Sandia National Laboratories

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Boundary Condition Influence on Shock Test Damage Potential

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Overview

Introduction and Motivation

Damage Related Quantities of Interest (QoIs)
- Physical Damage
- Peak Acceleration and Peak Displacement
- Input Energy

Test Structure
- BARBECUE - Box And Removable Bridge with External Components Under Evaluation
- ANSYS Models
  - Mode Shapes

Drop Shock Tests
- Description
- Test Results

Summary and Conclusions

Introduction & Motivation

The objective of component testing is to

- Identify potential in-service failure modes
- Demonstrate robustness (ability to survive and perform) to in-service environments

Component testing is always performed independently of the actual system

- Boundary interface stiffness and impedance in a component level test frequently differ from the system level conditions

Question

- How do boundary conditions affect damage potential or component robustness under shock excitation in the laboratory?

Approach

- Perform drop shocks on the BARBECUE
  - BARBECUE = Box And Removable Bridge with External Components Under Evaluation
- Evaluate responses with a variety of QoIs
- Evaluate failure modes and assess robustness

Damage Related Quantities of Interest (QoIs)

Physical Damage

- Clearest indicator of damage
- Predictive if there is a sacrificial unit tested to failure

Peak Acceleration and Relative Displacement

- Damage from extreme loading and strain
- Overstress damage

Pseudo-velocity SRS

- Computed with model and measured base inputs

Input Energy

- Integral of the product of base acceleration and relative velocity

All metrics relate to damage via test or material properties

- Must know damage thresholds to predict if environment could be damaging

Pseudo-Velocity and Input Energy

The EOM of a SDOF oscillator subject to base excitation is

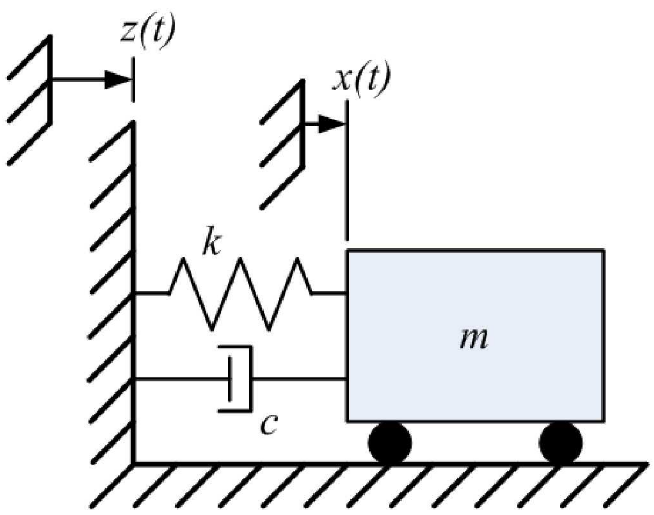
$$\ddot{w}(t) + f(\omega_n, \dot{w}(t), w(t)) + \omega_n{}^2 w(t) = -\ddot{z}(t)$$
$$w(t) = x(t) - z(t)$$

Pseudo-velocity is the relative displacement response times the natural frequency

$$PV(t) = \omega_n w(t)$$

Input energy is the integral of the base acceleration and the relative velocity

$$E_I(t) = -\int_{t_0}^{t_f} \ddot{z}(t)\dot{w}(t)dt$$



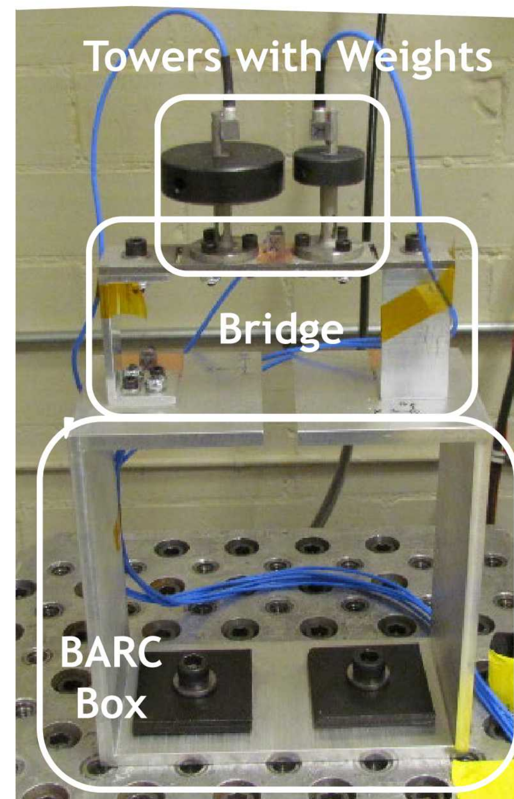
Dissipated energy can be estimated from input energy

$$E_D(t) = E_I(t) - E_{KE}(t) - E_{PE}(t)$$

BARBECUE Structure

BARBECUE = Box And Removable Bridge with External Components Under Evaluation

- Box and C-channel bridge legs are made from T6061 and T6063 aluminum
- The bridge span and towers are 3D printed from 316L stainless steel
- Removeable weights are attached to the towers
  - They change the failure modes and the modal properties
- The structure can be instrumented with accelerometers on the box, bridge span, and the towers



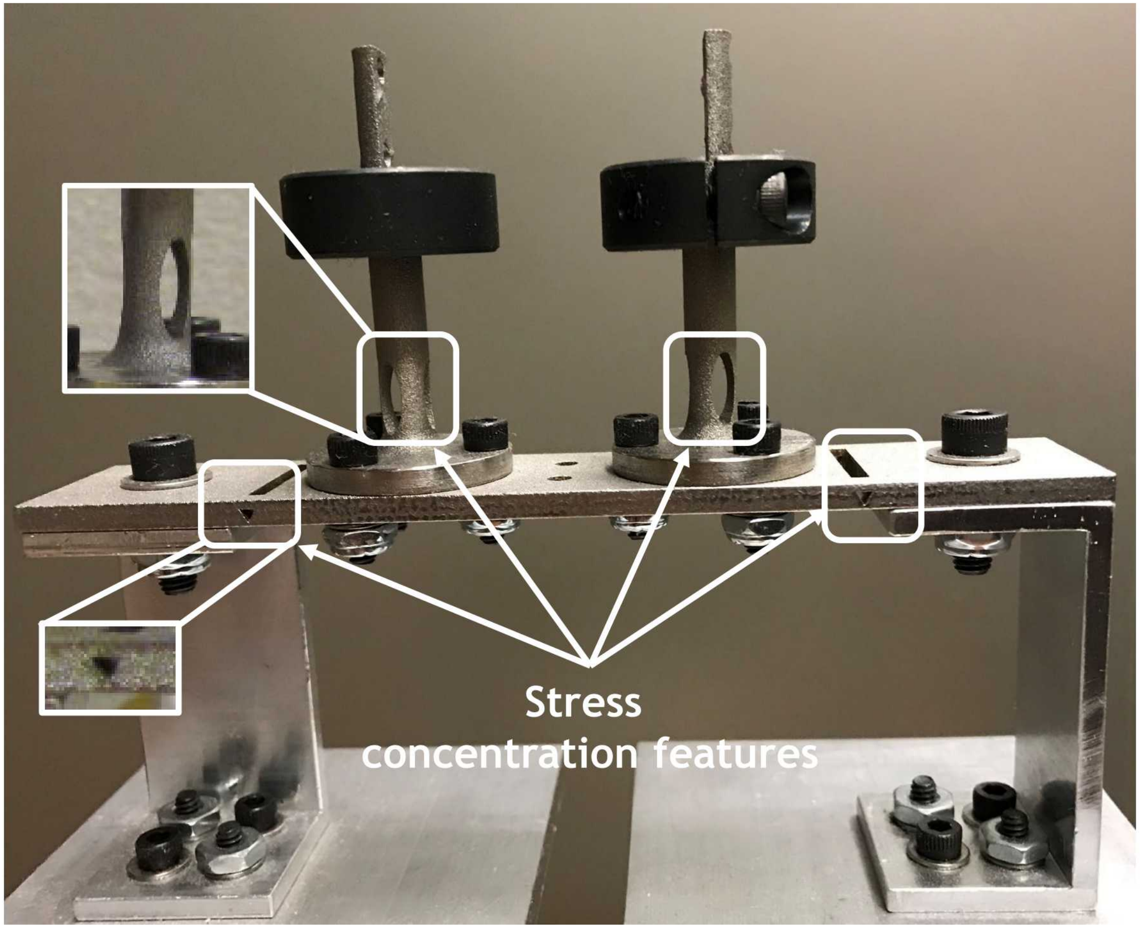
Bridge Structure

The Bridge is the component of interest on the BARBECUE Box

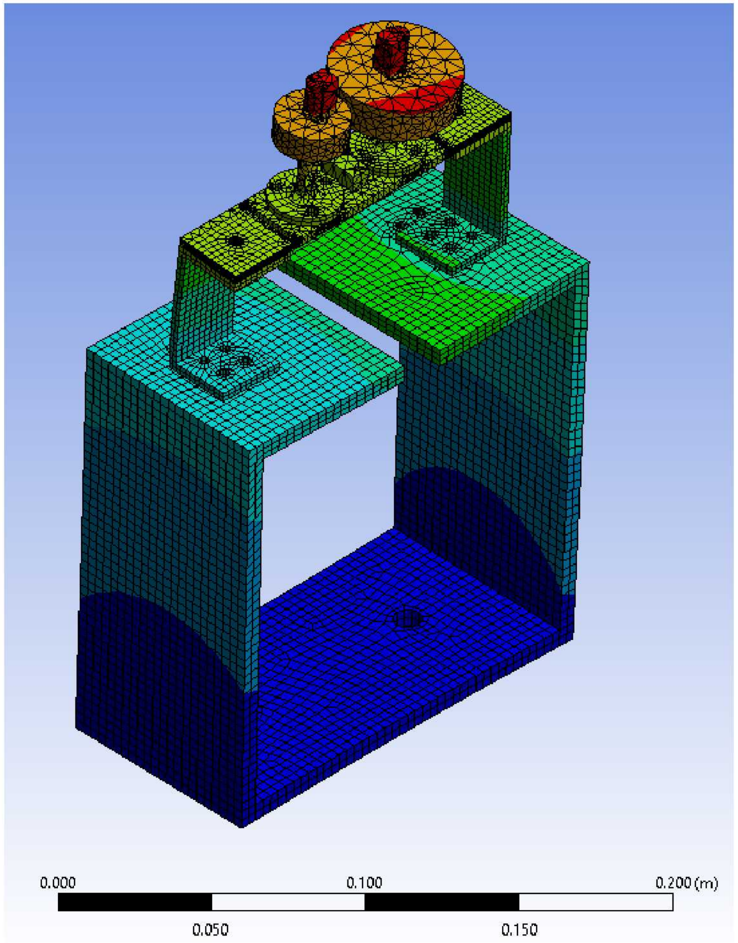
- Shown with 2 medium steel weights

Stress concentration zones are designed into the bridge span and towers

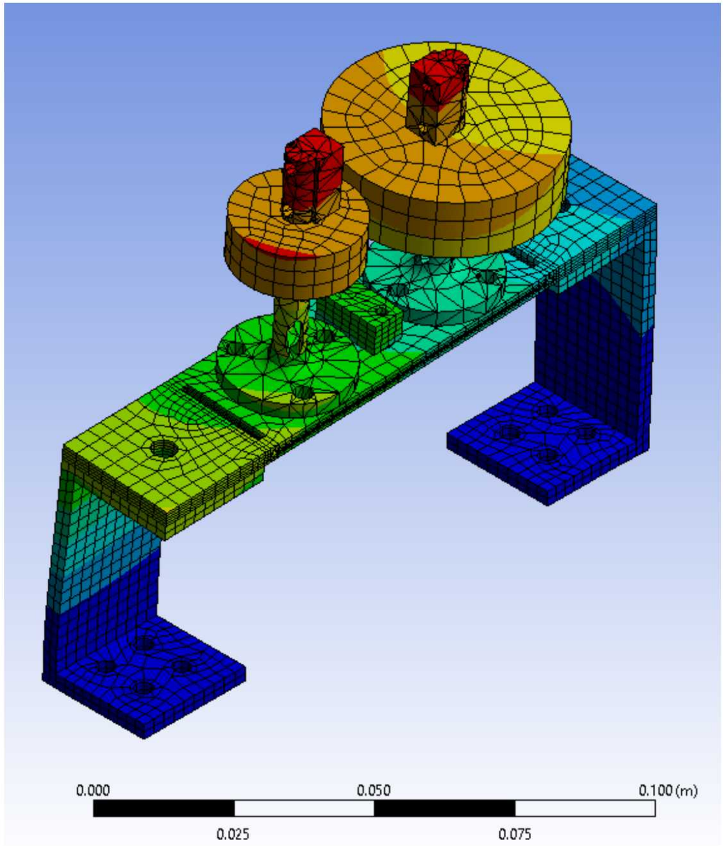
- Elliptical holes in towers and triangular holes in the bridge
- Provide repeatable and consistent failure modes



Mode Shapes – Fundamental Mode

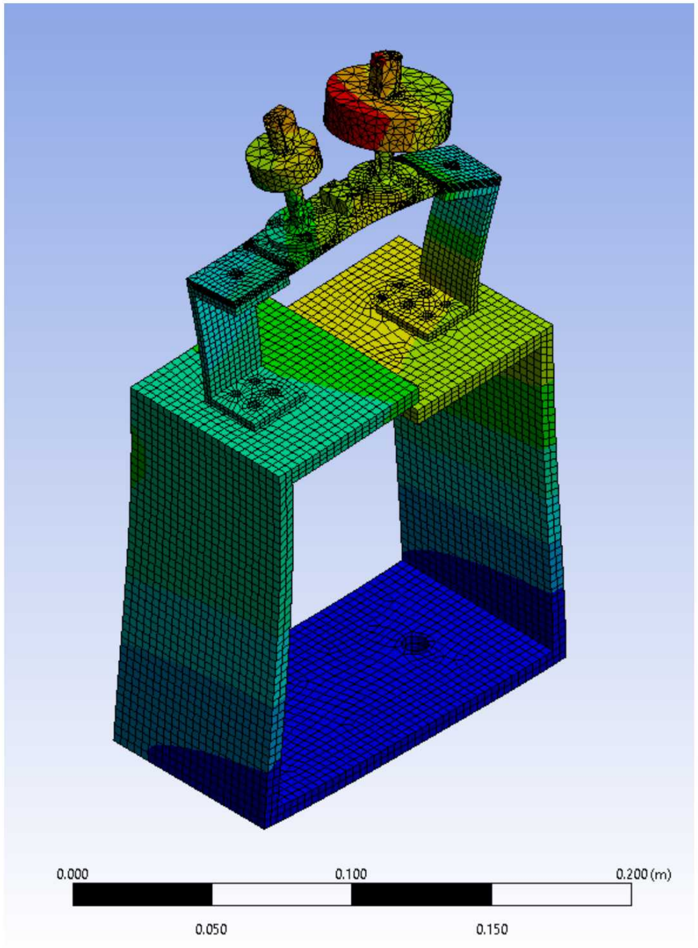


Mode 2, 93 Hz

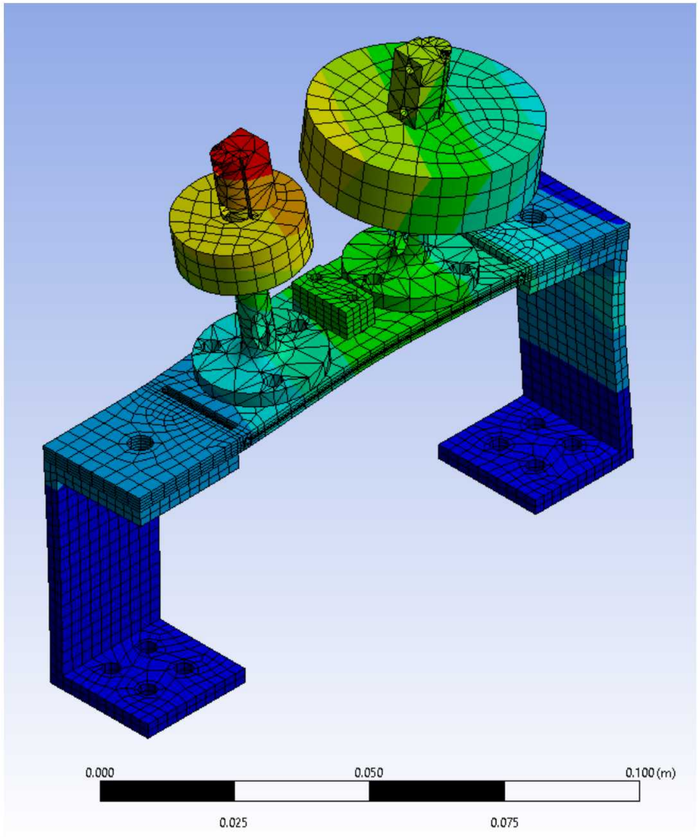


Mode 1, 166 Hz

Mode Shapes – Bridge Bending Mode

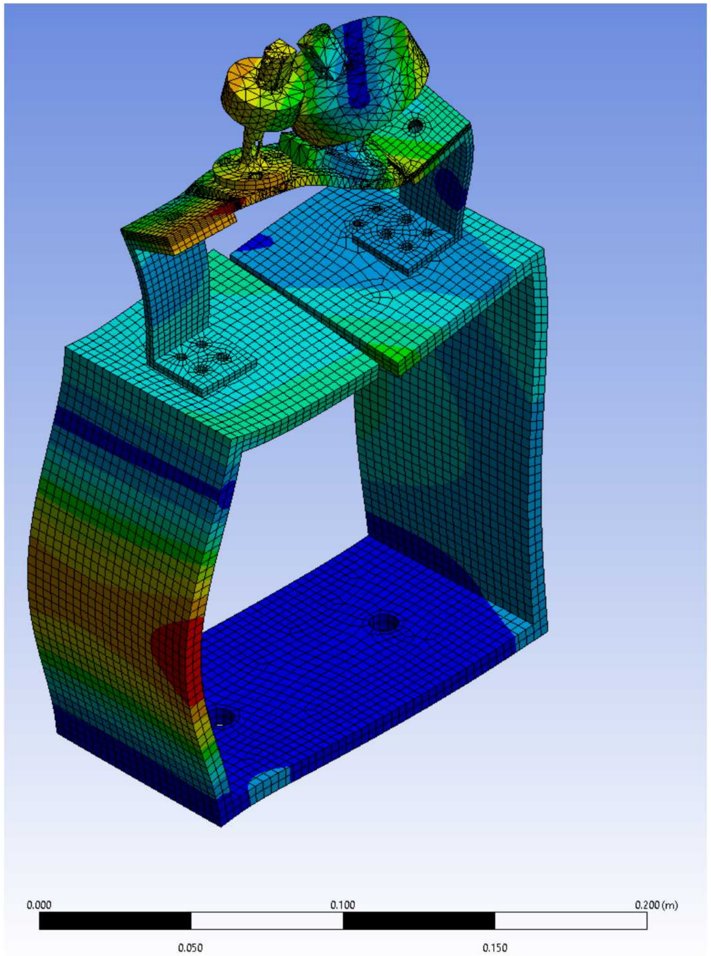


Mode 4, 236 Hz

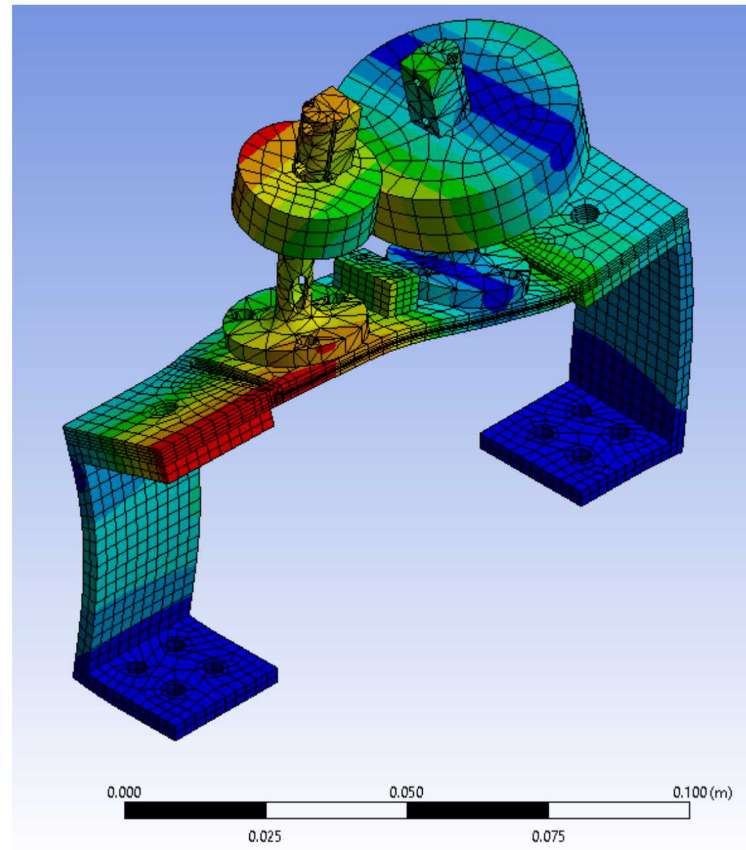


Mode 4, 400 Hz

Mode Shape – Bridge Deformation



Mode 20, 1480 Hz



Mode 11, 1561 Hz

Drop Shock Tests

Drop shocks were performed in the Sandia National Laboratories Shock Laboratory

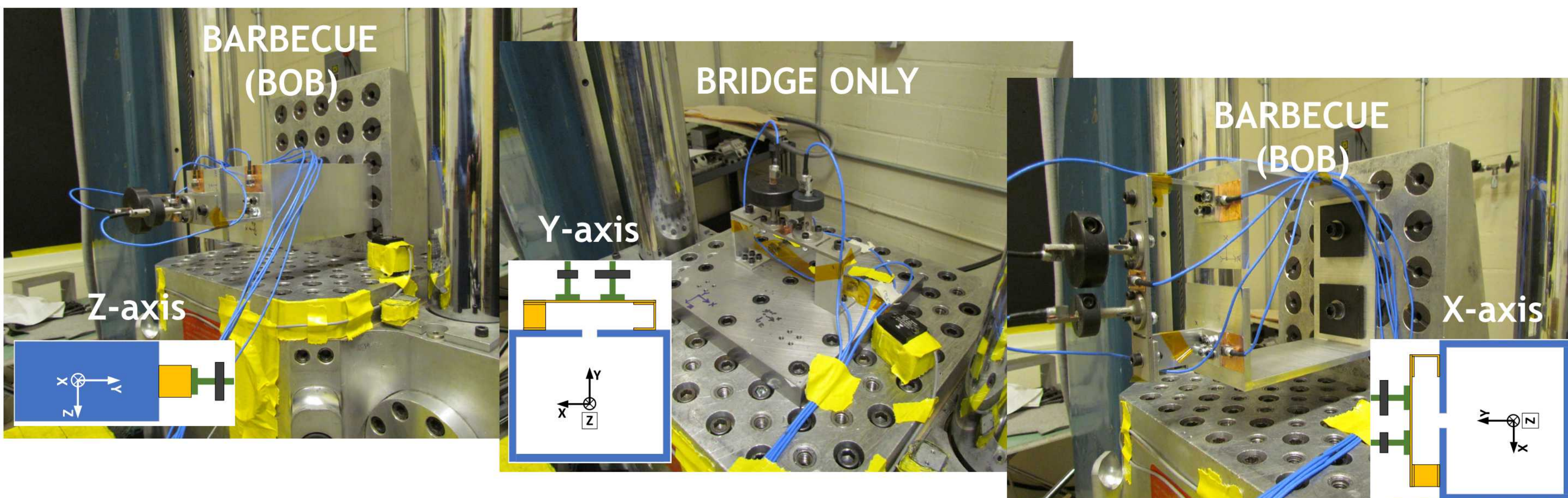
- MTS 12" Accelerated Drop Table
- Systems were mounted on an angle bracket or custom fixtures

Characterization tests

- < 100 G / 1 ms shock pulse (~2" drop height)

Failure Tests

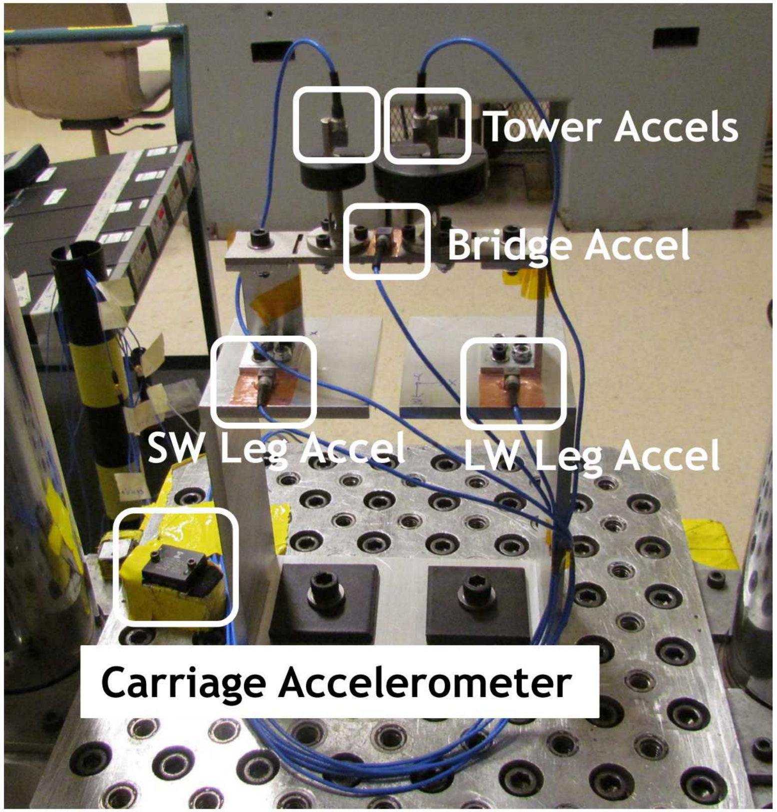
- > 400 G / ~1 ms shock pulses (25" – 85" drop heights)
- Failure was defined as deformation or cracking in a component of interest

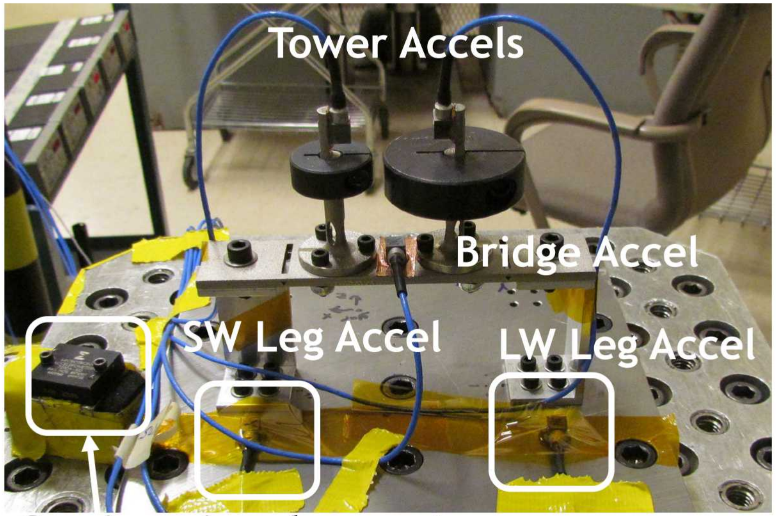


Instrumentation

Accelerometers

- Carriage - Endevco 7290A-100
- System - PE Triax





Carriage Accelerometer

SW = Small Weight
LW = Large Weight

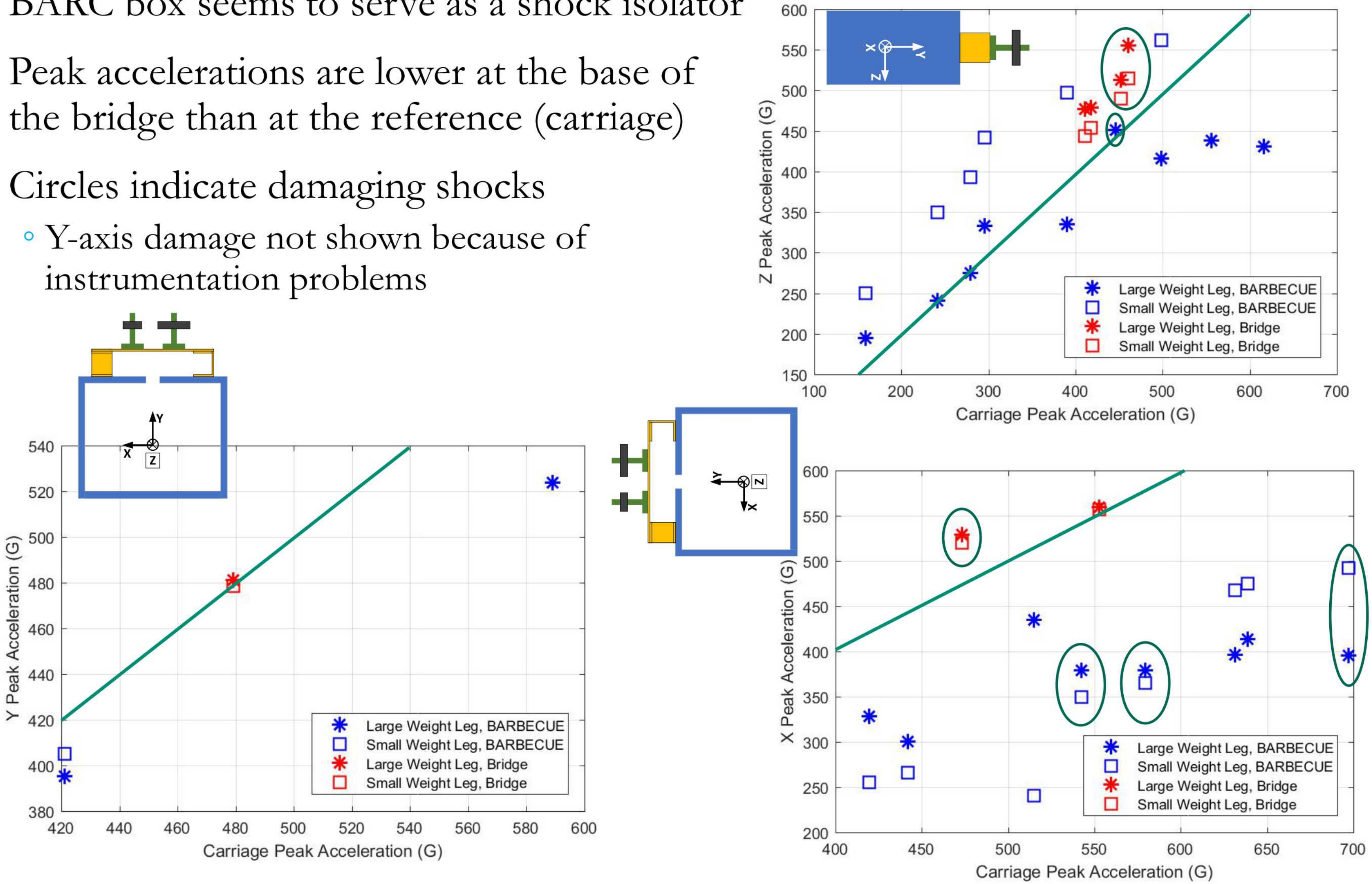
Results – Environment at the Base of the Bridge

BARC box seems to serve as a shock isolator

Peak accelerations are lower at the base of the bridge than at the reference (carriage)

Circles indicate damaging shocks

- Y-axis damage not shown because of instrumentation problems

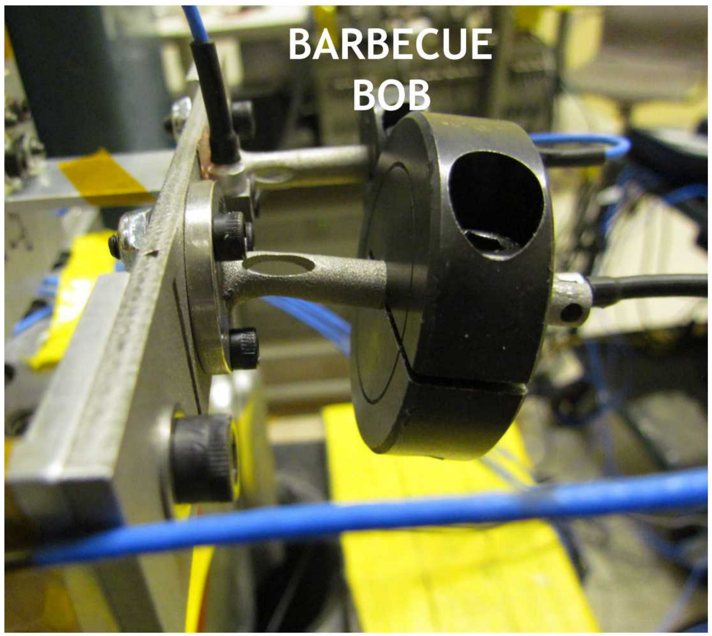


Results – Damage

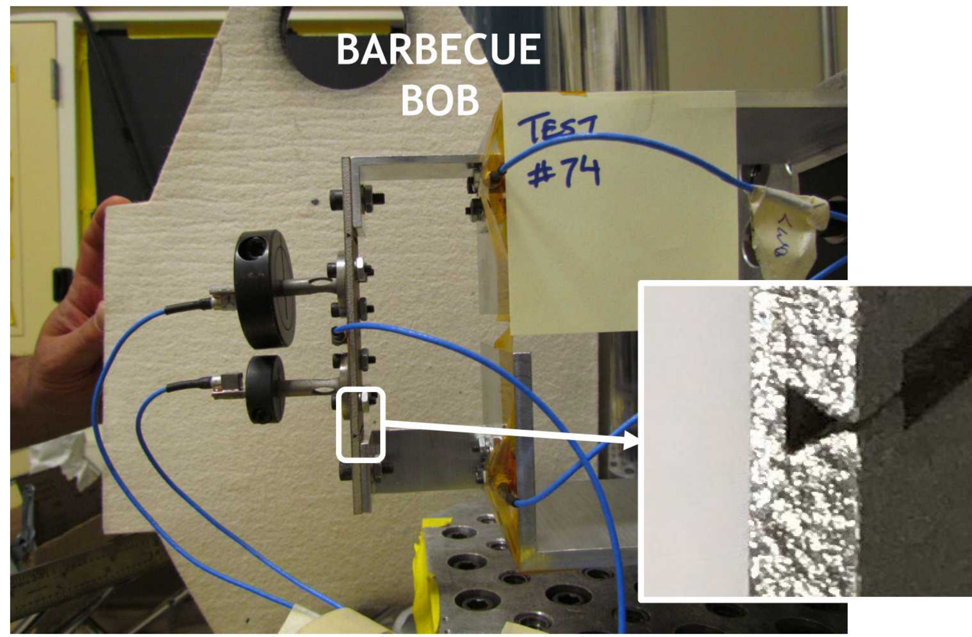
Damage is defined as visible deformation or fracture

Assumption

- Shock effects are not cumulative when the response is in the elastic range
- Shocks that do not cause plastic deformation or fracture are not damaging

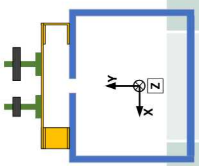


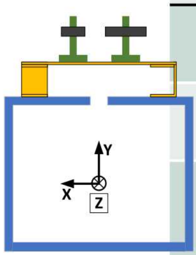
Example of plastic deformation



Example of fracture

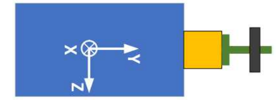
Results – Damage





Configuration	Axis	Test	Drop Height	Carriage Peak G	Damage
BARBECUE	Z	54	35”	445	Large Weight tower considerably bent Small Weight tower slightly bent
BRIDGE	Z	63	30”	451	Large Weight tower slightly bent Small Weight tower slightly bent
BRIDGE	Z	66	30”	550	Large Weight tower slightly bent Small Weight tower slightly bent
BARBECUE	X	73	35”	542	Large Weight tower slightly bent
BARBECUE (same)	X	74	40”	639	Large Weight tower considerably bent Bridge crack on Small Weight side
BARBECUE	X	77	35”	580	Large Weight tower slightly bent Small Weight tower slightly bent
BRIDGE	X	68	25”	493	Large Weight tower considerably bent
BRIDGE	X	70	25”	472	Large Weight tower considerably bent
BARBECUE	Y	82	45”	707	No damage
BRIDGE	Y	89	60”	719	Bridge bent on Small Weight side
BRIDGE (same)	Y	93	85”	1029	Bridge Small Weight side leg bent Large Weight tower buckled Bridge considerably bent on Small Weight side

Results – Peak Acceleration (Z-axis)



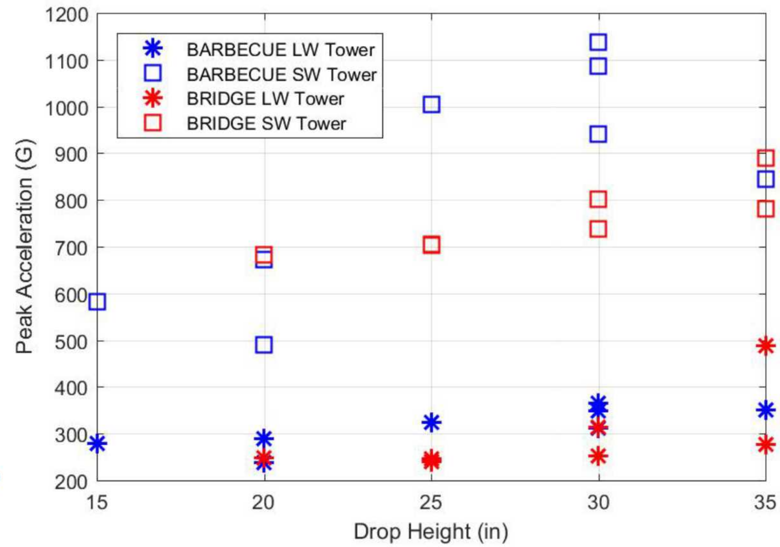
Small tower acceleration is consistently larger but large weight tower suffers more damage

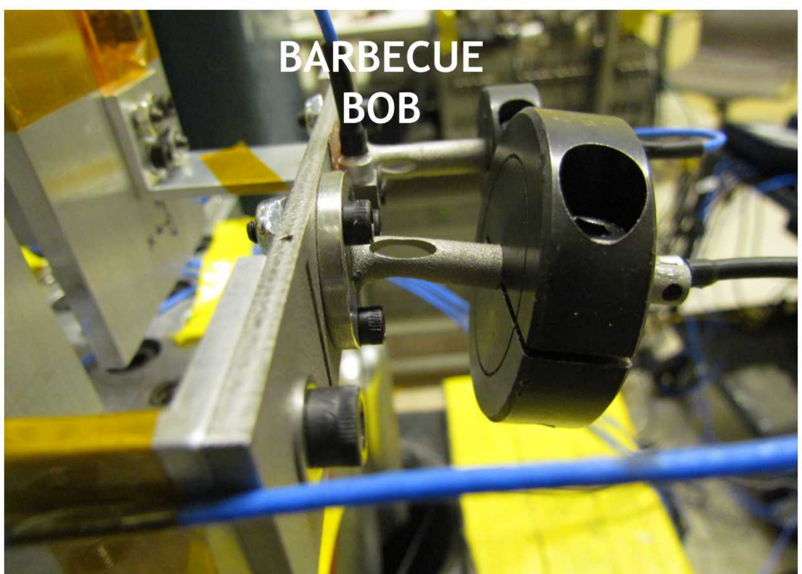
There is a compliant component in the load path

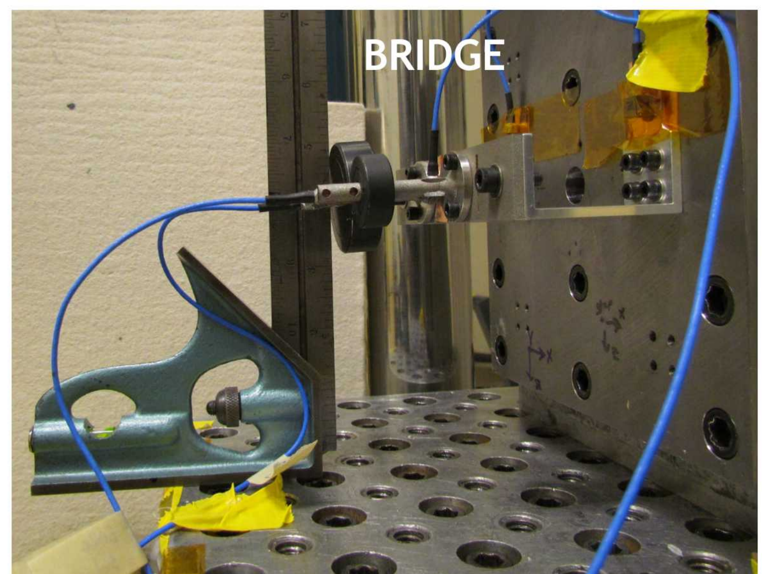
Independent of boundary conditions

- The box is comparatively rigid

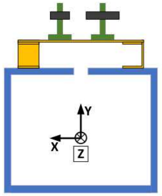
Peak acceleration may not be a good predictor of damage potential







Results – Peak Acceleration (Y-axis)



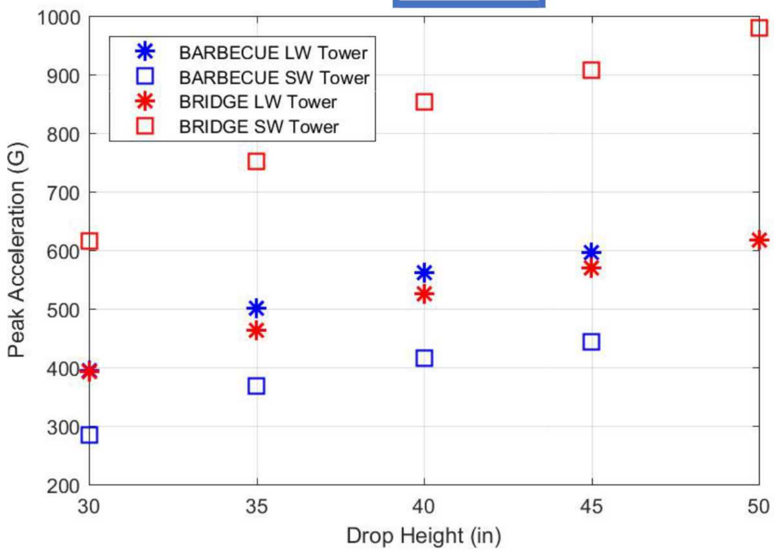
BARBECUE – LW tower acceleration is larger

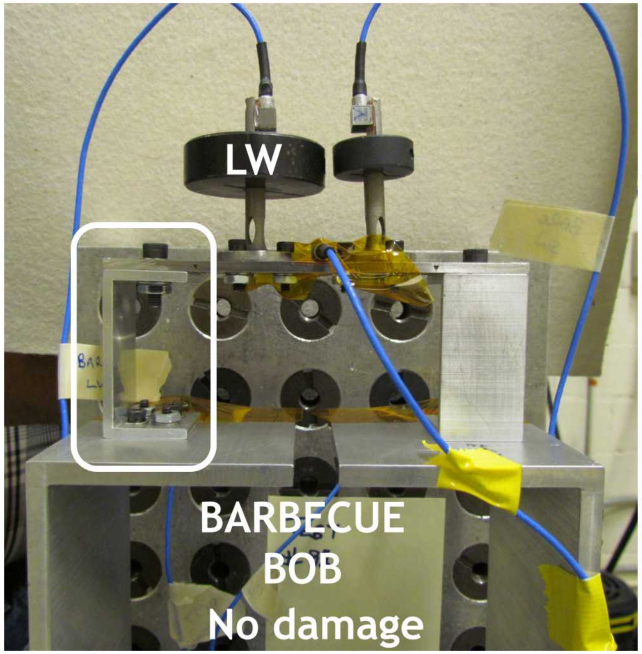
BRIDGE – SW tower acceleration is larger

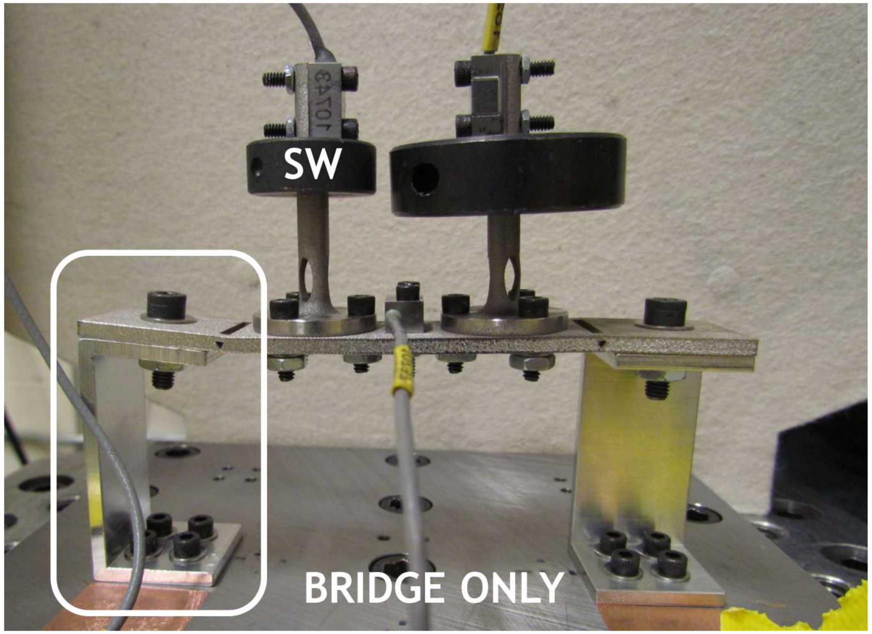
Acceleration is higher on the side with the inward leg

Compliance of the component is important

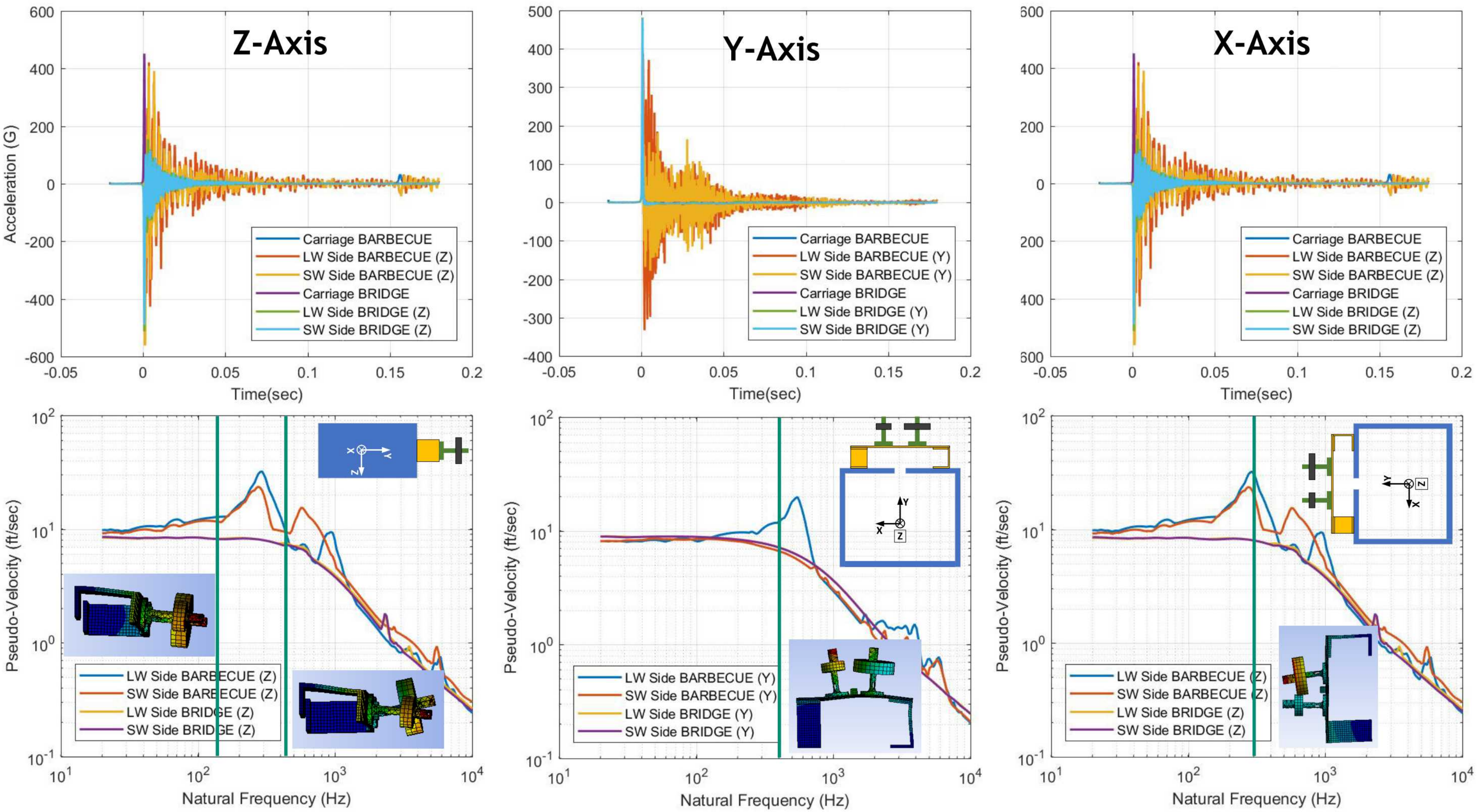
The BARC box acts as a shock isolator







Results – Bridge Base PVSRS



ANSYS model has not been correlated

- Work in progress

Results – Input Energy

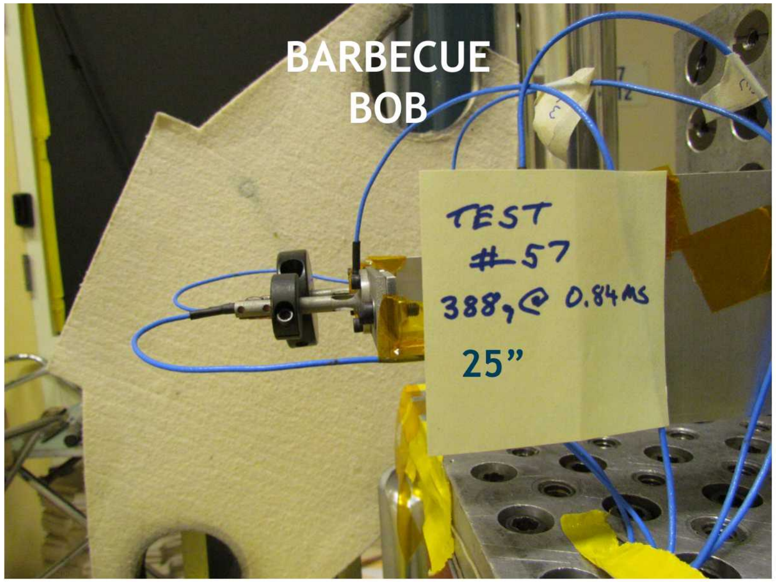
Input energy is the integral of a base acceleration and the relative velocity

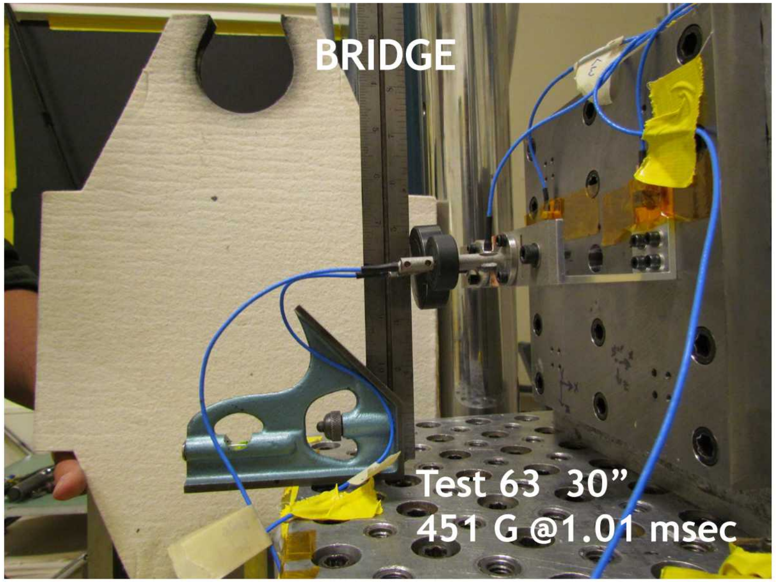
$$E_I(t) = -\int_{t_0}^{t_f} \ddot{z}(t)\dot{w}(t)dt$$

Must select the base acceleration

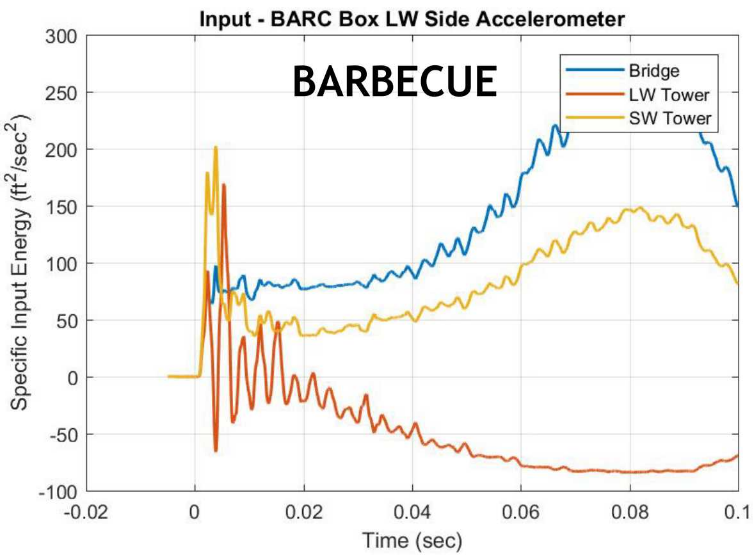
- Towers – base acceleration can be:
  - Bridge acceleration
  - Box acceleration (BARBECUE only)
  - Carriage acceleration
- Bridge – base acceleration can be:
  - Box acceleration (BARBECUE only)
  - Carriage acceleration

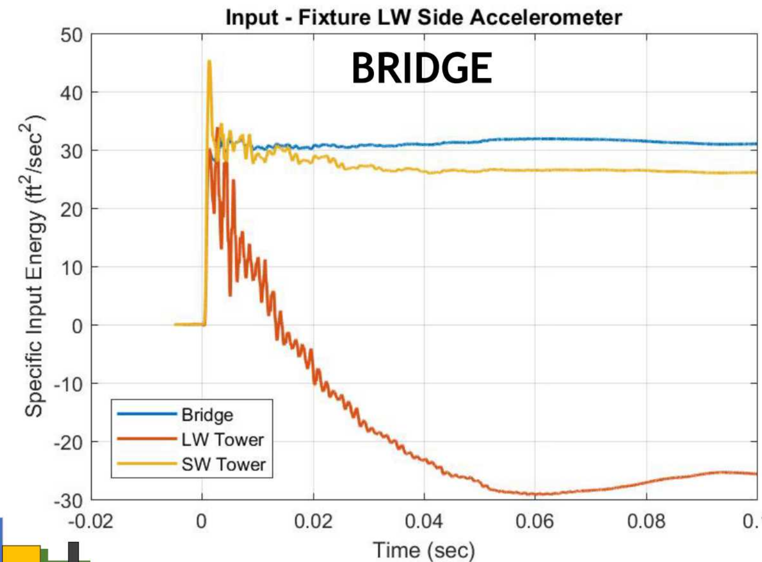
Look at cases with similar damage

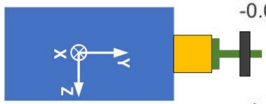


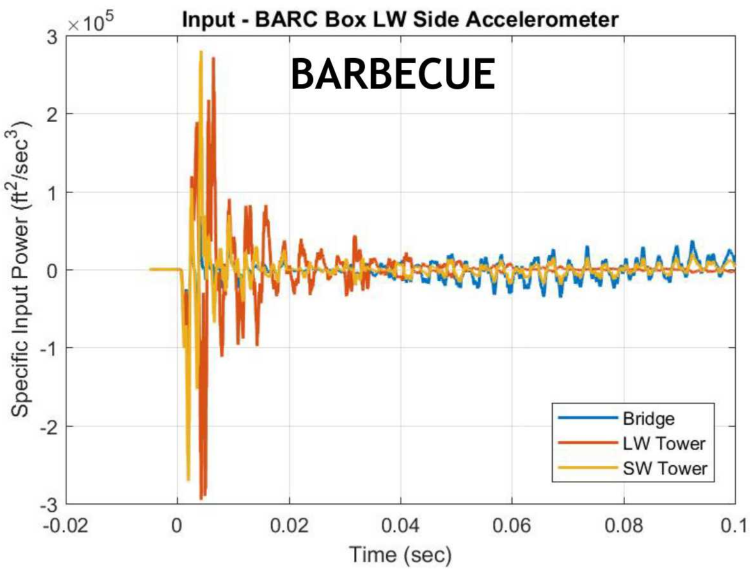


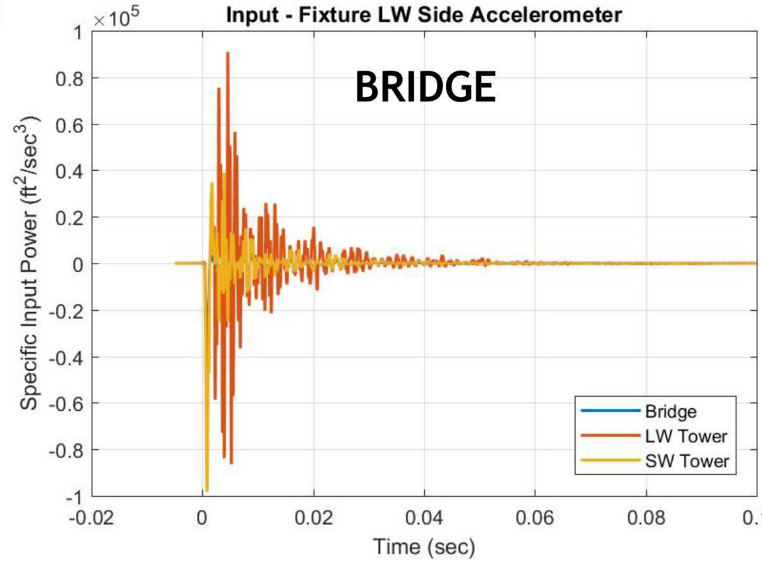
Results – Z-axis Input Energy (Input at Bridge Base)











Results – Input Energy

For input at the base of the bridge

- BARBECUE peak input energy is higher for all 3 components

For input on the bridge

- Initial peak input energy at the LW tower is higher in the BRIDGE configuration
- Initial peak input energy at the SW tower is higher in the BARBECUE configuration

The input energy sign depends on the phasing of the relative velocity and input acceleration

Did not estimate dissipated energy because of difficulty with integration to compute relative displacement

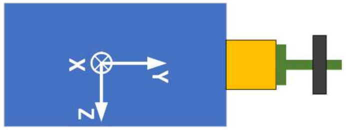
Results – Damage and QoIs

Configuration	Drop Height	Accel Loc	Peak G	Input Energy	Damage
Z-axis BARBECUE (54)	35”	CR	445	N/A	Large Weight tower considerably bent Small Weight tower slightly bent
		BR	402	100	
		LW	352	169	
		SW	844	202	
Z-axis BRIDGE (63)	30”	CR	451	NA	Large Weight tower slightly bent Small Weight tower slightly bent
		BR	331	32	
		LW	253	34	
		SW	739	45	
Z-axis BRIDGE (66)	30”	CR	550	NA	Large Weight tower slightly bent Small Weight tower slightly bent
		BR	352	41	
		LW	314	44	
		SW	801	55	

CR = Carriage; BR = Bridge; LW = Large Weight; SW = Small Weight

Table shows 1st damaging shocks for undamaged unit

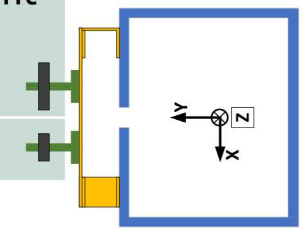
Input is at the base of the bridge on the LW side



Results – Damage and QoIs

Configuration	Drop Height	Accel Loc	Peak G	Input Energy	Damage
X-axis BARBECUE (73)	35”	CR	542	N/A	Large Weight tower slightly bent
		BR	290	131	
		LW	205	182	
		SW	571	357	
X-axis BARBECUE (77)	35”	CR	580	N/A	Large Weight tower slightly bent Small Weight tower slightly bent
		BR	NaN	N/A	
		LW	234	62	
		SW	522	359	
X-axis BRIDGE (69)	30”	CR	553	N/A	Large Weight tower slightly bent (2nd drop; 1st damage at 25”)
		BR	560	42	
		LW	1153	53	
		SW	1264	57	
X-axis BRIDGE (70)	25”	CR	473	N/A	Large Weight tower considerably bent
		BR	541	34	
		LW	339	37	
		SW	726	57	

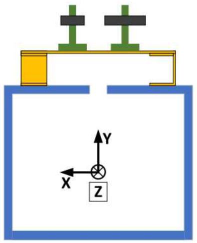
CR = Carriage; BR = Bridge; LW = Large Weight; SW = Small Weight



Results – Damage and QoIs

Configuration	Drop Height	Accel Loc	Peak G	Input Energy	Damage
Y-axis BARBECUE (82)	45”	CR	707	N/A	No damage
		BR	NaN	N/A	
		LW	595	190	
		SW	443	210	
Y-axis BRIDGE (86)	45”	CR	690	N/A	No damage
		BR	NaN	N/A	
		LW	617	104	
		SW	980	95	
Y-axis BRIDGE (89)	60”	CR	345	N/A	Bridge bent on Small Weight side
		BR	351	74	
		LW	314	56	
		SW	801	79	
Y-axis BRIDGE (93)	85”	CR	345	N/A	Bridge Small Weight side leg bent Large Weight tower buckled Bridge considerably bent on Small Weight side
		BR	351	N/A	
		LW	314	118	
		SW	801	161	

CR = Carriage; BR = Bridge; LW = Large Weight; SW = Small Weight



Summary and Conclusions

Question

- How do boundary conditions affect damage potential or component robustness under shock excitation in the laboratory?
- It is complicated

Shock damage sensitivity to boundary conditions depends on the relative flexibility between the component and the structure to which it is attached

- Test and configuration dependent
  - In the Z-axis case, the BARC box is stiffer than the bridge so its presence was not critical to component robustness to drop shock events
  - In the Y-axis the BARC box introduced flexibility into the load path (acted as a shock isolator) so it was a contributor to damage sensitivity

Loading is important in assessing boundary condition sensitivity

- Modal frequency differences associated with boundary condition differences should be evaluated with respect to the shock characteristics

Acceleration may not be a good QoI for damage sensitivity

Input energy did not provide as much insight as I had hoped