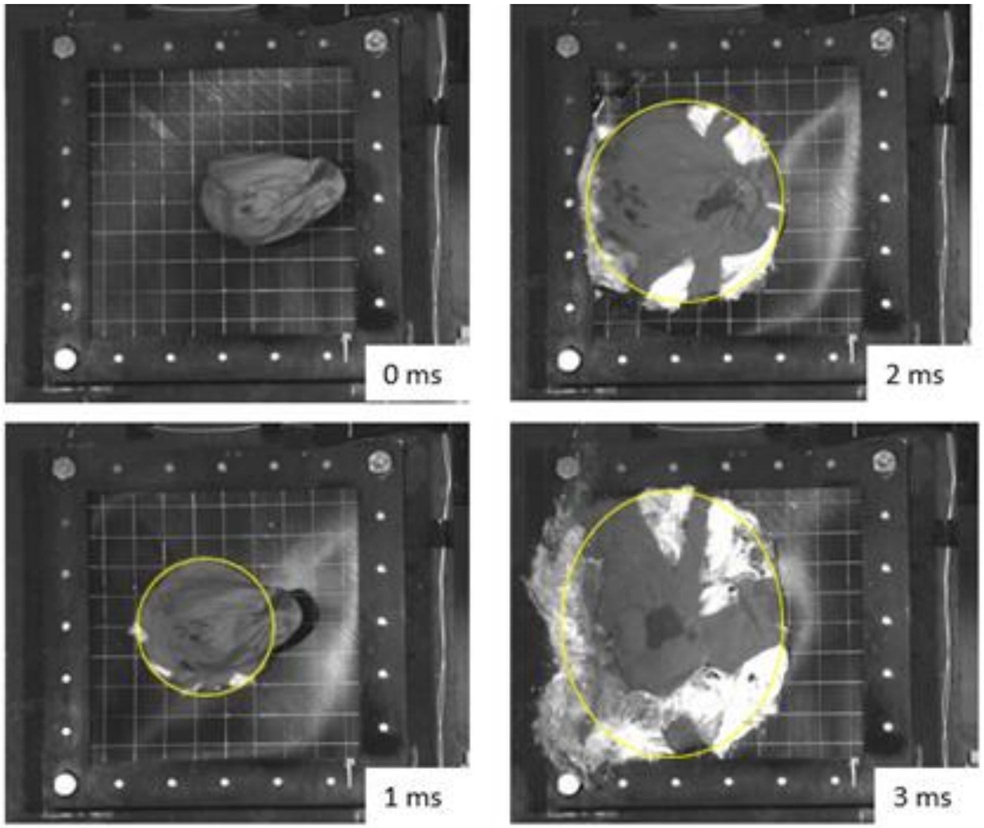

Composite


Aluminum

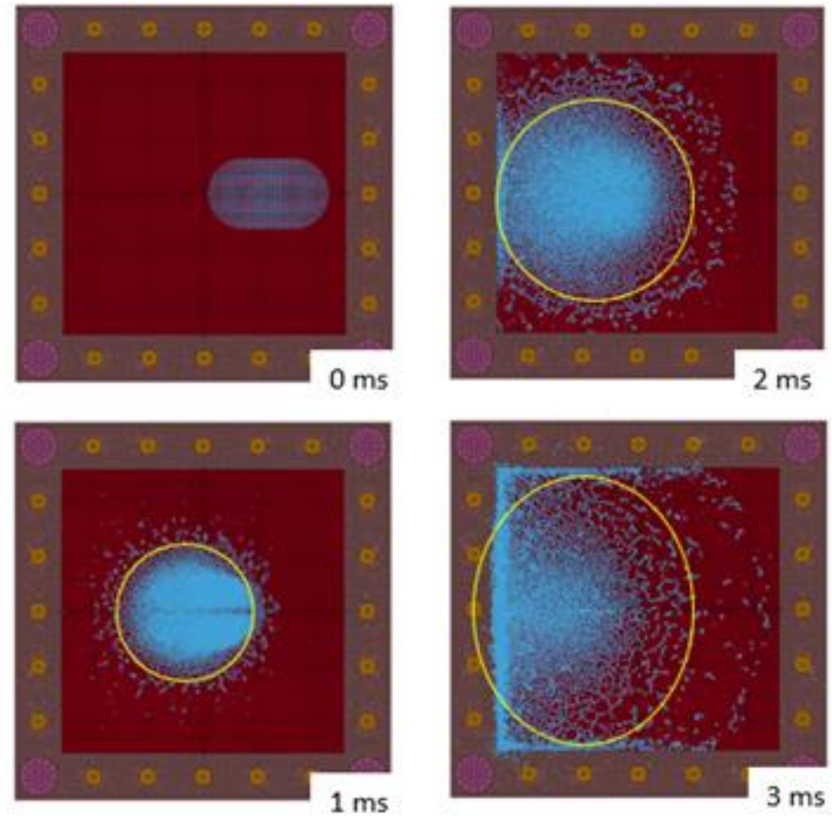

Polycarbonate


Composite

High-Speed Video to Simulation Comparison – Qualitative Front-Face Dynamic Response Comparison



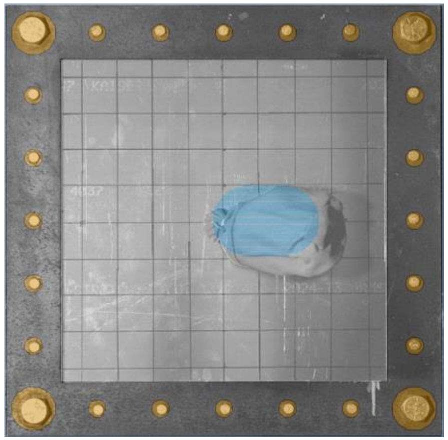
High-Speed Video



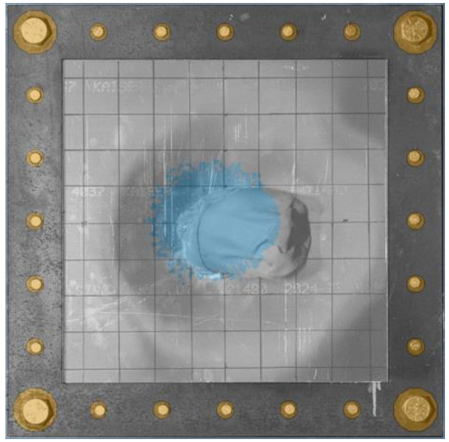
Simulation

High-Speed Video Test Data

Aluminum Target, 45° Obliquity, 2.2 lb. Bird



0 ms



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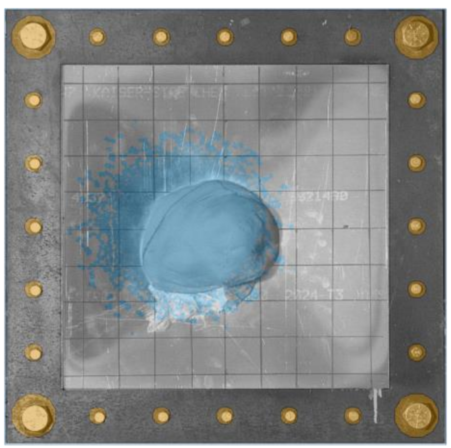
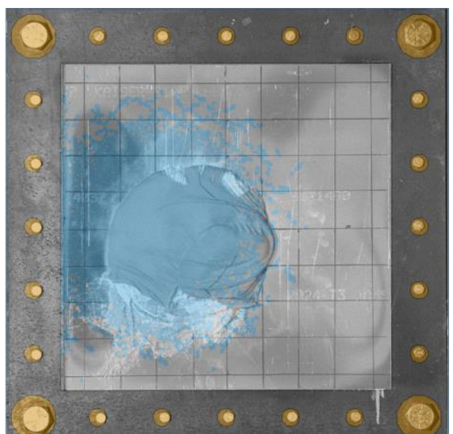
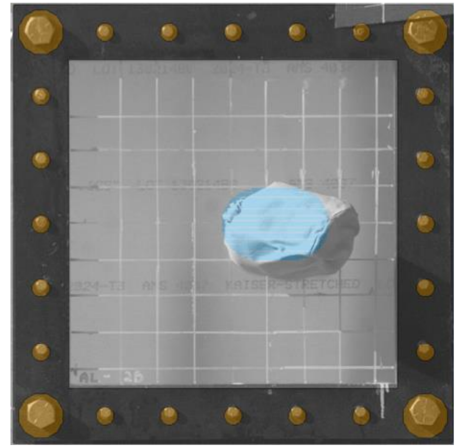


2 ms



3 ms

140 knots



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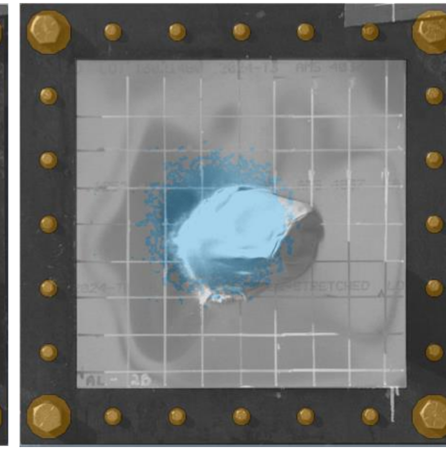

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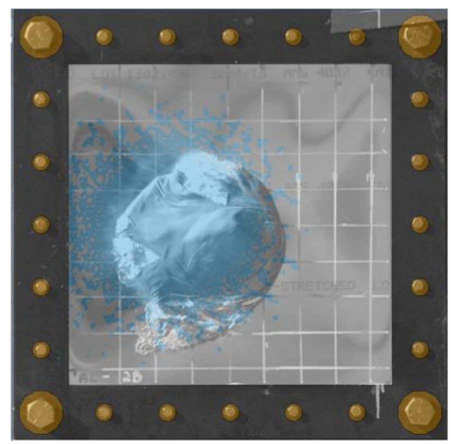

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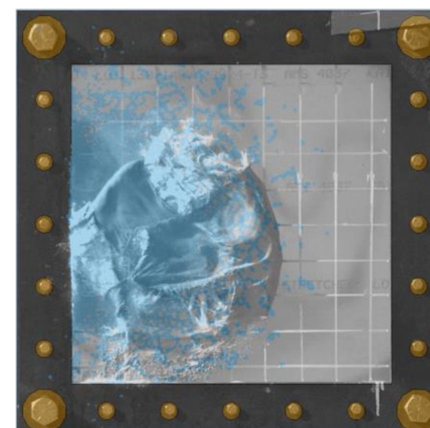
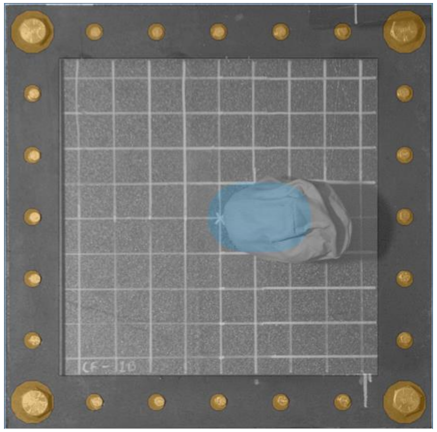


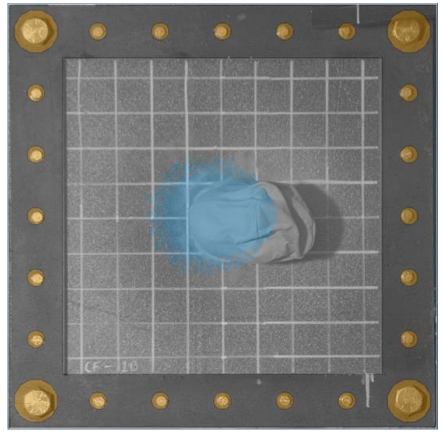
3 ms

180 knots

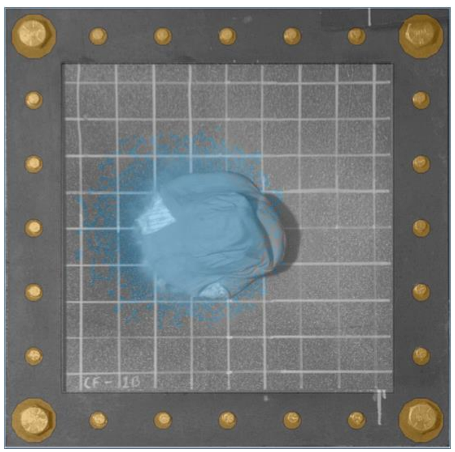
High-Speed Video Test Data



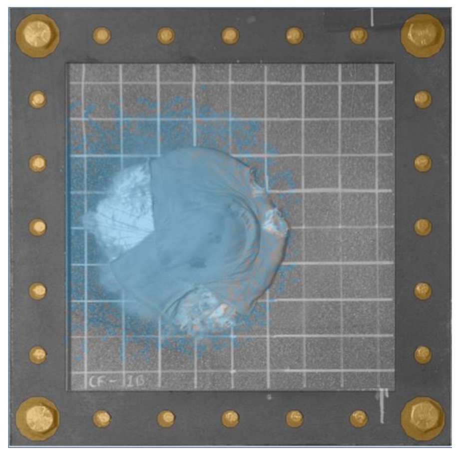
0 ms



1 ms

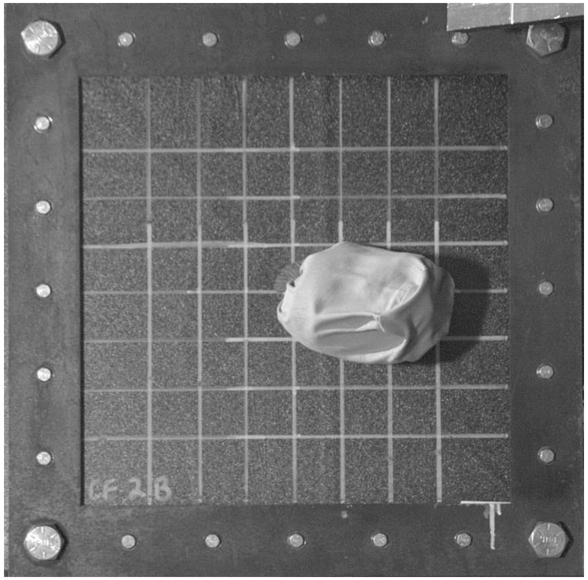


2 ms



3 ms

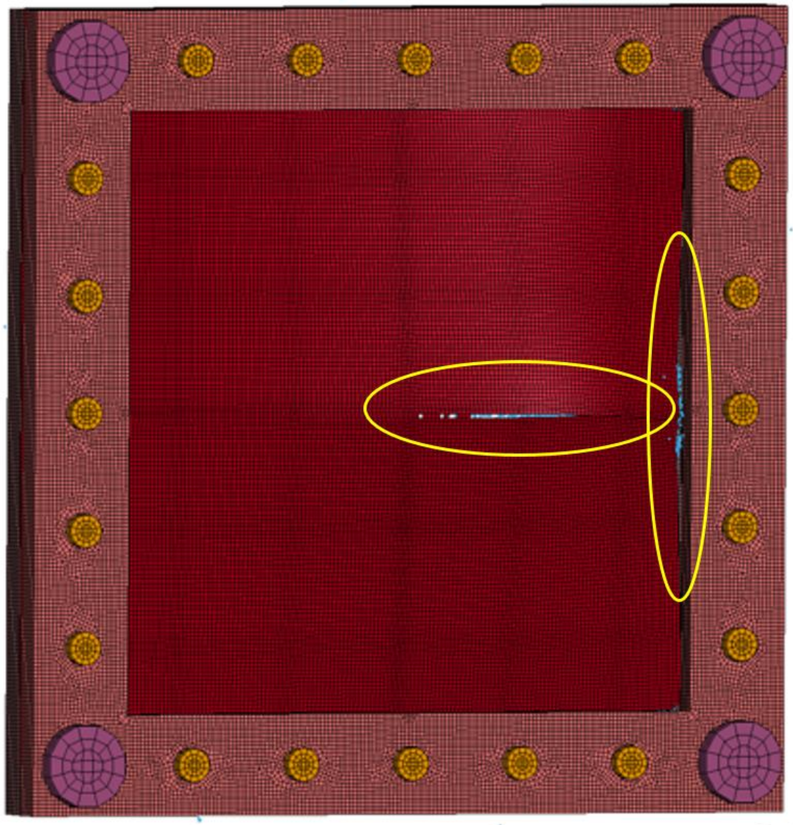
Carbon Fiber Target, 45° Obliquity, 2.2 lb. Bird, 140 knots

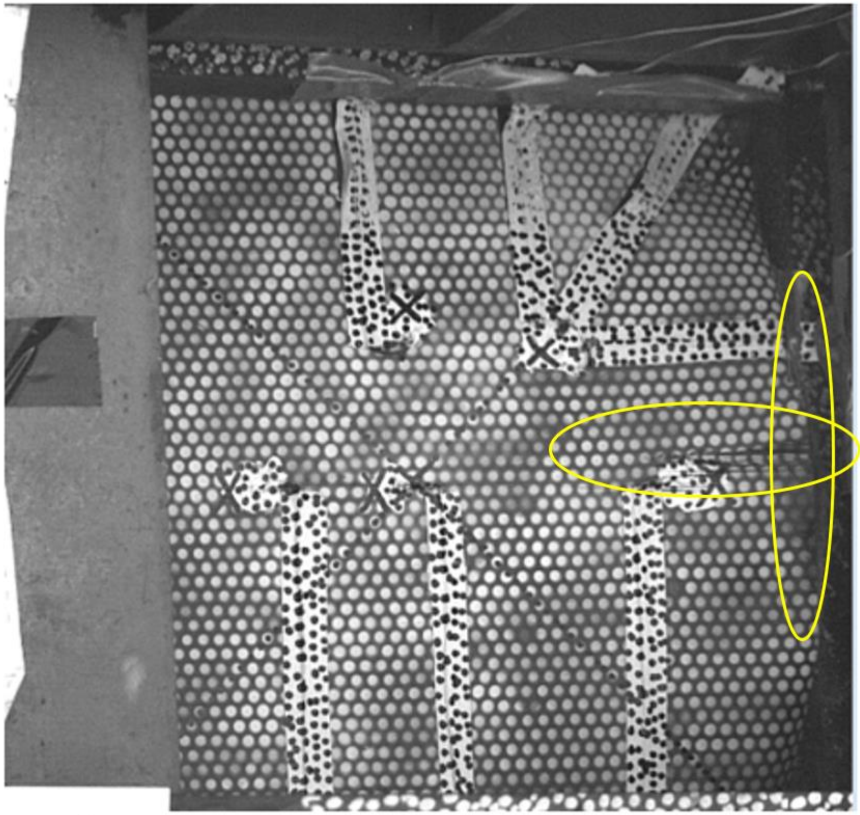


Polycarbonate Target, 45° Obliquity, 2.2 lb. Bird, 180 knots: Showing impact approx. 1.0” below center

High-Speed Video – Back-Face Failure Response to Simulation Comparison

Carbon Fiber Target, 45° Obliquity, 4.0 lb. Bird





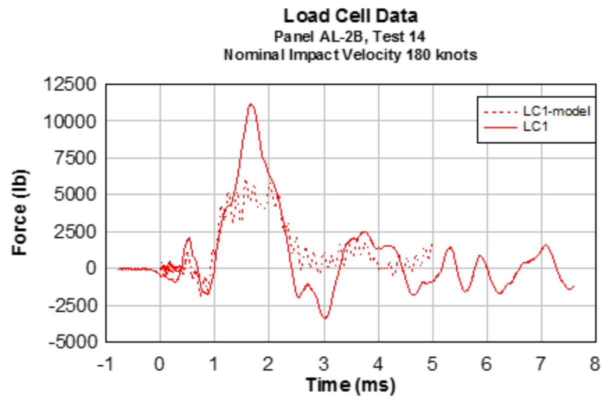
3.1 ms post impact

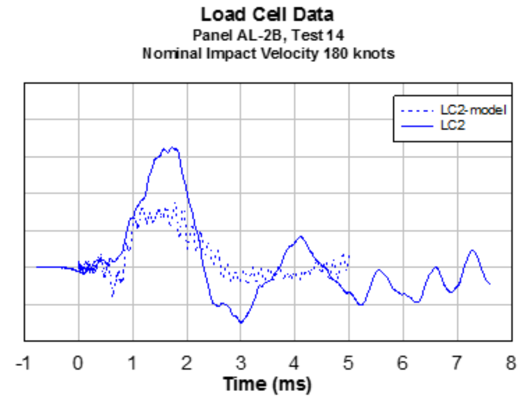
Simulation with MAT54

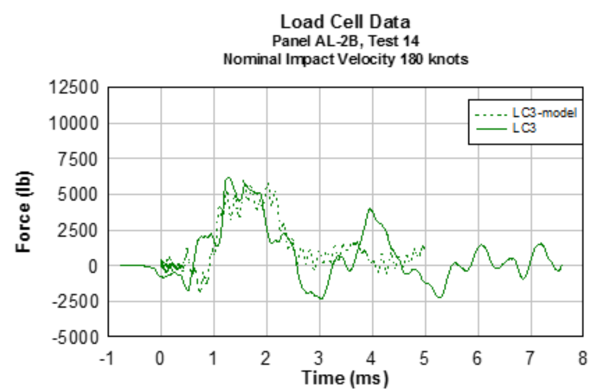
High-Speed Video

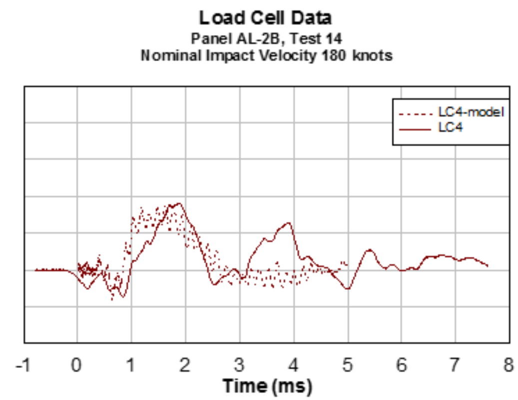
Load Cell Data

- Load cell data illustrates some trade-offs that must be made in between the simulation and experiment
  - The load cells were not explicitly modeled (force pulled from the large corner bolts)
  - Additionally, the frame was modeled as rigid (a model assumption – appears OK for target dynamic response)
  - In tests, video showed frame responding elastically (as well as post-test assessment)
- A moment is created on the load cells causing asymmetry in the data not observed in simulations
- Moment increased by actual bird impact location below target centerline
- General trend of simulation agrees with experimental measurements, though the peak magnitudes are not the same, plus excessive damping of rebound – these results suggest that additional grid refinement may be required as well as relaxing assumption of rigid frame





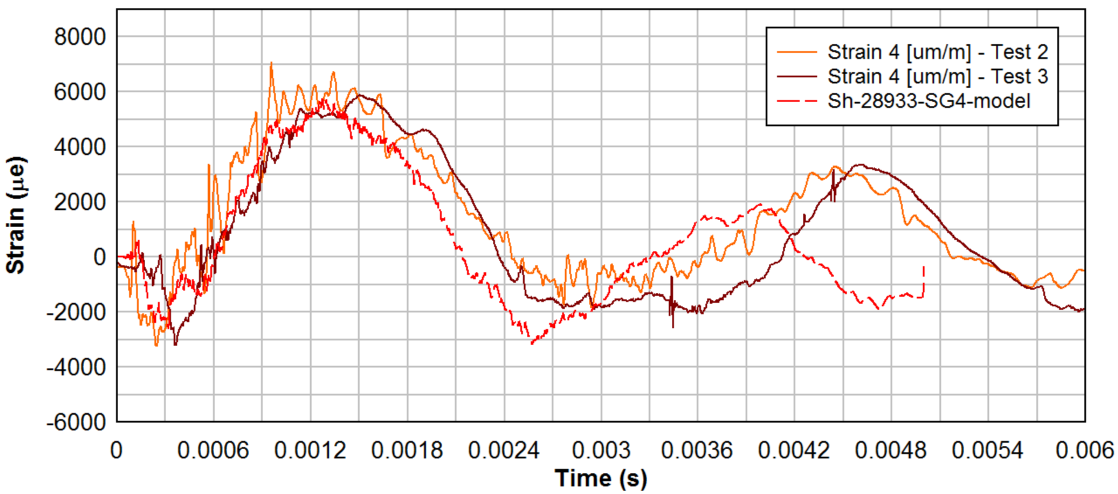




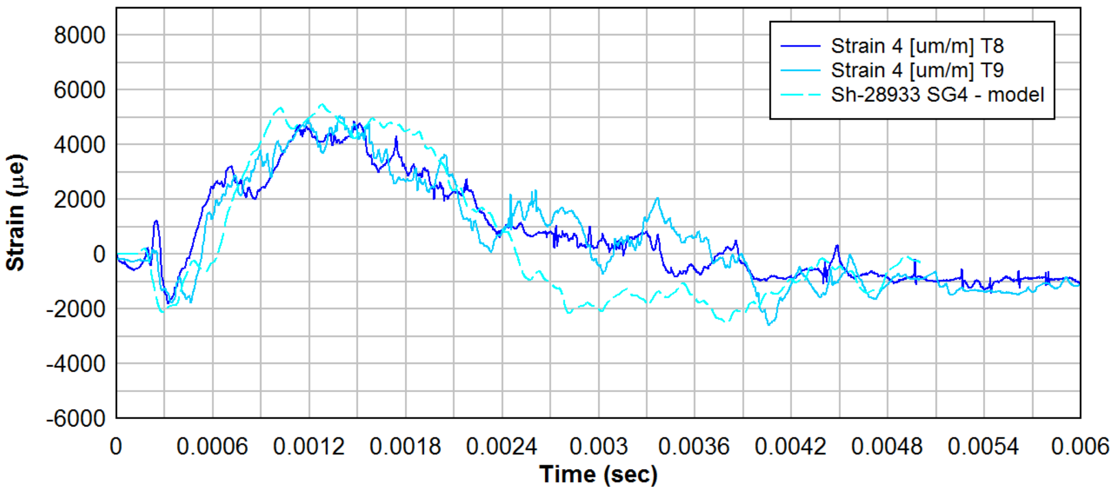
Load cells are frequently used in full component bird strike tests, because they are a natural fit between the test article and support frame: but care must be taken in how their data is used in V&V!

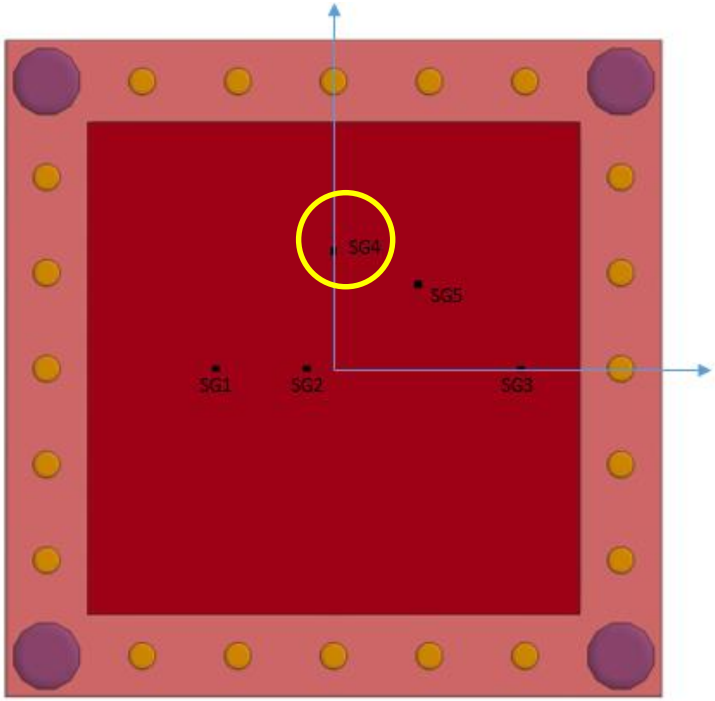
Strain Gauge Data: Experimental Variability and Comparison to Simulations (Single Location)

300 knots, 4-lb bird, 0.25" 2024-T3 Aluminum Target

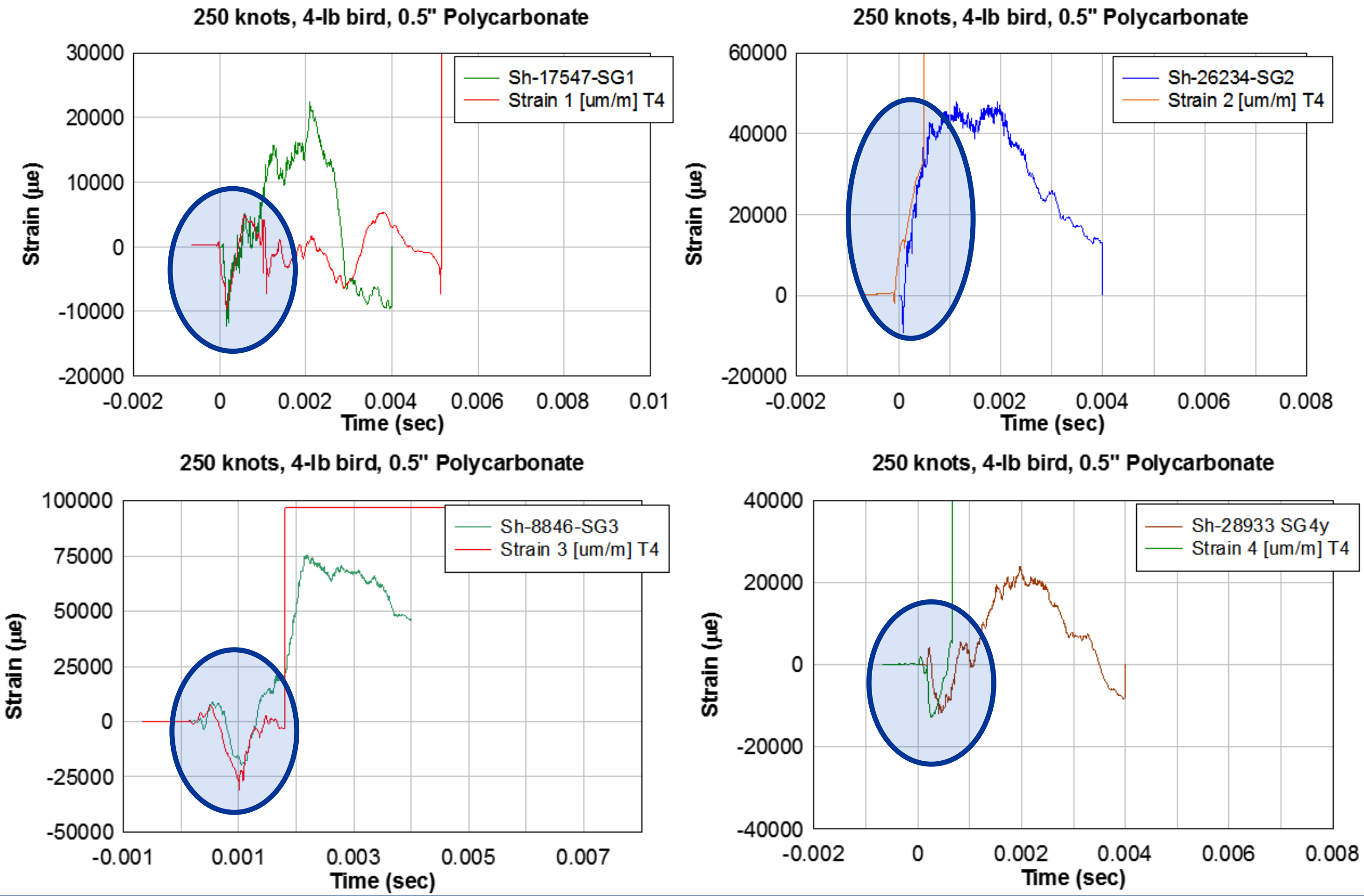


250 knots, 4-lb bird, 48-ply TORAY P707AG-15 $[(0/45/90/-45)_6]_s$



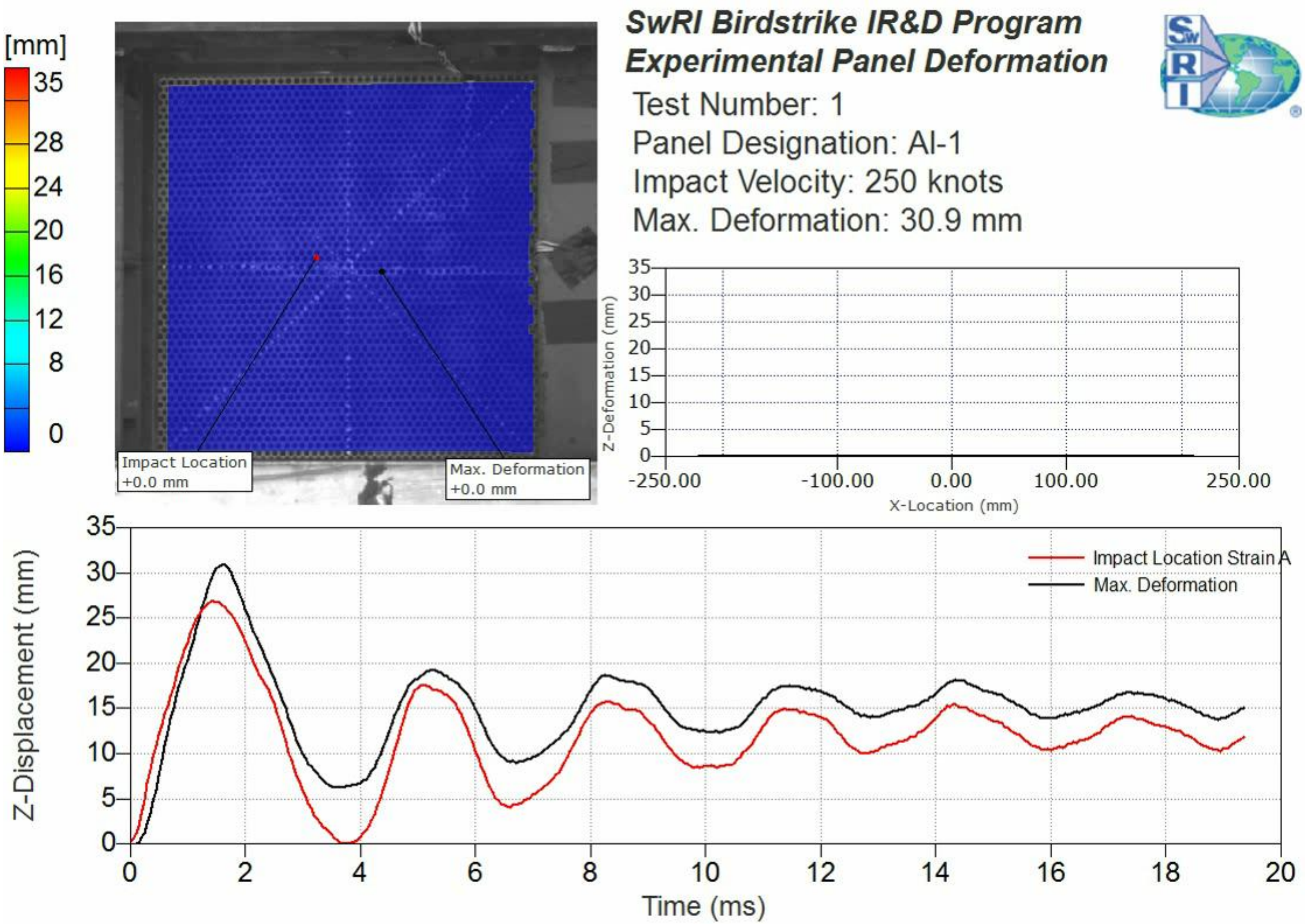


Strain Gauge Data: Experiment Compared to Gauges at Multiple Locations (Polycarbonate Test)

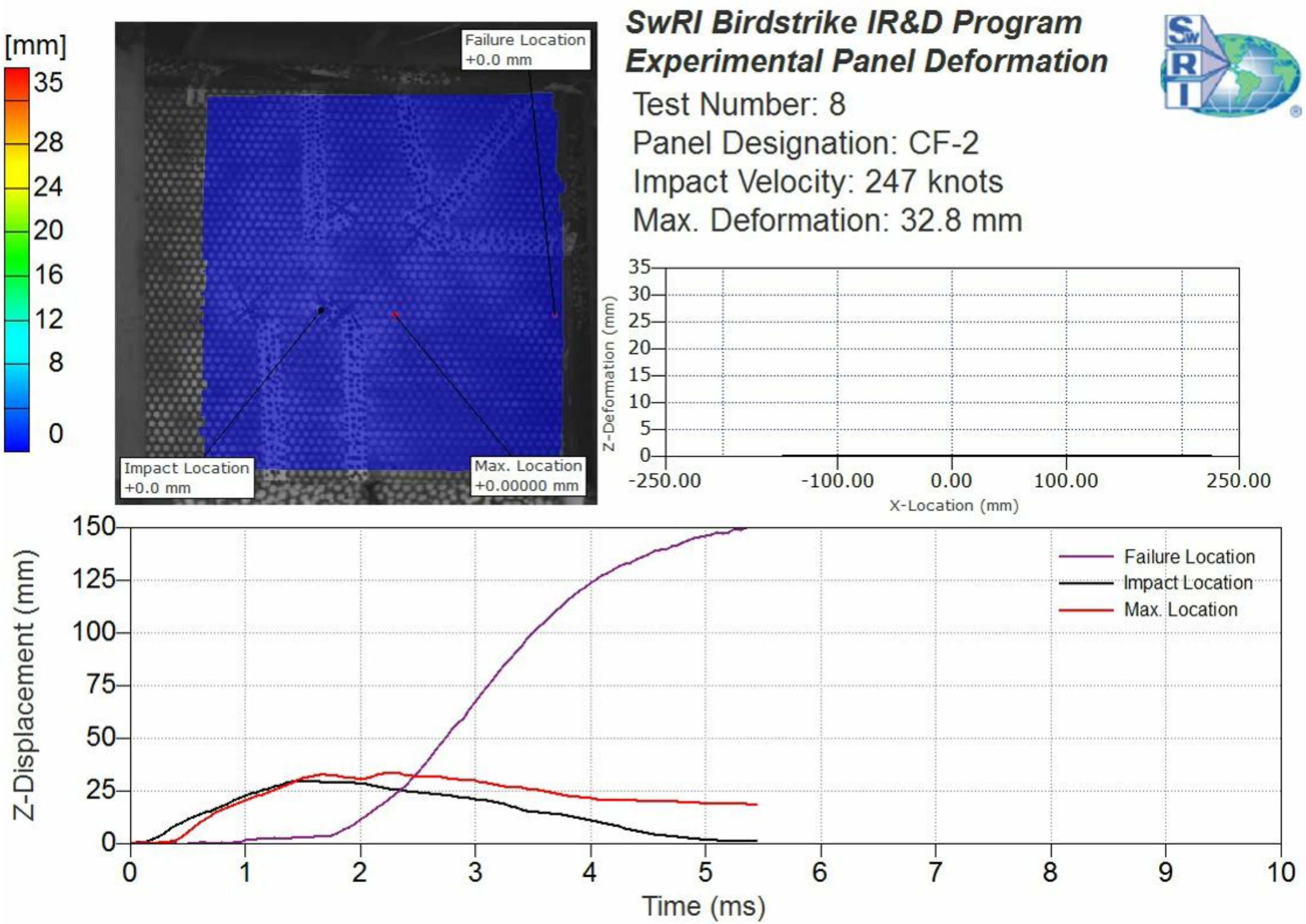


Data match well until failure – in early simulations, the polycarbonate did not fail at the correct strain level: critical to proper simulations are models for plastic response and failure

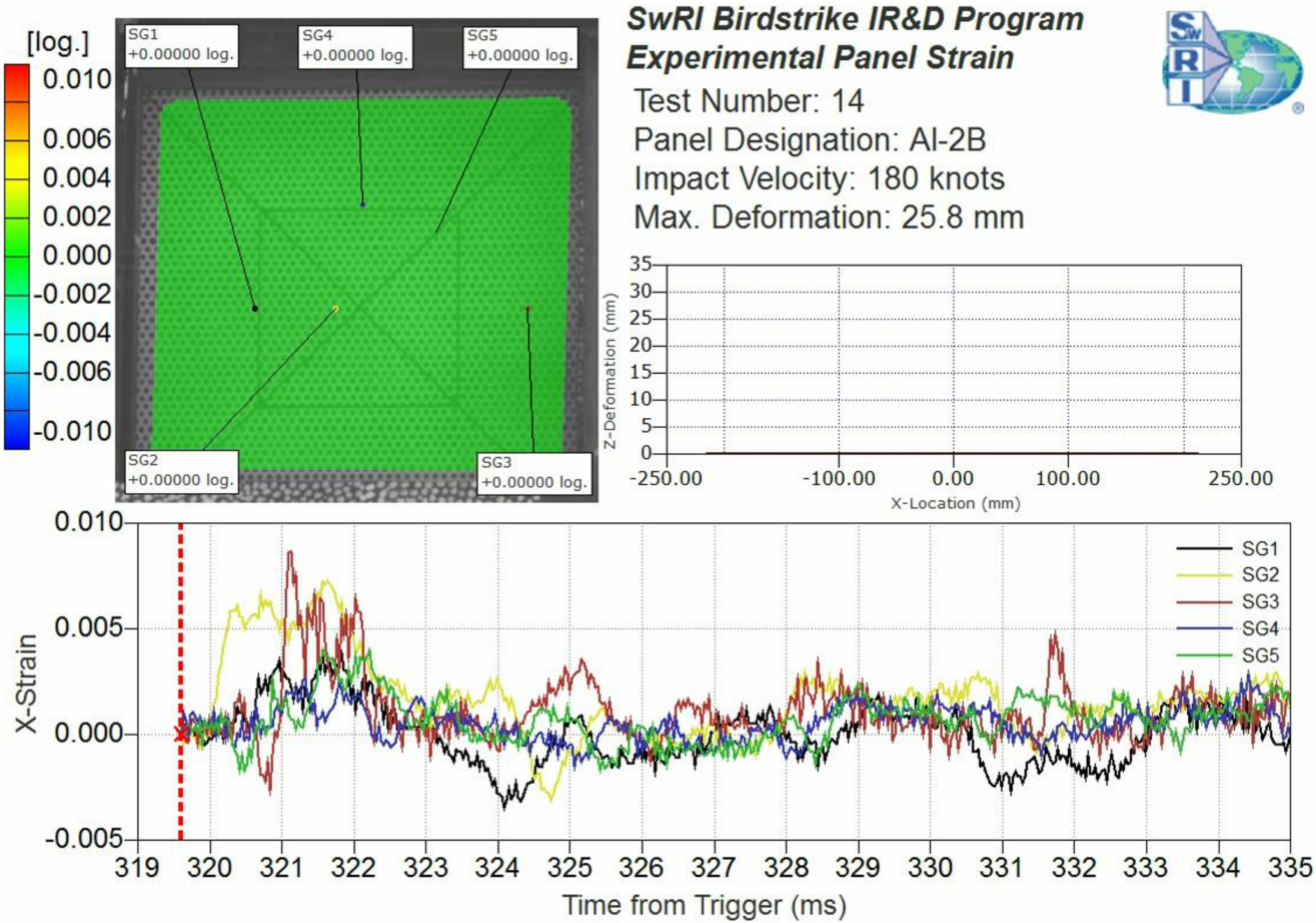
DIC: Deformation on a Pass (Aluminum, 4 lb. Bird)



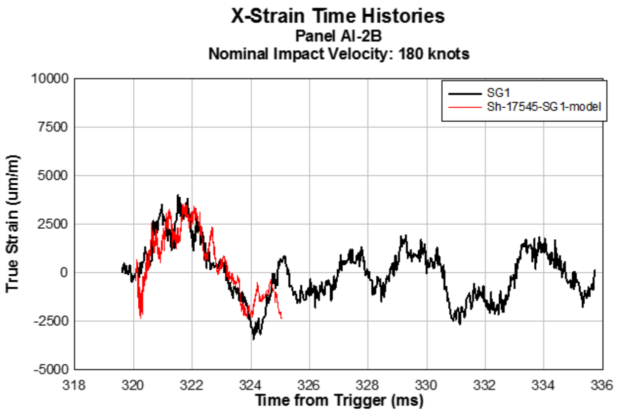
DIC: Deformation on Fail (Carbon Fiber, 4 lb. Bird)

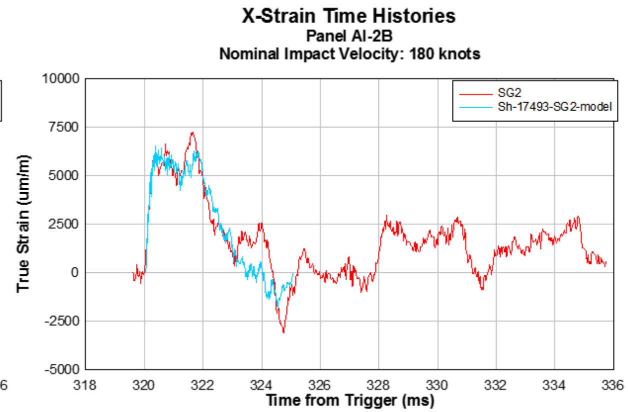


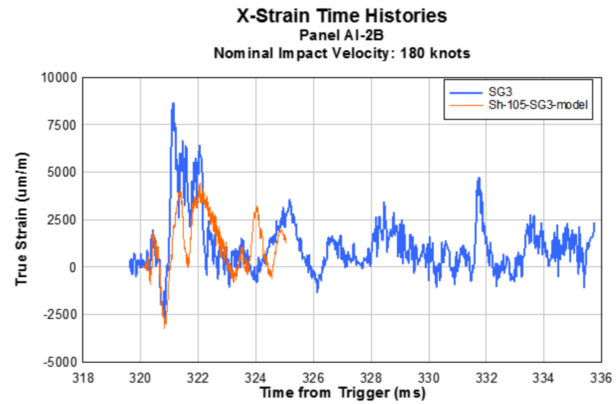
DIC: Strain Data (Al @ 180 knots, 2.2 lb Bird: DIC Used in Lieu of Gauges)

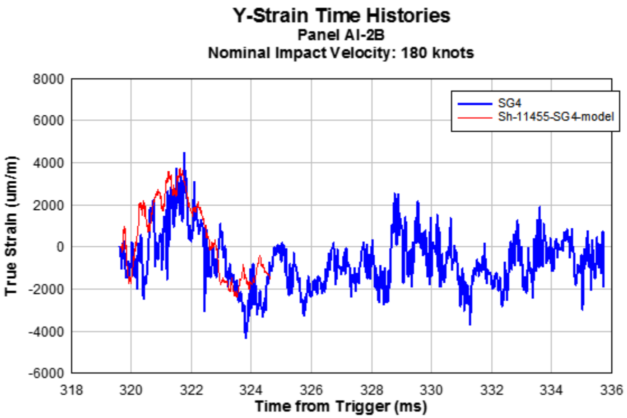


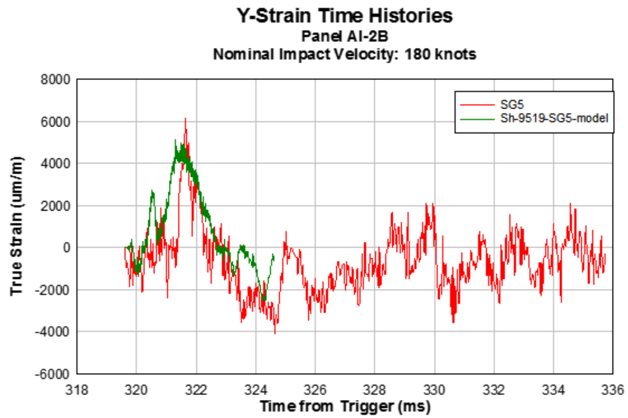
DIC Strain: Single Experiment, Data from Multiple Gauge Locations – Aluminum @ 180 knots (2.2 lb)

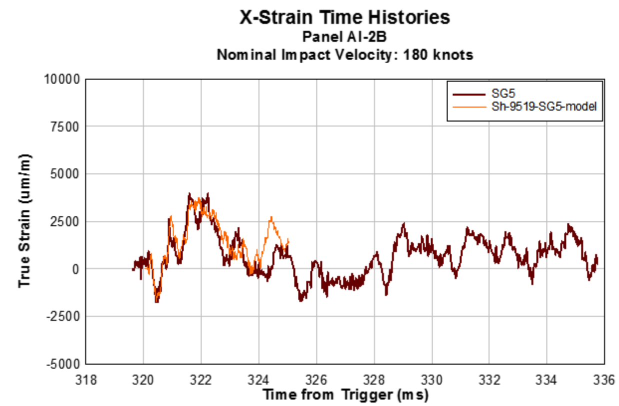








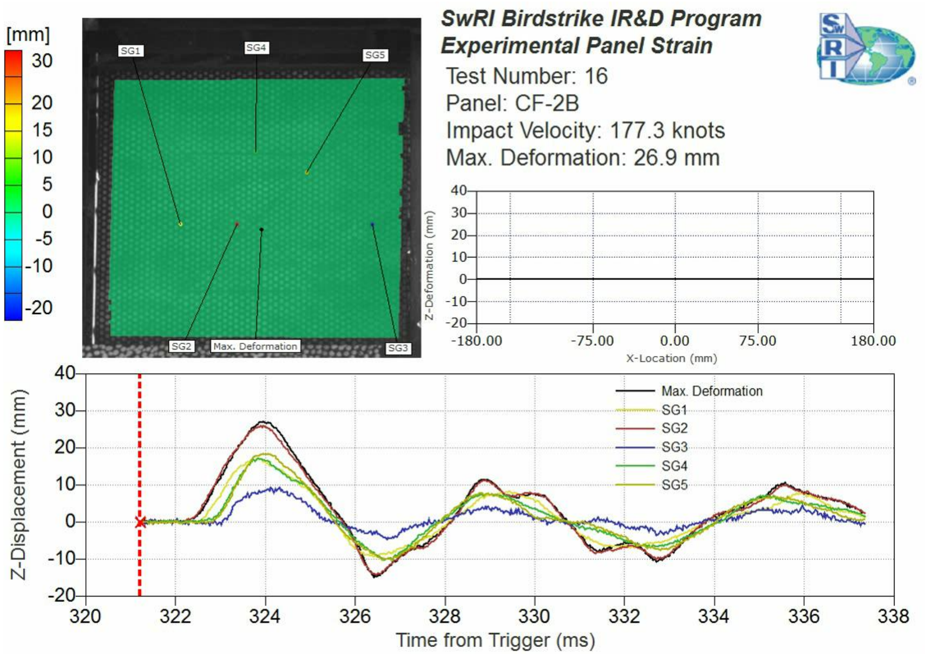


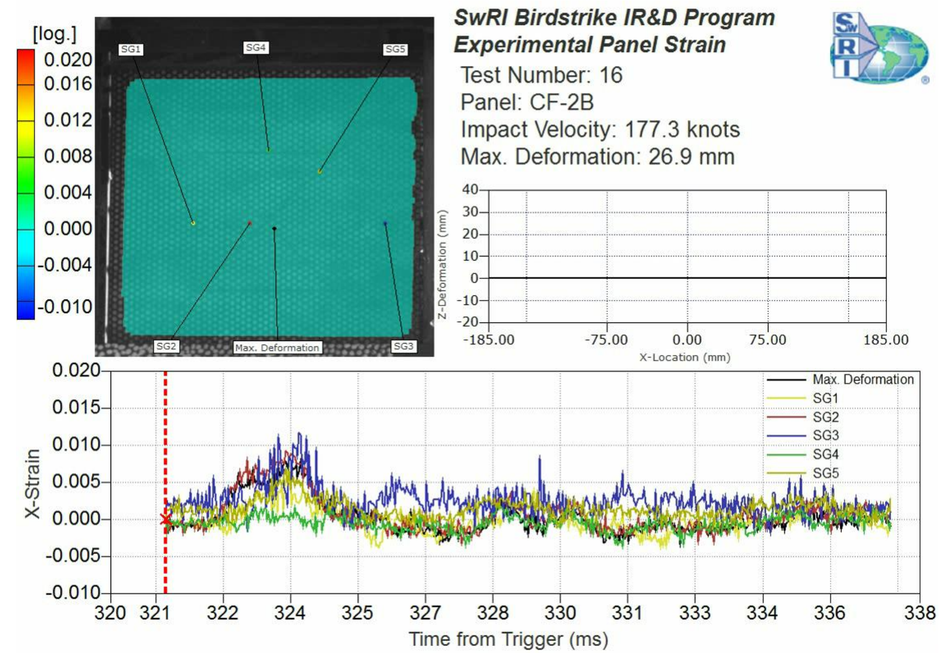


Simulations were performed before testing – the use of calibration of input parameters must carefully be assessed and only allowed after code verification, solution verification and an appropriate set of simulation validation exercises – the size of "appropriate set" should be defined at initiation of project if possible, we do not want calibration to mask model failings

DIC: Deformation and Strain on Carbon Fiber

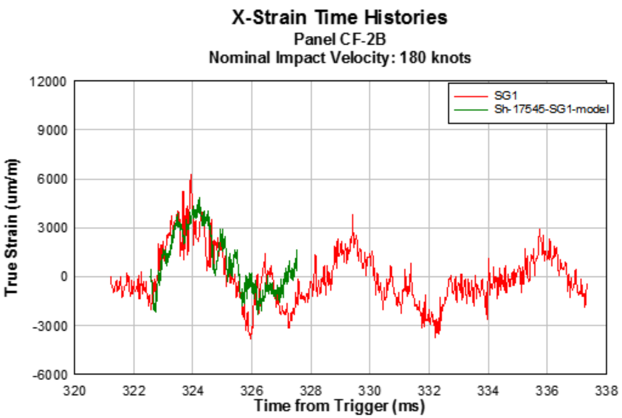
2.2 lb Bird at 180 knots

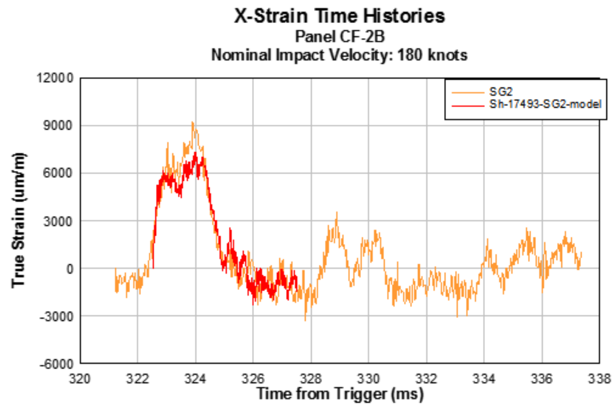


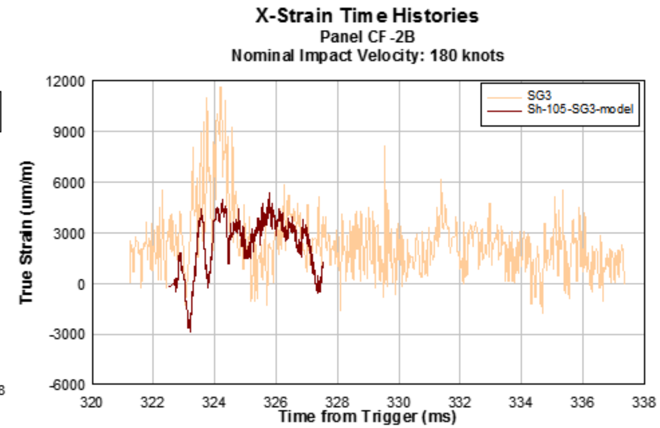


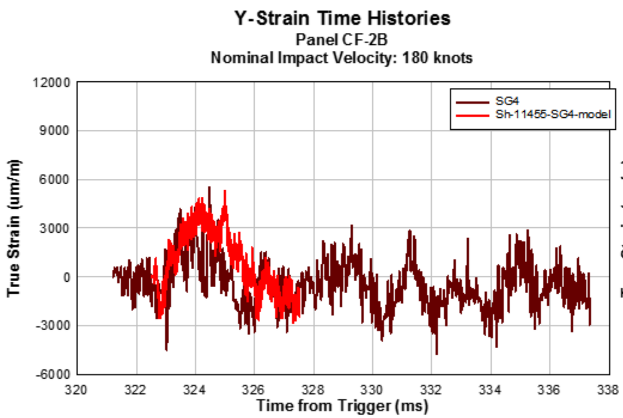
We looked at the correlation between points where gauges were located during the 4 lb. tests and compared to DIC measurement data, DIC gives a full field measurement – both correlated local and global strain measurements should be used in simulation validation

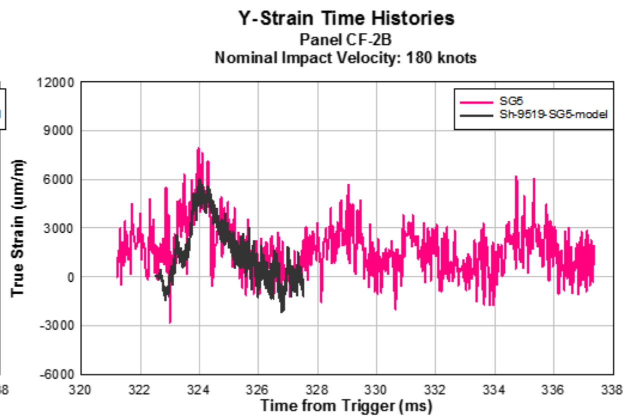
DIC Strain and Model Data for Carbon Fiber

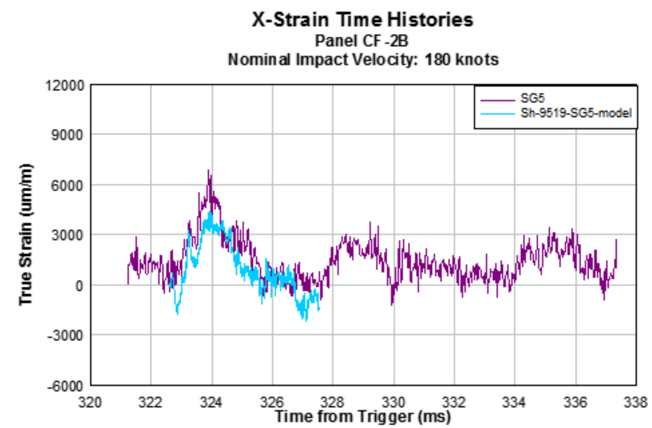






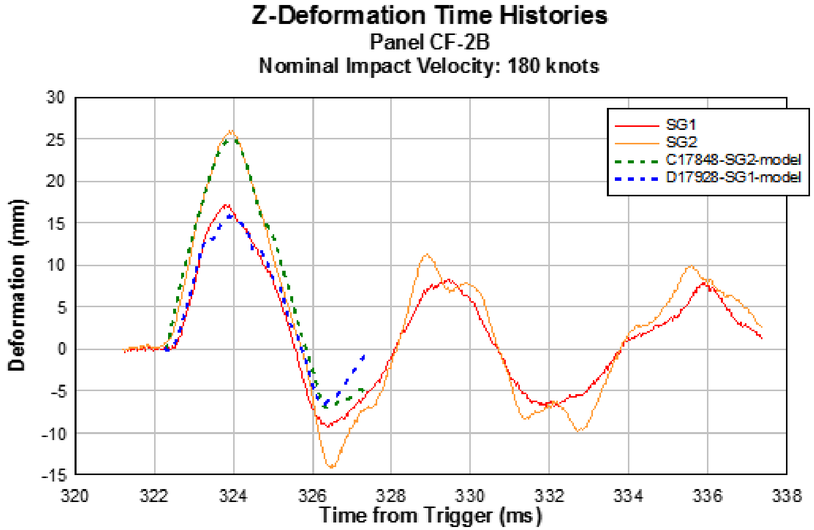


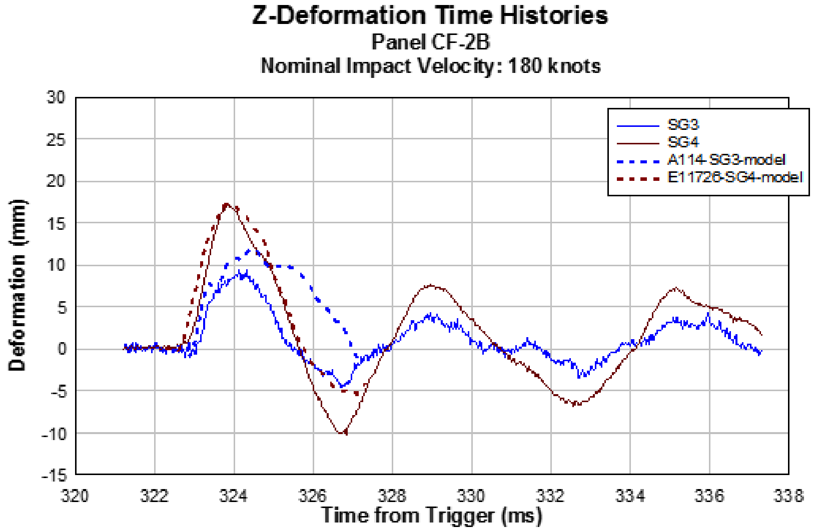


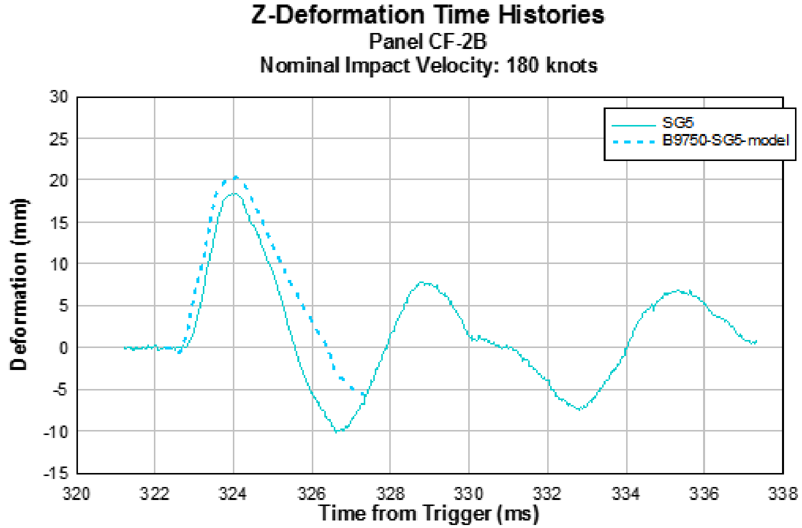


Qualitatively, the agreement looks very good: our challenge moving forward is to standardize comparisons of magnitude and timing to define what constitutes a validated model

DIC Deflection and Model Data for Carbon Fiber







Lots of Data!

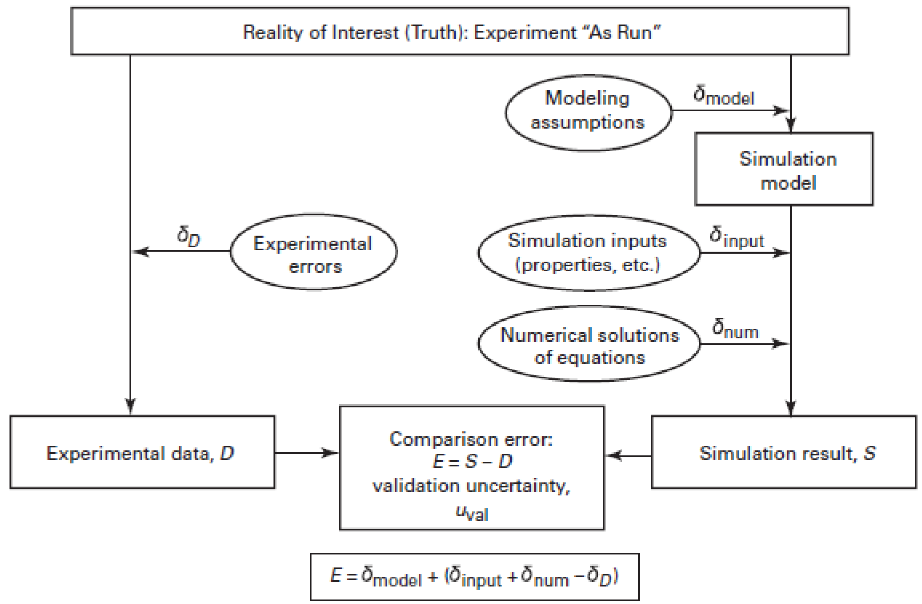
- With the current suite of measurement tools, it is possible to collect massive amounts of data that is high-resolution in time and covers the entire test article surface
- Most of this data can be used in simulation validation
- Some data is more useful than other data
- Through comparison of the appropriate test data to simulation results, we can validate a simulation and for a range of validation setpoints we can validate a model for a region of interest relevant to the application
- In order to say we are validated, we need a metric to calculate the level of validation and we need a threshold or objective specification
- ASME V&V20 in 2009 & V&V10 in 2012 have defined two different methods for validation
- The threshold or objective requirements are typically defined by the "client"
- We can leverage existing best practices and standards (ASME for example) to develop and demonstrate a best practice standard for achieving certification by analysis for crash and impact relevant to FAA applications

Validation Metrics

- V&V 20 in 2009 proposed the use of a "comparison error" based on estimates of standard uncertainties, resulting in a validation standard uncertainty – defined as an estimate of the standard deviation of the parent population of the combination of errors: $E \pm u_{val}$ which characterizes an interval within which model error falls
- V&V 10 in 2012 proposed the use of an "area metric" also based on uncertainty estimates, but where the uncertainty in the simulation outcome may also be quantified through a probabilistic analysis with uncertain model inputs; the "area metric" is the area between the cumulative distribution functions for the experimental and the simulated parameter of interest

From ASME V&V20-2009 Standard

Fig. 1-5-2 Overview of the Validation Process With Sources of Error in Ovals



From ASME V&V10-2012 Standard

Fig. 5 Illustration of the Two Validation Approaches

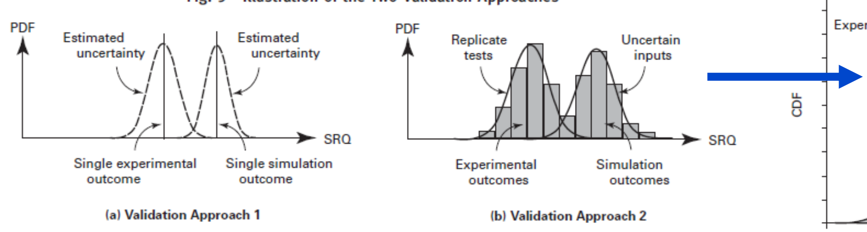
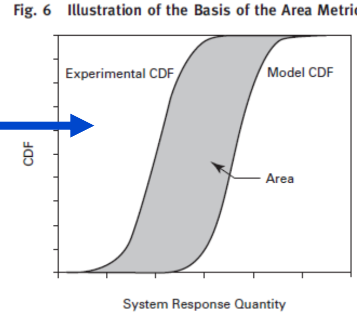
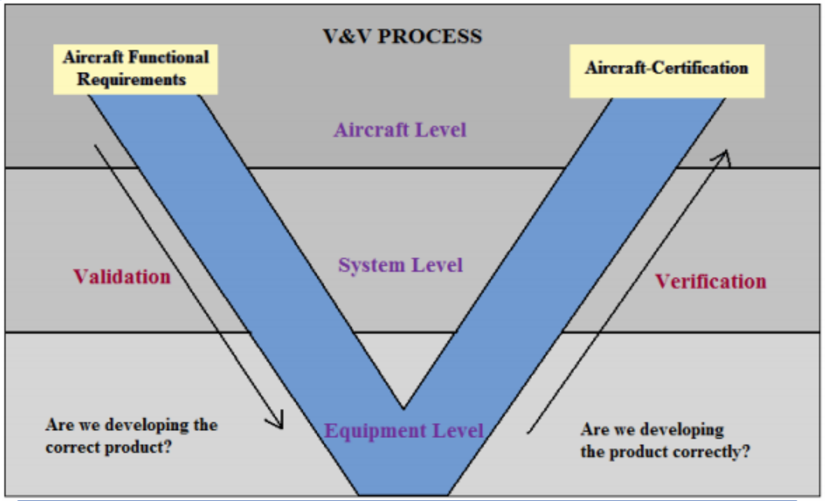


Fig. 6 Illustration of the Basis of the Area Metric

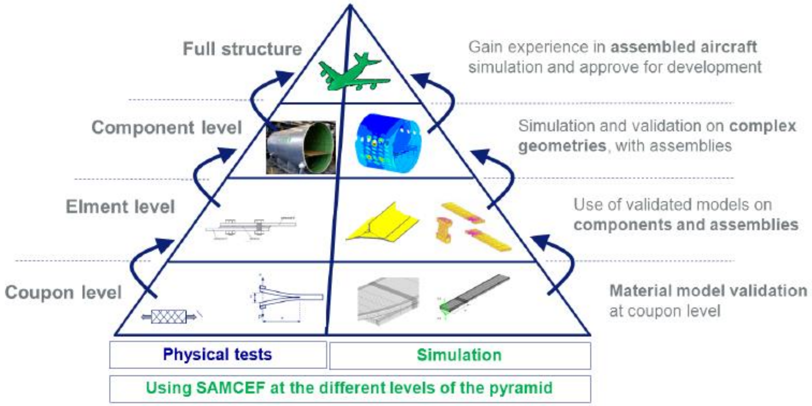


Improve Models and Test Systems

- Full-scale structures, bird impact testing are used to further validate models, originally validated using single effects experiments
- A full system typically uses multiple materials and structures
- The single effects validated models are used in conjunction with estimates of uncertainty propagation from the single effects scales to coupled or full-scale systems
- Procedures for the roll-up of validation results and uncertainty is an active area of research and standards development
- ASME V&V20 committee is working this topic now, the most mature approach for roll-up from single effects is in the Nuclear Power Industry and NUREG documents (ASME V&V 30 committee)

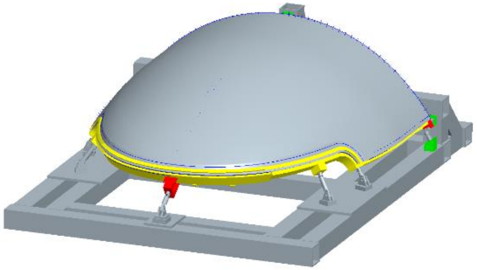


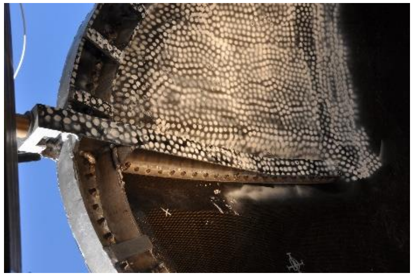
Arthasartsri & Ren, 2009 – V&V Methodologies for A380

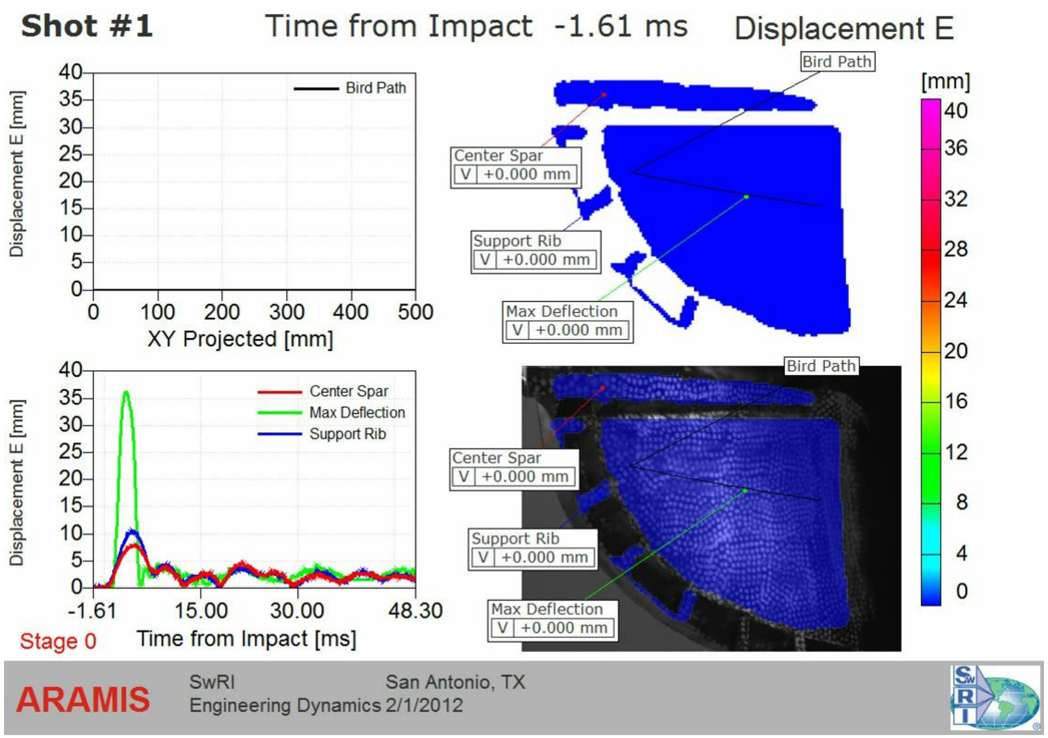


Bruyneel et al, 2014 – Damage Modeling of Laminated Composties in SAMCEF

Example System Response Test







Summary & Discussion Points

- Experimental methods for validation of impact simulations are well defined
- For instance, SwRI has developed a dataset for bird impact on aluminum, carbon composite, and polycarbonate transparency that can be used for validation
- Once models are validated, component-level modeling and testing can take place
- Although less expensive than full airframe tests, none of these tests are trivial
- How do we make this data and other experimental data available to the community?
- How to quantify & make known its uncertainty & limitations?
- How do we write the standards to ensure that the data is used appropriately in subsequent V&V?
- Ultimate goal: CBA!

Thank You!

Questions/Discussion