LOCKHEED MARTIN

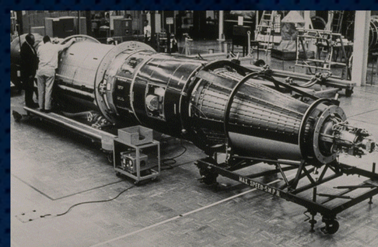
Corporate Overview 2015

September 29th, 2015

Lockheed Martin





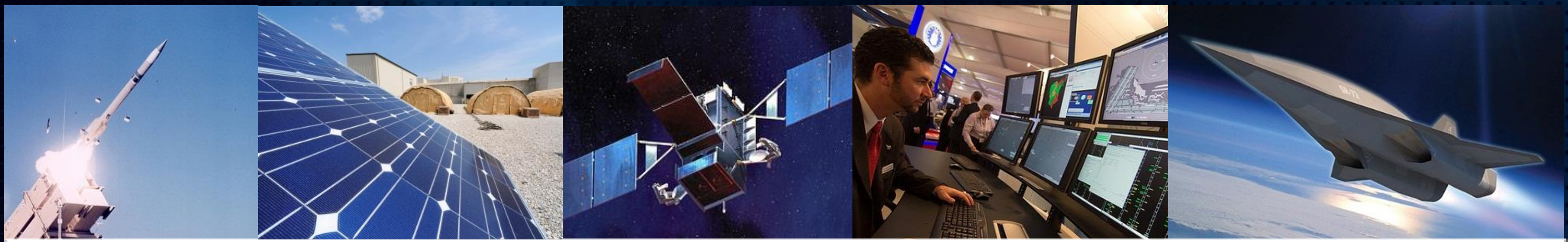






100 Years of Accelerating Tomorrow

Vision



Be the Global Leader in Supporting Our Customers to
Strengthen Global Security,
Deliver Citizen Services, and
Advance Scientific Discovery

The Men and Women of Lockheed Martin

- 112,000 employees
- 60,000 scientists, engineers and IT professionals
- 500 + facilities across the US
- Operating in 70 countries with over 7,000 personnel

Partners Helping Customers Achieve Their Goals

Lockheed Martin Business Structure

Aeronautics

Information Systems & Global Solutions

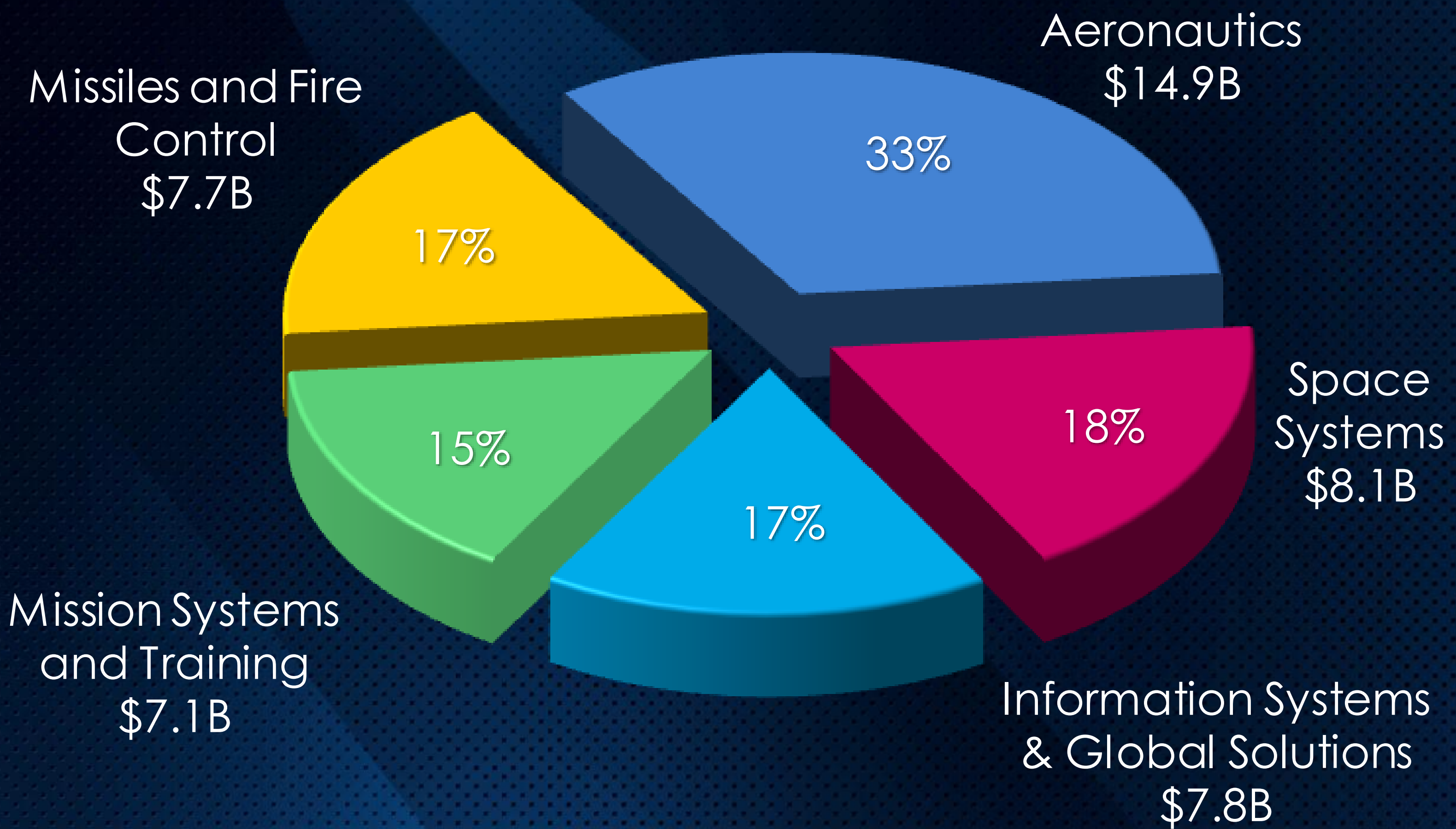
Missiles & Fire Control

Mission Systems & Training

Space Systems

International

2014 Sales by Business Area



Total Sales - $45.6B

LOCKHEED MARTIN

QuadCity Manufacturing Lab

DOE Nuclear Energy Enabling Technologies (NEET) AMM

Direct Manufacturing of Nuclear Power Components

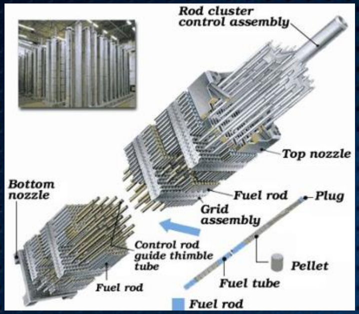
September 29th, 2015

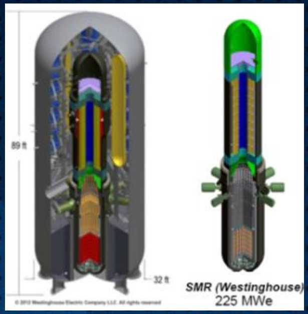
Acknowledgment: "This material is based upon work supported by the Department of Energy, Office of Nuclear Energy, Idaho Operations, *under Award Number DE-NE0000542"*

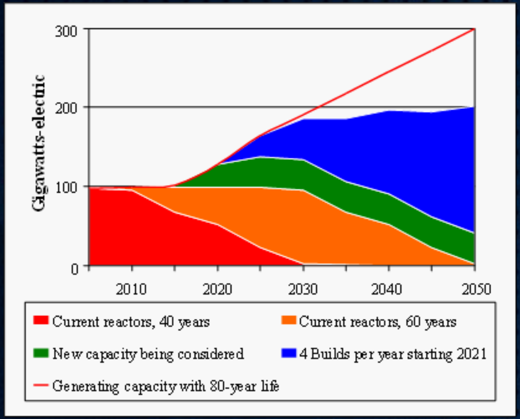
NEET Program Introduction

- Purpose:
  - Support U.S. development to thrive in $B international market for nuclear power additive technologies that significantly reduce development and operational costs and manufacturing lead time for nuclear Rx components
- Objectives:
  - Develop baseline and advanced rad tolerant alloys
    - Investigate nanophase modification
    - Identifying reduced life cycle costs
  - Demonstrate cost and schedule reduction using additive methods.

- Approach:
  - Build manufacturing demonstrations of complex parts demonstrating design flexibility and shortened design-to-manufacturing cycles
  - Employ nanophase alloy modification via Laser Direct Manufacturing (LDM) to create enhanced rad tolerant components
  - Explore cost and schedule benefits through case study and business case analysis







Advanced/Affordable Manufacturing Methods are Key Enablers for competing in $700B global market

Overview

- Materials selection
- Fabrication and characterization of alloy samples – Nanoscale modification
- ODS SS Development
- Demo Fabrication
- Manufacturing Study
- Path Forward

	Inconel 600	Inconel 718	Inconel 800	316L SS	ODS 316L SS
LDM Trials	Complete	Complete	Complete	Complete	Complete
Microstructures	Complete	N/C	N/C	Complete	Complete
Mechanical Properties	Complete	N/C	N/C	Complete	N/C
Test Specimens	Complete	Complete	Complete	Complete	Complete
Demo Articles	Complete (3x3*, 10x10 and 15x15)	Complete (3x3*)	Complete (3x3*)	Complete (3x3)	N/A

**** Baseline 3x3 and thin wall demo samples***

Baseline & Alternative Alloys

Comparison criteria for selection of alternative nuclear materials

Comparison criteria

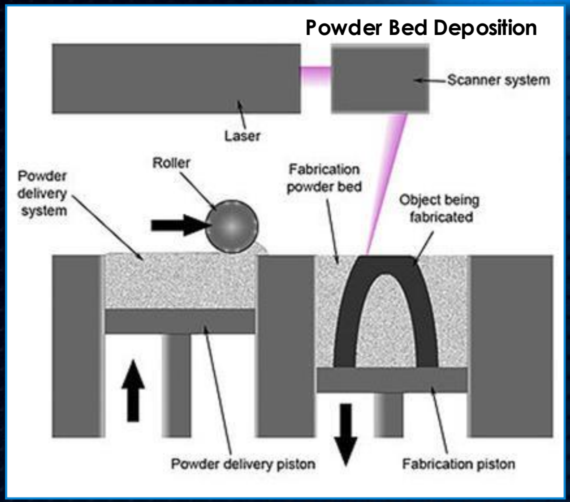
- Low neutron absorption
- Elevated temperature mechanical properties
  - Creep resistance
  - Long-term stability
  - Compatibility with reactor coolant
- Resistance to irradiation-induced damage (greater than 200 dpa)
  - Radiation hardening and embrittlement
  - Void swelling
  - Creep
  - Helium-induced embrittlement
  - Phase instabilities

Alternate Nuclear Materials

- BASELINE: Traditional ferritic/martensitic steels (HT-9) or later generations of F/M steels
- OPTION 1: ODS steels to examine effect of direct manufacturing methods on nanoscale oxide domains
- OPTION 2: Inconel 800 series of materials to study the effect of processing parameters offered by direct manufacturing methods to improve performance under irradiation
- OPTION 3: Among the refractory alloys, the Mo (TZM) alloys. These have a high operating temperature window and also, the most information on irradiated material properties

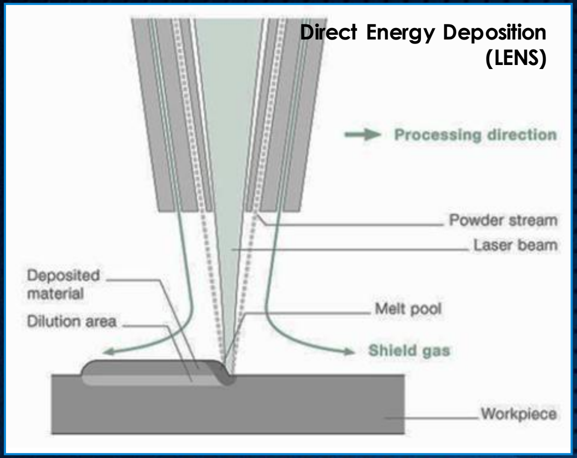
Based on customer discussions, materials down-selected to 316L SS, Inconel alloys and ODS steels

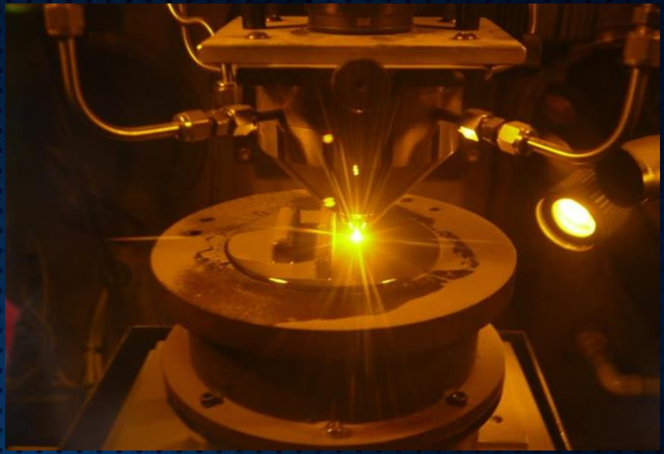
Metal AM Technologies – Powder Bed Fusion and Beam Deposition



Applications
- Functional prototype parts
- Legacy parts
- Parts with complex geometries
- Small production runs

Equipment at QCML
- EOSINT M270 Extended-Ti
- Build Vol: 9.85" x 9.85" x 8.5"





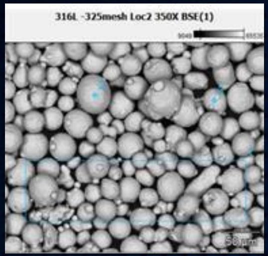
Applications
- Laser Cladding
- Part fabrication
- Adding features to parts
- Part repair

- Equipment at QCML
  - Customized 4-axis Cell
    - 48" h x 20" w x 20" d x 360° roll
  - Customized 3-axis Cell
    - 12" x 12" x 10"

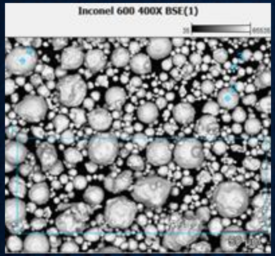
Powder bed and Beam deposition methods were both utilized in samples processing

Approach to Samples Development

- Method of Fabrication
  - Powder bed dep. process
    - 316L SS, Inconel alloys (600, 718, 800)
  - Beam deposition method
    - ODS – 316L SS
- Availability of powders
  - Particle size
  - Specification
- Parameter optimization for QCML Electro Optical System (EOS)
  - Alternative alloys
  - Scan speed
  - Laser power



316L SS -325 mesh

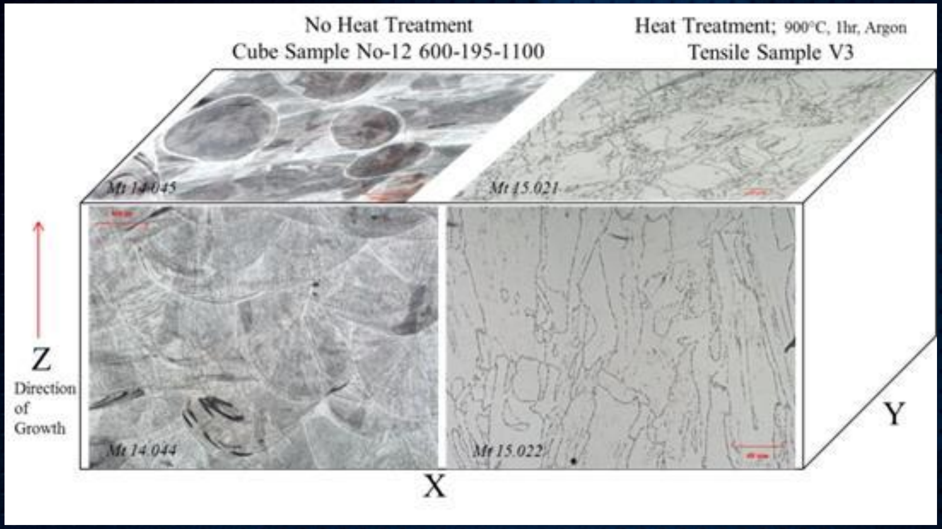


Inconel 600

	Inconel 600	Inconel 718	Incoloy 800
Chemical composition (%)	72 **Ni**, 14-17 **Cr**, 6-10 **Fe**, 0.15 max **C**, 1 max **Mn**, 0.015 **S**, 0.50 **Si**, 0.50 **Cu**	50-55 **Ni**, 17-21 **Cr**, 11-22.5 **Fe**, 0.08 max **C**, 0.35 **Mn**, 0.015 **S**, 0.35 **Si**, 0.3 **Cu**, 0.2-0.5 **Al**, 0.65-1.15 **Ti**, 0.015 **P**, 1 **Co**, 4.75-5.5 **Nb**, 0.006 **B**, 2.8-3.3 **Mo**	30-35 **Ni**, 19-23 **Cr**, 39.5 min **Fe**, 0.1 max **C**, 0.8 max **MN**, 0.008 max **Si**, 0.4 **Cu**, 0.15-0.60 **Al**, 0.15-0.60 **Ti**,
Melting point (F)	2470-2575° F	2300-2435°F	2471-2525°F
Density (g/cm³)	8.47	8.19	7.94
Crystal structure*	FCC	FCC	BCC or FCC
Process parameter study conditions: Power (W)	150 - 195	150 - 195	150 - 195
Process parameter study conditions: Scan Speed (mm/s) in increments of 100	800-1400	800-1400	800-1400
Density (g/cm³) data range results:	8.29-8.39	8.11-8.20	7.80-7.91
Test coupon build conditions:	195 W, 1100 mm/s	195W, 1200mm/s	195W, 1200mm/s

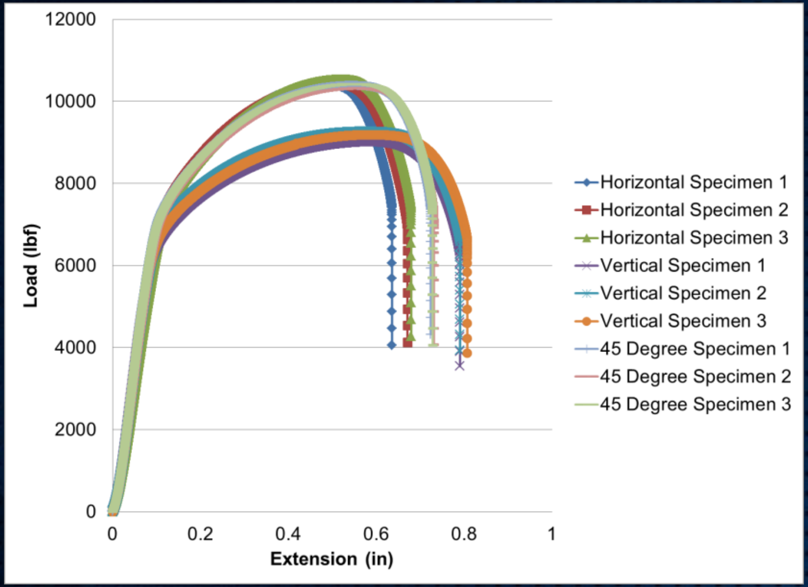
Inconel 600 Results

Microstructure Inspection



Etched Inconel 600 non heat treated vs. heat treated

Mechanical Performance

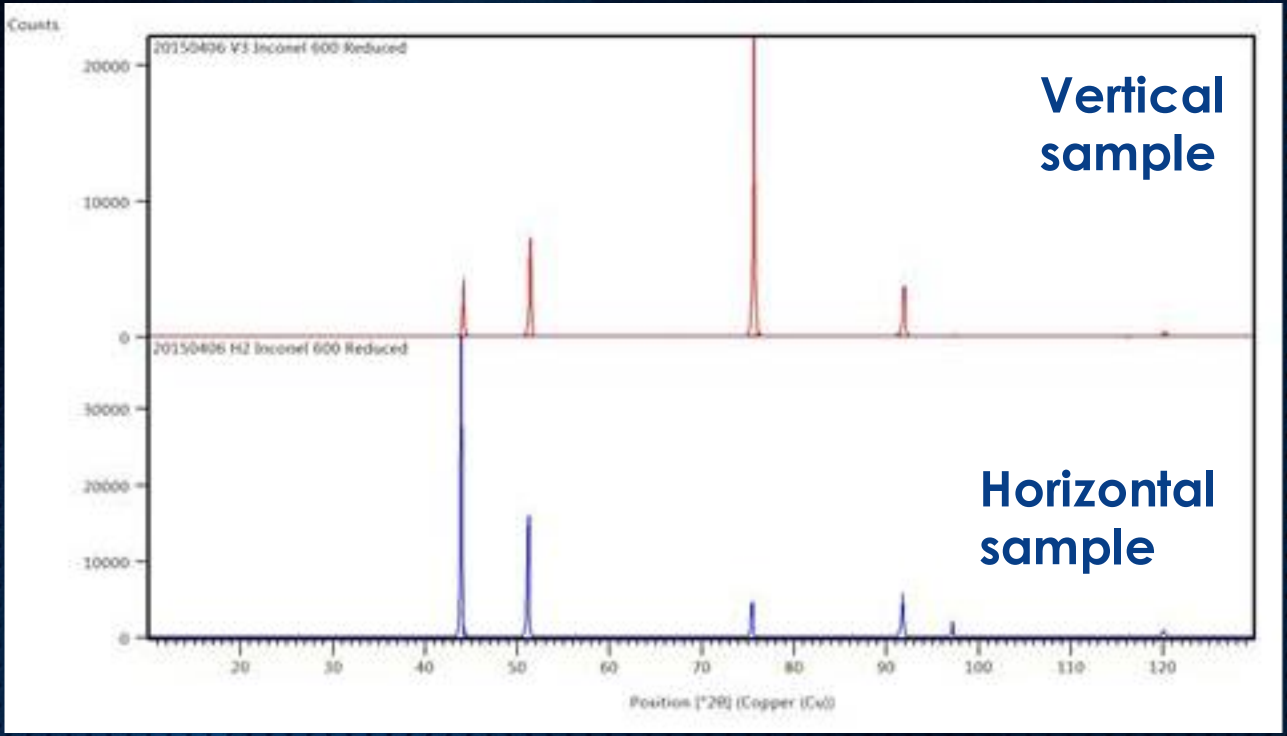


Inconel 600 horizontal, vertical and 45° specimen mechanical testing

The directionality of manufacture has impact on the grain structure and the maximum tensile strength

XRD data on Inconel 600 AM samples

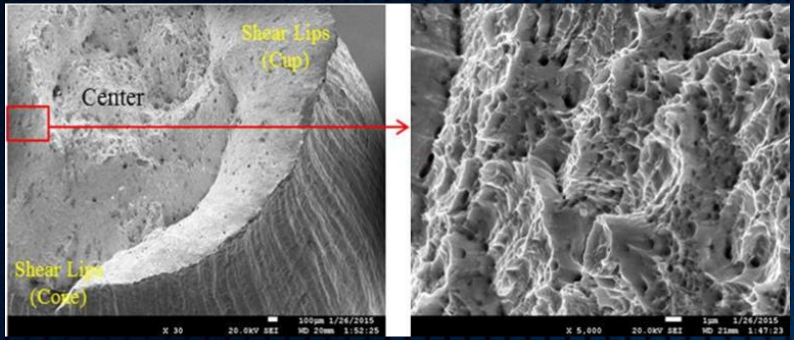
- XRD data shows the differences in peak ratios between the horizontally and vertically built specimens

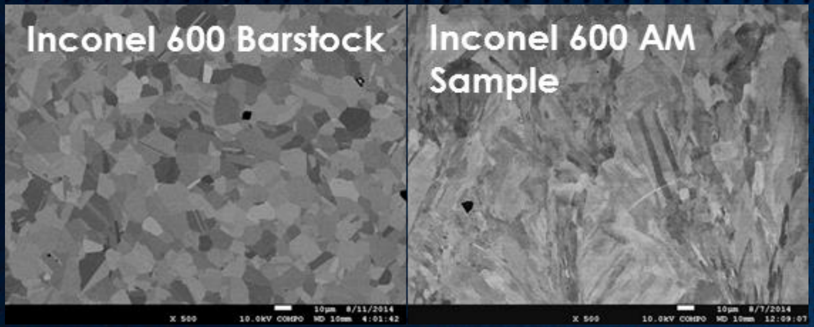


- Data supports directional solidification texturing seen in the micrographs

Summary of Sample Fabrication and Characterization

- Mechanical testing of AM samples shows directional dependence
- Optical micrographs show the laser solidification patterns for both planes
- Fracture surface analysis showed ductile cup-and-cone fracture
- Tensile and hardness properties comparable to bar stock
- XRD data supports observation of preferential grain growth
- Microstructure control possible by varying process parameters

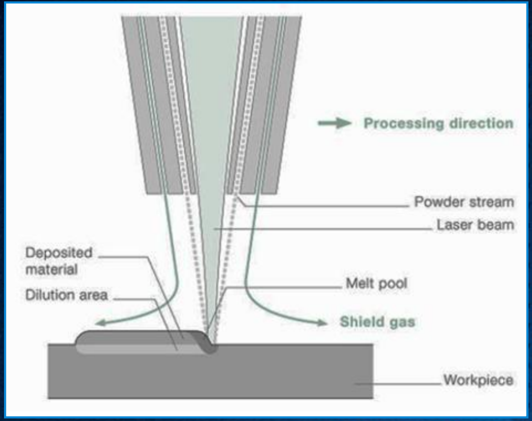




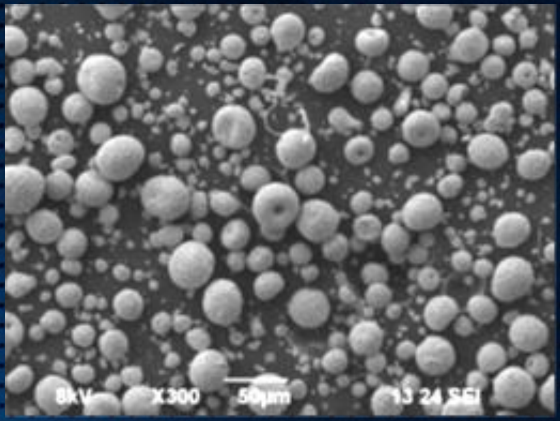
316L SS and Inconel alloys demonstrated bar stock performance w/ potential for designing to preferential directionality

Experimental Alloy – ODS 316L-SS

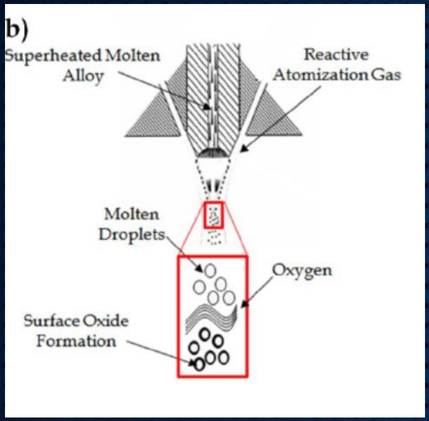
- Introduction of stable nanoscale phases of carbides, nitrides and oxides is method of obtaining high-temp strength
- Oxide Dispersed Strengthened (ODS) steels to examine effect of direct manufacturing methods on nanoscale oxide domains
- ODS powders not readily available
- Three methods explored to make the ODS steel powders:
  - Spray drying technique – Flurry Powders
  - Gas atomization reaction synthesis – Ames Laboratory (Anderson)
  - Mechanical Ball milling



LENS Beam Dep Process



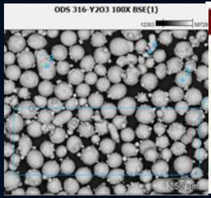
Spray Drying Formulation (Flurry)



Gas Atomization (Ames)

ODS Trials / Samples / Summary

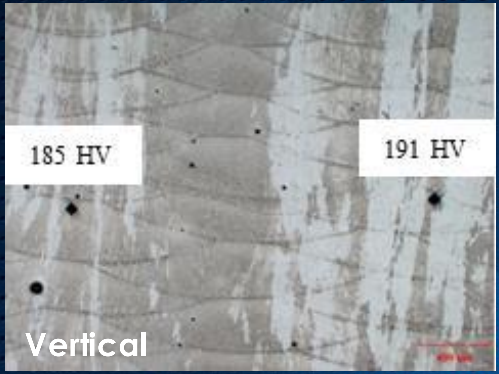
- Ball milling technique successful in creating ODS powder
- Developed process based on best initial parameters – process not optimized
- Microstructure showed rapid solidification
- Yttria identified in EDS sample data
- Laser melt pools visible
- Hardness data (one sample only) correlates to the hardness to 316L SS
- HIP samples – to be tested and examined



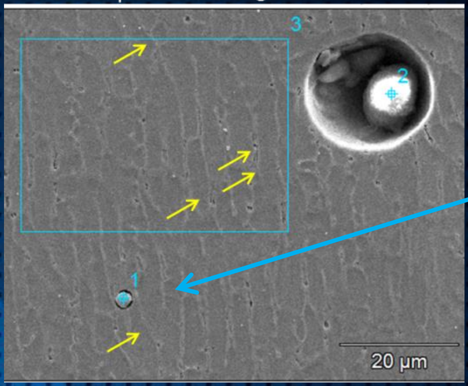
	O	Si	S	Cr	Mn	Fe	Ni	Y	Mo
ODS 316-Y2O3 pt1	5.0	0.6	0.3	16.0	1.8	59.2	8.9	7.3	0.9
ODS 316-Y2O3 pt2	4.5	0.6	0.2	15.3	1.6	60.4	9.8	6.5	1.2
ODS 316-Y2O3 pt3	4.3	0.7	0.0	15.1	1.2	64.8	10.1	2.3	1.6
ODS 316-Y2O3 pt4	1.4	0.2	0.0	16.5	2.4	66.4	7.5	5.2	0.4
No Spec for ODS									

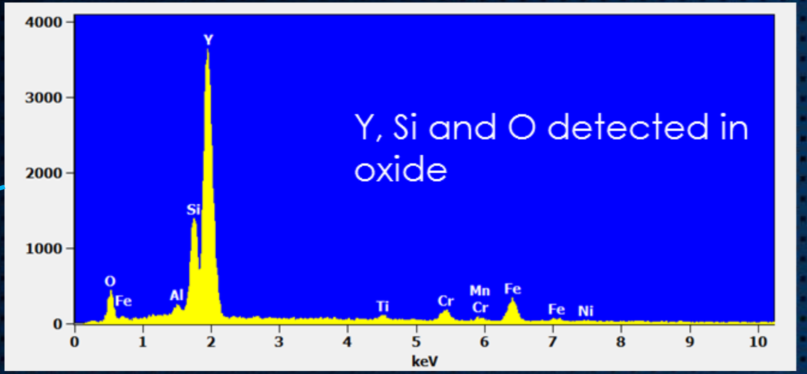
ODS Powder Formulation

Process Development Trials



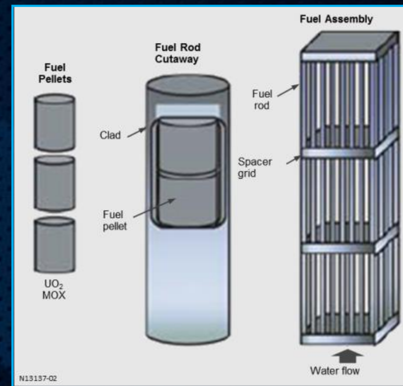
Sample A 7.862 gm/cm³

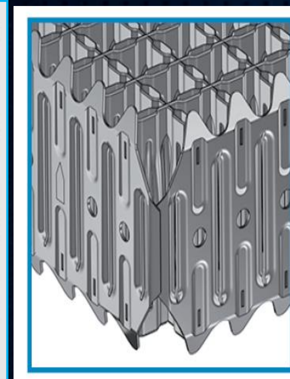


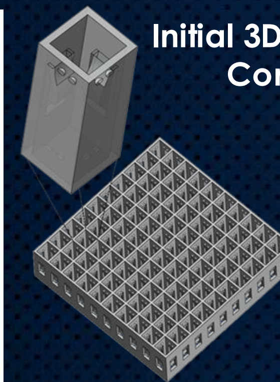


Demonstration Approach/Builds

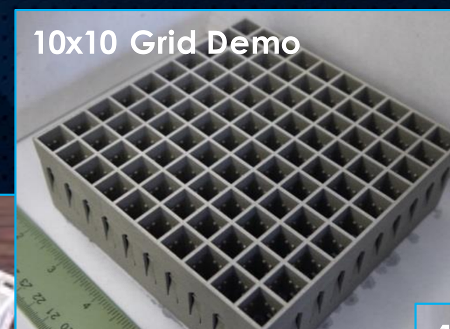
- Defined reactor component
- Developed notional design based on literature
- Explored collaborations to obtain actual CAD drawing
- Rapid prototyping
- Fabrication based on material process development
- Dimensional study



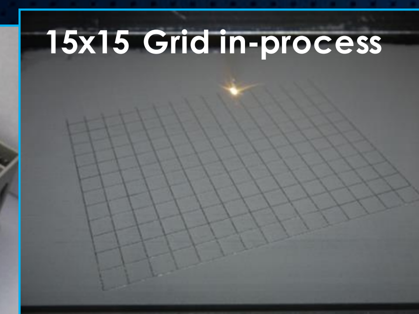




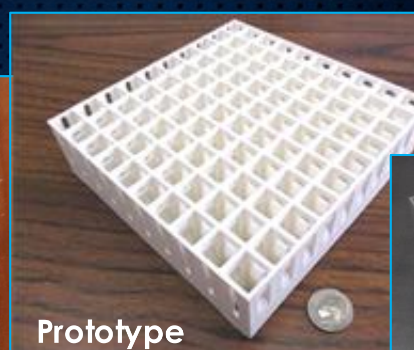
Initial 3D CAD Concept



10x10 Grid Demo



15x15 Grid in-process



Prototype

Actual 8x8 Spacer Grid

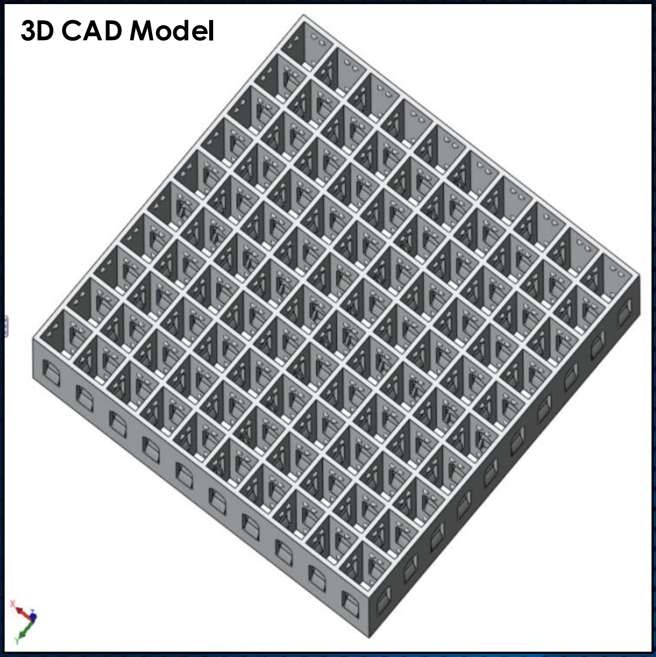
Wall Thickness Study

15x15 Thin wall Demo

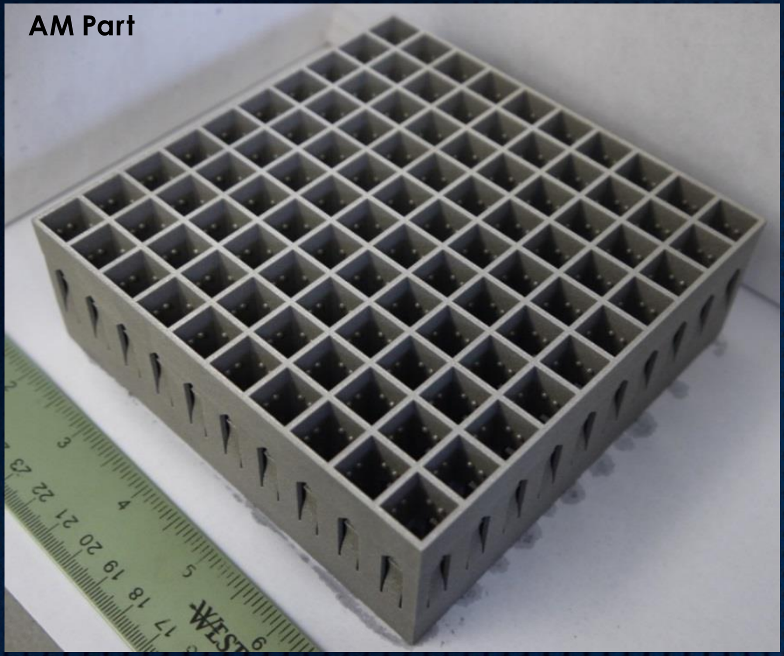
Case Study – AM Part Fabrication

- A simple 10x10 spacer grid design was developed w/ integral springs and rod positioning dimples
  - 5.19in x 5.19in x 1.75in
- Grid was fabricated out of Inconel 600 using a EOSINT M270 powder bed fusion tool at QCML in Rock Island, IL

CAD model



AM Part



Major Cost Elements by Fabrication Method

	Cost Element	Category	Traditional Manufacture	Cost Estimate	Additive Manufacture	Cost Estimate	Comments
1	Design and Analysis	Labor	Grid design, FE modeling for analysis, assembly fixture design, programming/teaching laser welding robot.	(# hrs) x ($__/hr labor rate)	Grid design, FE modeling for analysis, preparing part file for AM tool (scale for CTE shrink, add supports).	(# hrs) x ($__/hr labor rate)	Design is optimized for each fabrication method
2	Raw Materials	Materials	Inconel bar/plate stock	unknown	Inconel alloy powder	(part vol)x(density)x($__/lb metal powder)	
3	Pre Machining	Labor	Initial machining of subcomponents prior to welding into grid assembly	(# hrs) x ($__/hr labor rate)	N/A	N/A	No pre machining for AM part
4	Set-Up	Labor	Set-up or assembly of sub pieces into grid using fixtures	(# hrs) x ($__/hr labor rate)	Prepare AM tool (set-up platen, load powder, purge, etc.)	(# hrs) x ($__/hr labor rate)	Traditional method is skilled labor intensive
5	Hardware Run	Capital, Facilities, Labor	Laser welding system cost, power usage, purge gas usage, other consumables cost, maint/service contract, etc.	(# hrs run time) x ($__/hr)	AM system cost, power usage, purge gas usage, other consumables cost, maint/service contract, etc.	(# hrs) x ($__/hr rate)	Data available for AM from QCML
6	Post Processing	Capital, Facilities, Labor	Post weld heat treat for stress relaxation	(# hrs) x ($__/hr rate)	HIP and/or heat treat	(# hrs) x ($__/hr rate)	
7	Post Machining	Labor	N/A	N/A	Post machine to remove from platen and clean-up critical locations as needed.	(# hrs) x ($__/hr labor rate)	Probably not required for traditional part
8	Quality Check	Labor	Post fabrication qualification of part (dimensional accuracy check)	(# hrs) x ($__/hr labor rate)	Post fabrication qualification of part (dimensional accuracy check)	(# hrs) x ($__/hr labor rate)	Assume same for both
9	Scrap Loss	Materials	Scrap loss	unknown	Scrap loss	unknown	Assume same for both

- Low volume fabrication estimate of 10 x 10 Inconel grid ~ $6300
- Fabrication time on the order of days
- Would constitute ~ 40 to 50% of total refueling fabrication costs at this price
- Value comes in schedule savings, strategic build capabilities and enabling of new designs and improved performance.

Manufacturing Study Summary

- Manufacturing
  - Fabrication cost elements
  - Direct comparisons are challenging
  - Analysis suggests cost savings may not be readily attainable except for specific cases
  - Strategic value as driver for additive manufacturing
- Path Forward
  - Develop a more comprehensive understanding of the component design and parts
  - Identify areas where additive manufacturing enables new capabilities and designs
    - Obsolete parts
    - New designs not attainable through traditional manufacturing
    - Enabled performance (e.g., ODS SS)
  - Develop mature cost capture models and business cases

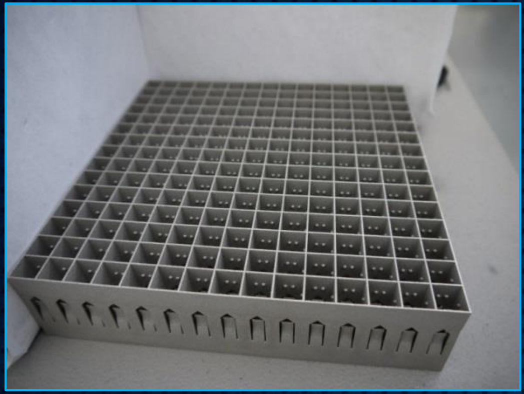
Path Forward

- Continued development on alloys
  - Design impact of directional performance
  - Powder formulation
  - ODS process development
- Radiation testing
  - Nominal alloys
  - Novel nano-tailored alloys
- Business case development

- NEET Sample Testing w/ Texas A&M
  - Approval from DOE to use samples for testing
  - Low dpa in-core testing and high dpa accelerator testing of X/Y/45° build directions

Summary

- Completed manufacturing demonstrations of notional fuel bundle spacer grid
- Demonstrated design flexibility (size and thickness) and shortened design-to-manufacturing cycles
- Demonstrated directionally dependent structure variation and performance via LDM for enhanced rad tolerant components – Inconel and ODS alloys
- Investigated cost and schedule benefits of spacer grid manufacturing cycle



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QuadCity Manufacturing Lab

- *Lockheed Martin would like to thank the Department of Energy , Office of Nuclear Energy for their support under Award Number DE-NE0000542*

Innovative Manufacturing Process for Nuclear Power Plant Components via Powder Metallurgy & Hot Isostatic Pressing Methods

David W. Gandy, FASM
Nuclear Materials
Electric Power Research Institute
Davgandy@epri.com

DOE Advanced Methods of Manufacturing Workshop
September 29 , 2015

Innovative Manufacturing Process for Nuclear Power Plant Components via PM-HIP

Objective: Conduct design, manufacturing, and validation studies to assess PM-HIP as a method to produce both large, near-net shaped components for nuclear applications across 3 families of alloys:

1. low alloy steels
2. austenitic stainless steels
3. nickel-based alloys

Rolls-Royce® CARPENTER GE HITACHI

U.S. DEPARTMENT OF ENERGY

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Three Years Ago
at Start of DOE Project…

- No Experience in Power Industry with PM-HIP
- Good industry experience in Aerospace, Aircraft, and Off-Shore Oil & Gas:
  - However, Power Industry had/has a lot to learn….
- Began work on 316L SS and Grade 91 (toward Code Acceptance)

Since 2012….

- Three ASME Code Cases—316L SS and Grade 91
- Developed Detailed EPRI Roadmaps for PM-HIP
- Developed New Co-free Hardfacing Alloy--NitroMaxx
- Initiated R&D aimed at Eliminating DMWs—Phase 2
- Began research/Code acceptance to recognize several other alloys:
  - 304L, 625, 690, 718, and SA508
  - ASTM and ASME
  - Aimed at SMRs and ALWRs
- Crack growth and SCC testing to support NRC recognition of 316L SS

Since 2012….

- Very Strong Collaborations with Carpenter Technology, GE-Hitachi, Rolls-Royce, U. of Manchester, NAMRC, ORNL, Synertech.
- Research at NSUF (ATR) on radiation embrittlement for multiple PM-HIP alloys—starts in 2016
- Valve and hardfacing project with EDF and Velan (2016)
- ORNL/EPRI project on “Can Fabrication”
- Continue to strive to meet Goals established by AMM Roadmap targeting Heavy Section Manufacturing

Powder Metallurgy Methods for Large Nuclear & Fossil Components

- Project Objectives
- Why Consider Powder Metallurgy for Large or Intricate Nuclear Components?
- Optimize an Alloy for Nuclear Performance
- Review 7 Project Tasks & Descriptions
  - Highlight 2 Components Manufactured
- Defining Success
- EPRI Roadmap on PM-HIP
- The Bigger Picture…

Why Consider Powder Metallurgy-HIP To Produce Pressure Components?

- Industry leadership in the manufacture of large NPP components (Gen III & SMRs)
  - eg., RPVs, SG, valves, pumps, turbine rotors
- Transformational technology
  - Moves from forging and rolled & welded technologies to powder met/HIP
- Enables manufacture of large, complex "*Near-Net Shape*" components
- Excellent Inspection characteristics
- Eliminates casting quality issues
- Alternate supply route for long-lead time components

P/M-HIP Valve

ELECTRIC POWER RESEARCH INSTITUTE

Optimize An Alloy for Nuclear Performance

Valve/Pump Housing/Flange

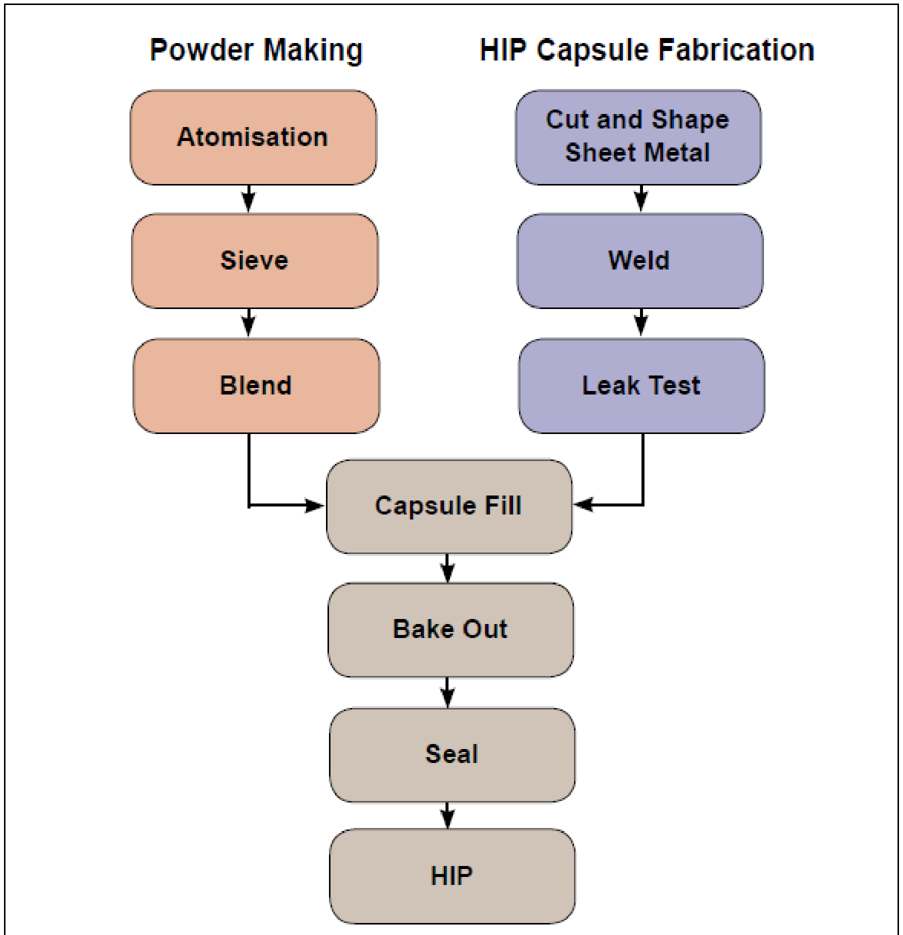
- Tensile/Yield Strength
- Adequate Ductility & Toughness
- Weldability (optional)
- Corrosion Performance

RPV Internals

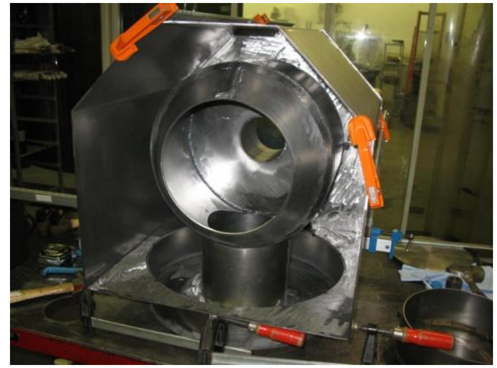
- Tensile/Yield Strength
- High Ductility & Toughness
- Weldabililty
- Corrosion Performance
- Fatigue Resistance
- Radiation Resistance
- Good Inspection Characteristics

- Near-Net Shape Capabilities
- Alternate Supply Route for Long-Lead Time Components

Powder Metallurgy-Hot Isostatic Processing



Courtesy of Steve Mashl, Z-Met Corporation



(courtesy of Carpenter Technology)

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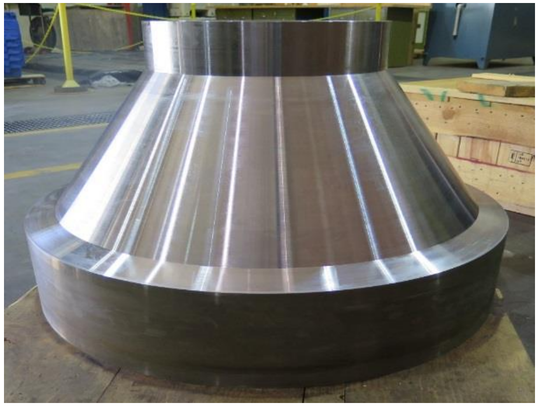
DOE Project Tasks

1. Modeling of NNS Component Alloy & Mold/Can Design
2. Test Coupon Development, Demonstration, & Screening for Surfacing Applications
3. Low Alloy Steel PM/HIP Component Development
4. Nickel-based Alloy PM/HIP Component Development
5. Austenitic Stainless Steel PM/HIP Development
6. Mechanical & Metallographic Characterization
7. Corrosion Testing of Test Coupons



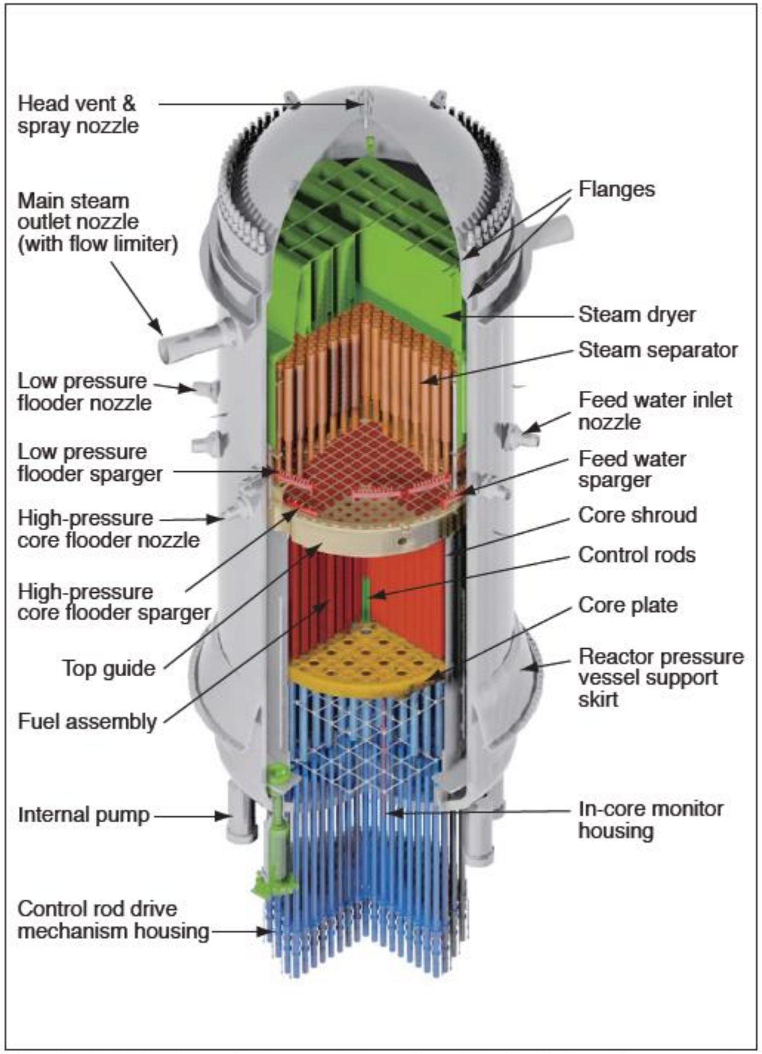
Task 5--Austenitic Stainless Steel PM/HIP Development

Lead Organization: GE-Hitachi

Steam Separator Inlet Swirler

(Austenitic Stainless Steel)

- Manufacture of a *complex geometry* to demonstrate PM/HIP for 316L SS
- SMR and ALWR applications
- Produce a NNS Inlet Swirl via PM/HIP
  - Evaluate dimensionally, metallurgically, and mechanically
  - Corrosion assessment is Task 7
  - **Status: Year-3 (2015).**



Structural sketch of reactor pressure vessel and reactor internal components

GEH → Validation of 316L PM capabilities

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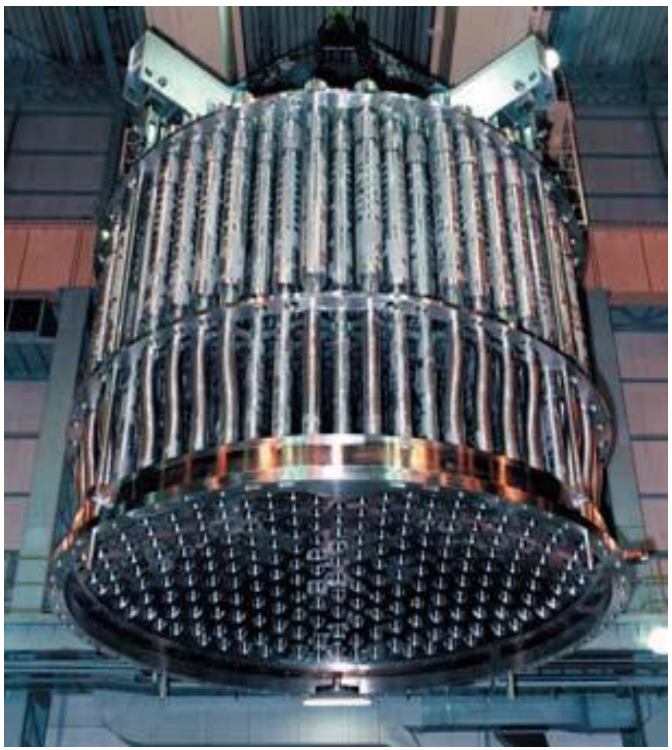
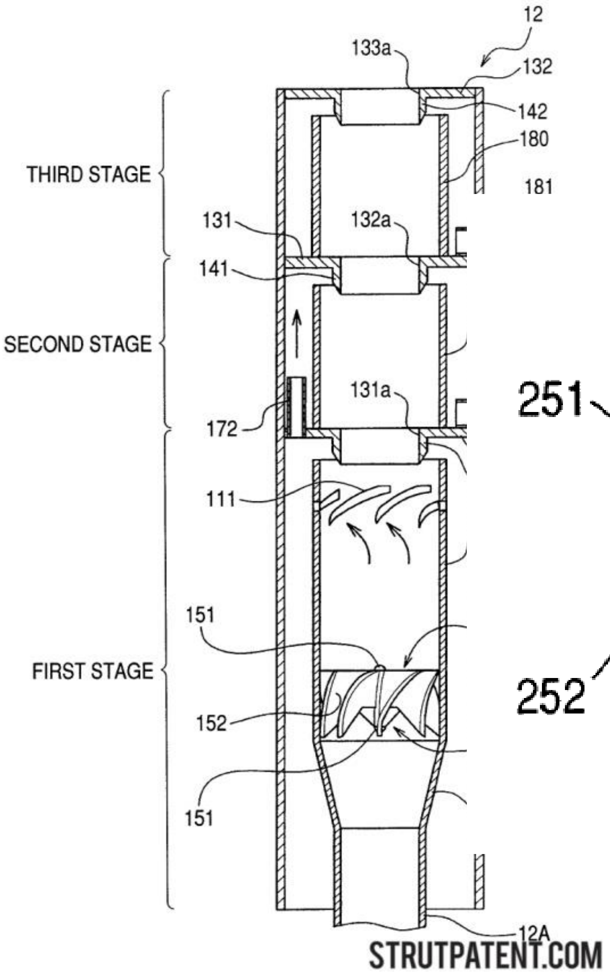
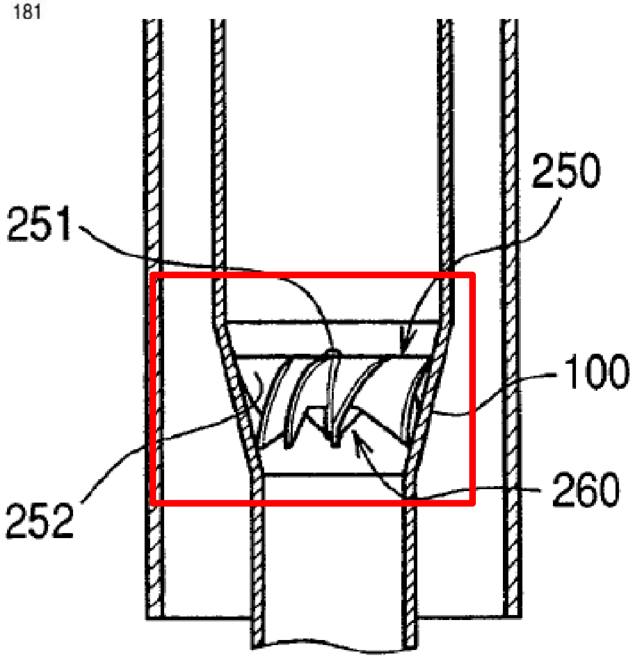
BWR or ALWR Steam Separator Inlet Swirl







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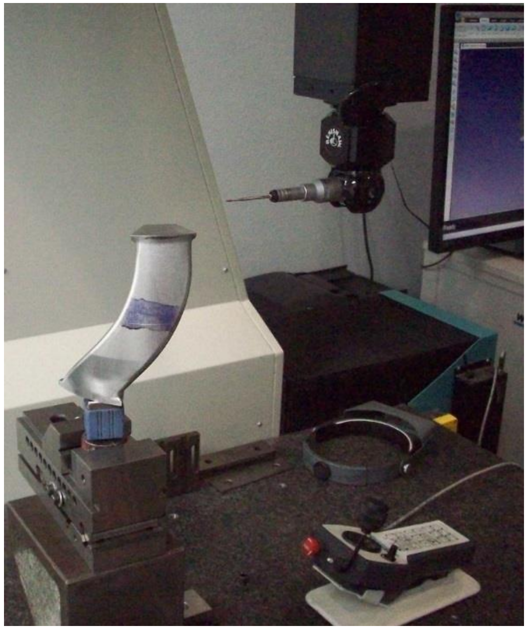
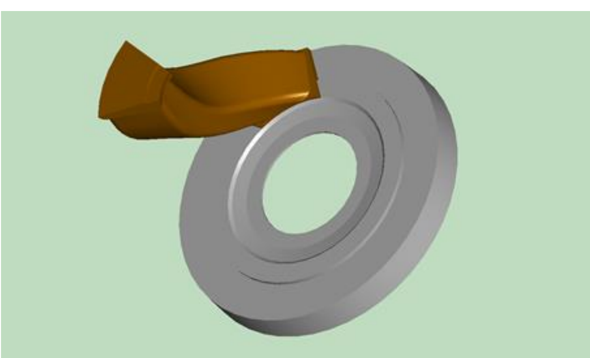
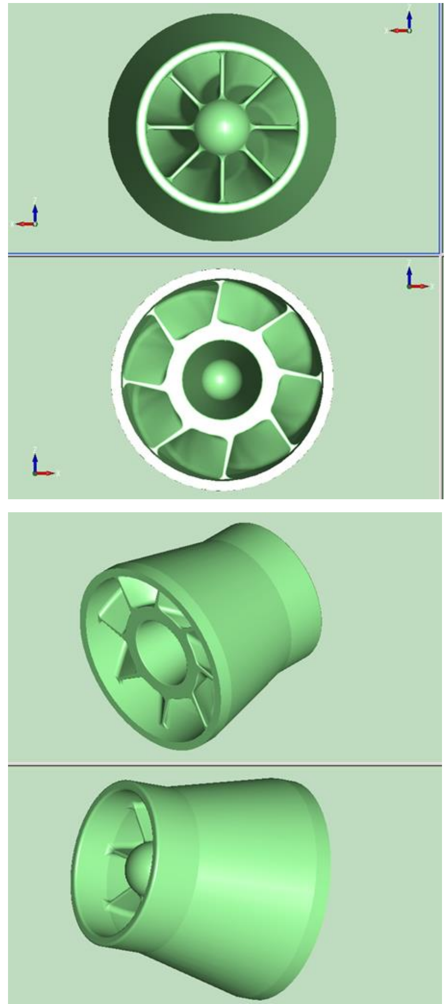
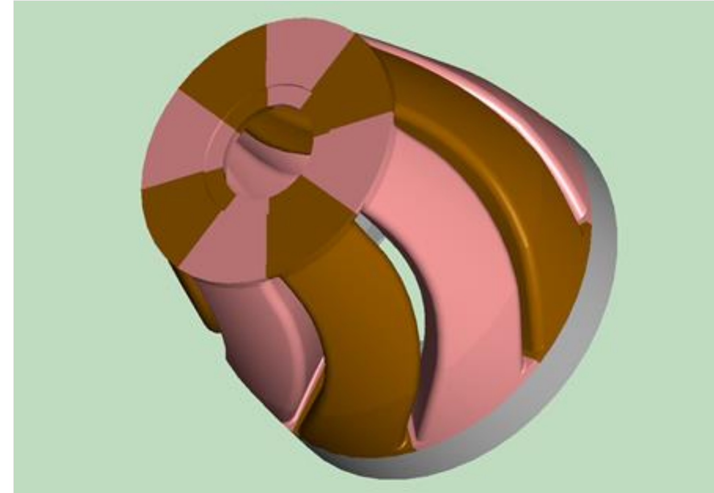
Inlet Swirl
-- 3D Geometry





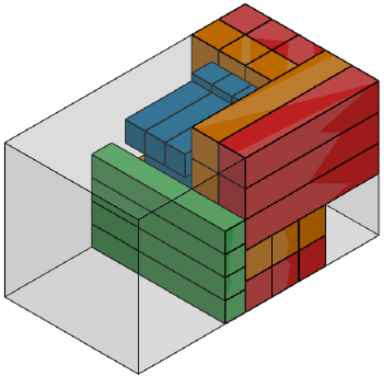


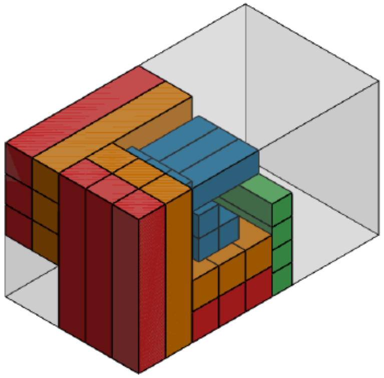


Vane Insert—one of 8
that fit into the swirler

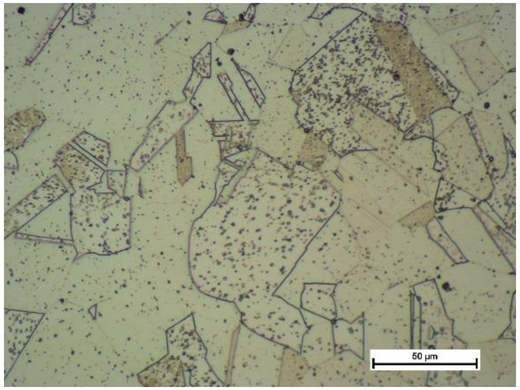
Inlet Swirl Block—Mechanical Properties

- **Tensile Properties @ RT**
  - UTS = 88.2 ksi (608 MPa)
  - YS = 49.8 ksi (343 MPa)
  - Elongation = 50.3%
  - ROA = 73.3%





- **Toughness** (Charpy Impact)
  - 173 ft-lbs (235 J) avg across 3 directions
- **Hardness**
  - 87.0 RHB

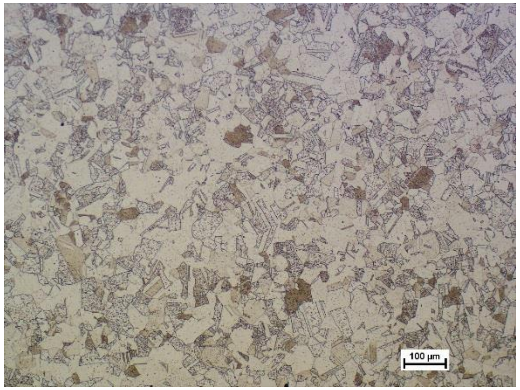


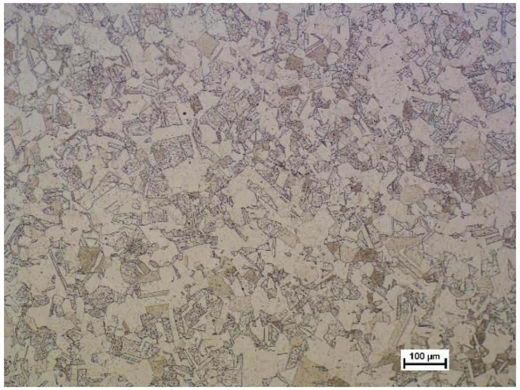
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	O	Fe
CF3M-ASTM A351	0.03 max	1.5 max	0.040 max	0.040 max	1.5 max	17-21.0	9-13.0	2-3.0	NA	NA	Bal
Powder	0.013	1.70	0.009	0.006	0.50	17.60	12.30	2.46	0.05	0.0145	Bal
Block--Inlet Swirl	0.014	1.73	0.023	0.007	0.49	17.67	12.34	2.49	0.04	0.02	Bal

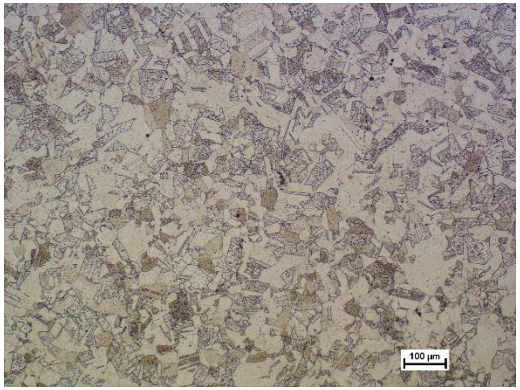
Meets GEH 316L wrought/cast requirements

Sensitization Susceptibility (ASTM A262) -- Acceptable

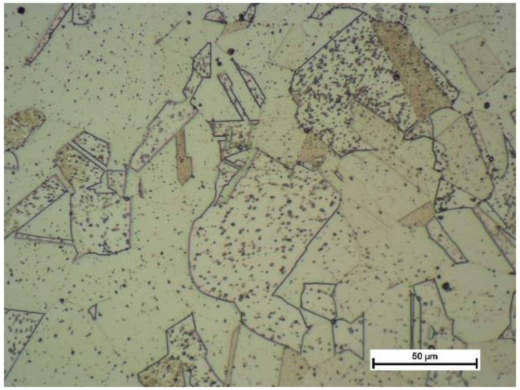
100x

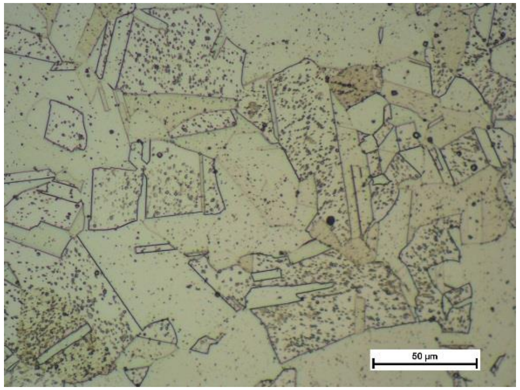


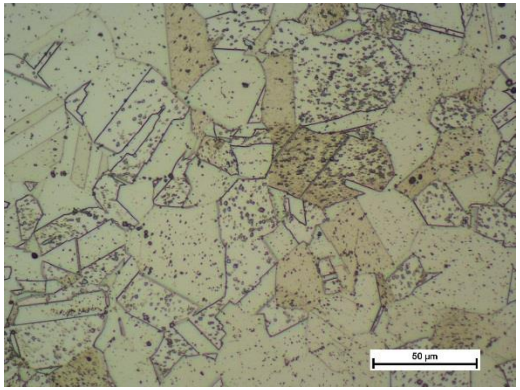




500x







Direction 1 | Direction 2 | Direction 3

Density, Porosity, Inclusions, Grain Size

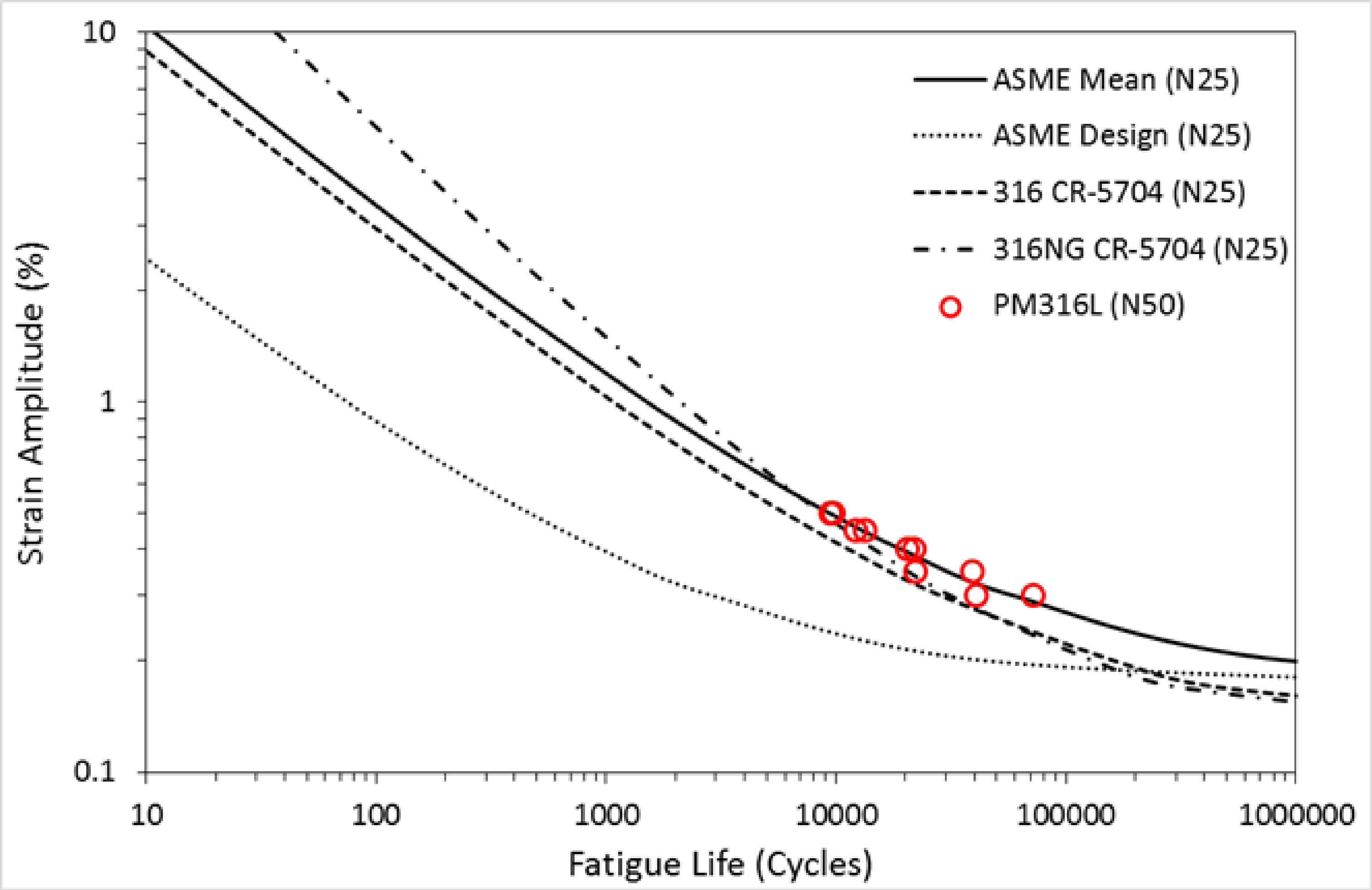
- Porosity – 99.9%
- Density – 7.959 g/cm^3
- Grain Size – ASTM 7.0

Laboratory Number	Type A	Type B	Type C	Type D	Series	Direction
15757-MET1	0	0.5	0	2.0	Thin	X
	0	0	0	1.0	Heavy	
15757-MET2	0	0.5	0	2.5	Thin	Y
	0	0	0	0.5	Heavy	
15757-MET3	0	0.5	0	2.0	Thin	Z
	0	0	0	1.0	Heavy	

Samples were taken at the longitudinal direction and examined at 100x magnification.
Method(s): ASTM E45-13

Grain structure and inclusion content exceed GEH SS CRB wrought requirements

Fatigue Data—316L SS



Measured 316LSS LCF data compared with ASME and NUREG- 5704 data.

NUREG-5704: Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels

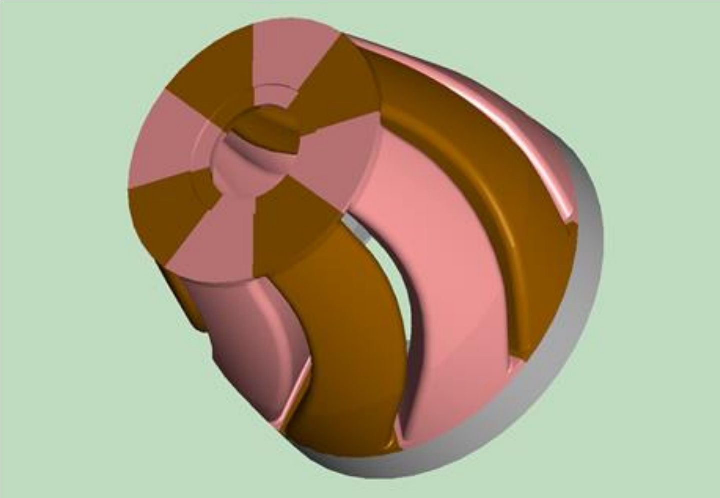
Corrosion Testing
--SCC Crack Growth Rates (Preliminary Results)

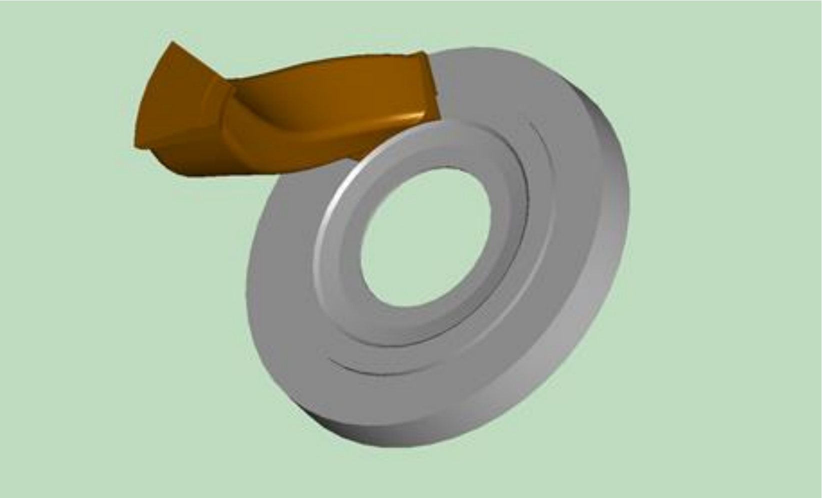
Preliminary Table of SCC Growth Rates of Wrought and Powder Metallurgy 316L and 600M
288C Water with 20 ppb Sulfate as H_2SO_4 – ~30 MPa√m

			SCC Growth Rate, mm/s	
Alloy	**Specimen**	**K, MPa√m**	**High ECP**	**Low ECP**
			As-Received	
Wrought 316L	---	~40	(≈3 x 10^{-8})	(≈2 x 10^{-9})
PM 316L	C720	~40	~1 x 10^{-7}	~2 x 10^{-9}s
			20% Cold Work	
Wrought 316L	C126	~30	~2 x 10^{-7}	~2 x 10^{-8}
PM 316L	C719	~30	~2 x 10^{-7}	~1 x 10^{-8}
			As-Received	
Wrought 600	---	~35	(≈2 x 10^{-8})	(≈1 x 10^{-9})
PM 600M	C735	35	5 x 10^{-8}	2 x 10^{-9}
			20% Cold Work	
Wrought 600	C129	30	2 x 10^{-7}	3 x 10^{-8}
PM 600M	C734	30	1 x 10^{-7}	1 x 10^{-8}

* High ECP is 2 ppm O_2, which is ~150 – 200 mV_{she} Low ECP is 63 ppb H_2 which is ~-510 mV_{she}

Inlet Swirler Design & Manufacture --Modeling





Inlet Swirler Design & Manufacture --Fit up

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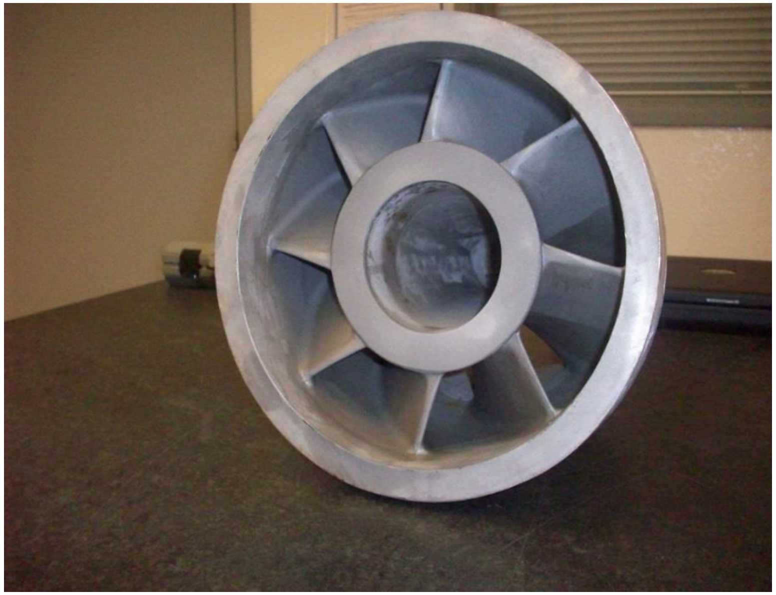
Inlet Swirler Can Design & Manufacture

Inlet Swirler Manufacture



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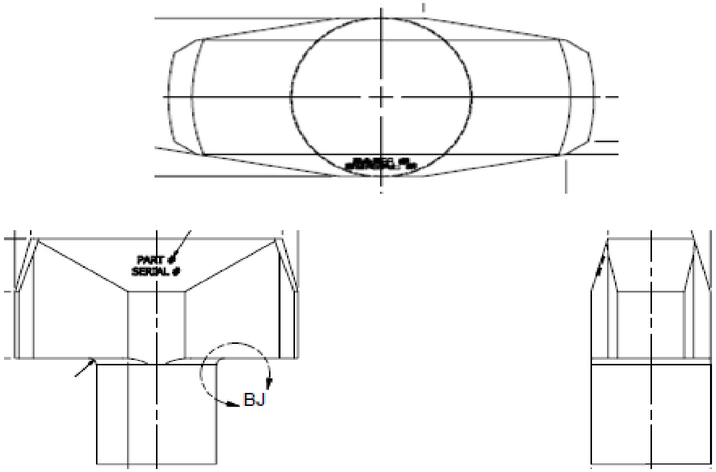
Task 4--Nickel-based Alloy (600M) PM/HIP Component Development

Lead Organization: GE-Hitachi

<u>Chimney Head Bolt</u> (Ni-based Alloy)

- Using PM/HIP, manufacture NNS bolt from Alloy 600M.
- Normally forged, then welded.
- Perform dimensional, microstructural, and mechanical characterization

Status: <u>Year-3</u> (2015).



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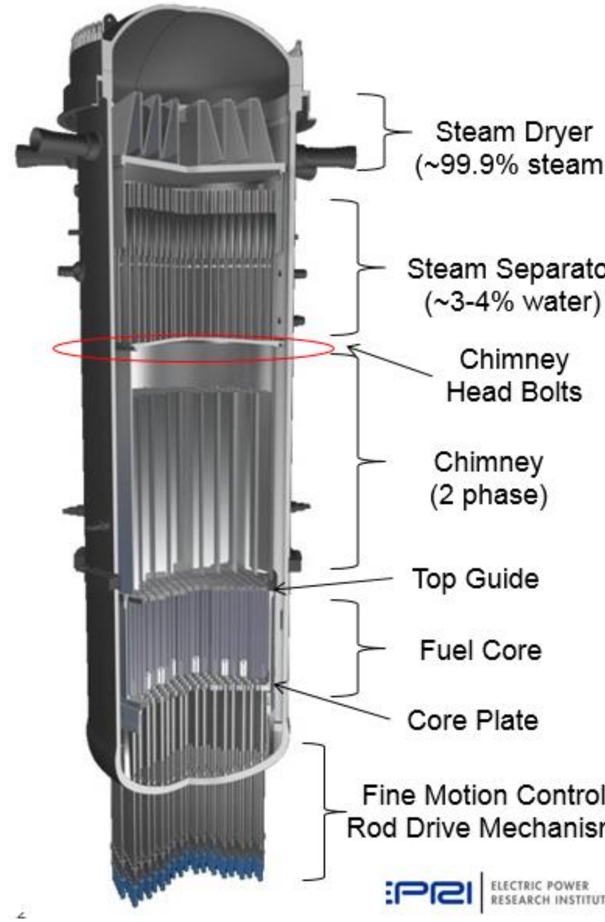
Chimney Head Bolt

Note: Mild steel can
is still attached.



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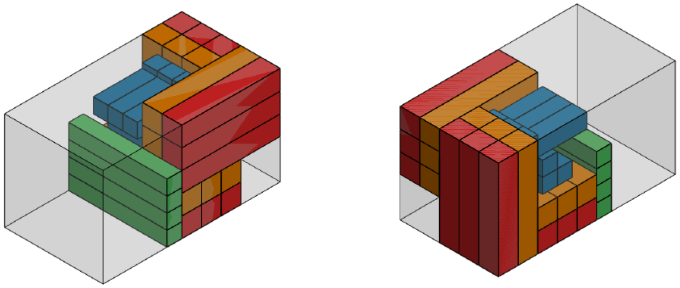
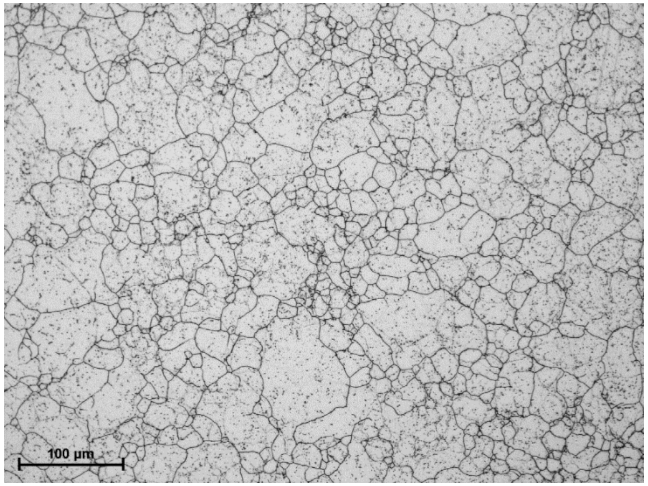
Chimney Head Test Block—Mechanical Properties



- **Tensile Properties @ RT**
  - UTS = 102.5 ksi (706 MPa)
  - YS = 46.2 ksi (318 MPa)
  - Elongation = 45.7%
  - ROA = 68.2%
- **Toughness** (Charpy Impact)
  - 144 ft-lbs (195 J) ave, 3 directions
- **Hardness**
  - 84.3 (HRB) ave



	C	Mn	S	Si	Cr	Ni	Cu	Fe	Cb
600-ASTM A351	0.15 max	1.00 max	0.015max	0.50 max	14.0-17.0	72min	0.50 max	6.0-10.0	N/A
600M-N-580-1	**0.05 max**	1.00 max	0.015 max	0.50 max	14.0-17.0	72min	0.50 max	6.0-10.0	**1.0-3.0**
Block – C Head Bolt	0.024	<0.01	0.001	0.05	15.96	Bal	0.02	8.73	1.31

Density, Porosity, Inclusions, Grain Size

- Porosity – 99.7%
- Density – 8.469 g/cm^3
- Grain Size – ASTM 8.5

Lab Number	Type A	Type B	Type C	Type D	Series	Direction
5977-MET1	0	0.5	0	0.5	Thin	X
	0	0	0	0	Heavy	
5977-MET2	0	0	0	0.5	Thin	Y
	0	0	0	0	Heavy	
5977-MET3	0	0.5	0	0.5	Thin	Z
	0	0	0	0	Heavy	

Samples were taken at the longitudinal direction and examined at 100x magnification
Method(s): ASTM E45-13

Defining Success….

- Success in this project is defined as:
  1. Manufacture of 4 large components from low alloy steel, stainless steel, and a Ni-based alloy (3 different alloy families)
     - Nozzle, curved RPV section, steam separator inlet swirl, chimney held bolt.
     - Establish design criteria, shrinkage & NNS quality
  2. Generate excellent mechanical properties, along with good product chemistry & uniform grain size
  3. Application of wear resistant surfacing material to a substrate alloy
  4. Corrosion performance comparable to forgings

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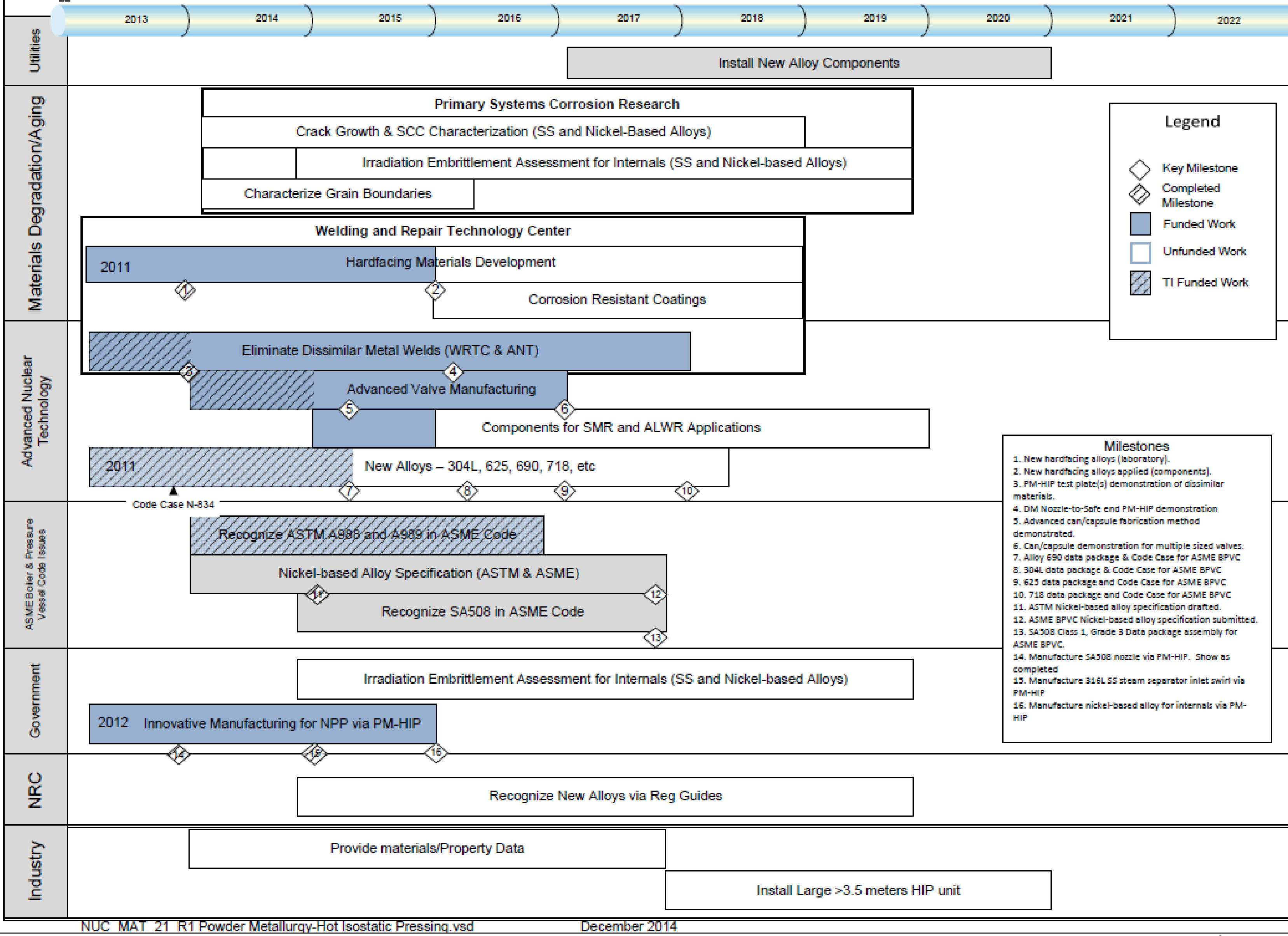
Powder Metallurgy-Hot Isostatic Pressing for RPV Internals and Pressure Retaining Applications



Technology Gaps/Applications Covered by PM-HIP Roadmap (1)

- Recognize ASTM A988 & A989 in ASME Code
- Nickel-based Alloy Specification Additions (ASTM and ASME)
- Recognize Alloys—304L, 625, 690, 718 & Property Data
- Recognize SA508 (RPV steels) in ASME Code
- Components for SMR and ALWR Applications
- Crack Growth and SCC Characterization (SS and Ni-based)
- Irradiation Embrittlement Assessment for Internals

Technology Gaps/Applications Covered by PM-HIP Roadmap (2)

- Hard-facing Materials Development
- Eliminate Dissimilar Metal Welds
- Advanced Valve Manufacturing
- Innovative Manufacturing for Nuclear
- Silicon Carbide Alloys
- Recognize Alloys via Regulatory Guides (NRC)
- Corrosion Resistant Coatings

Summary

PM-HIP for Structural & Pressure Retaining Applications:

- Large, complex, near-net-shape components
- Alternate supply route for long-lead time components
- Improves inspectability
- Eliminates rework or repair in castings
- Hardfacing applications

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The Bigger Picture……

Supporting DOE AMM Roadmap toward Heavy Section Manufacturing

Highest Priority Items

1. Develop technical position paper that allows welds in vessels outside the beltline region.
2. Develop/Demonstrate Powder metallurgy – HIP of Plate (Ring Sections)
3. Develop/Demonstrate Nozzle Manufacturing Capabilities
4. Install/Commission large diameter HIP Unit – 3.1 meters
5. Manufacture vessel internals via nickel-based alloys

The Team….

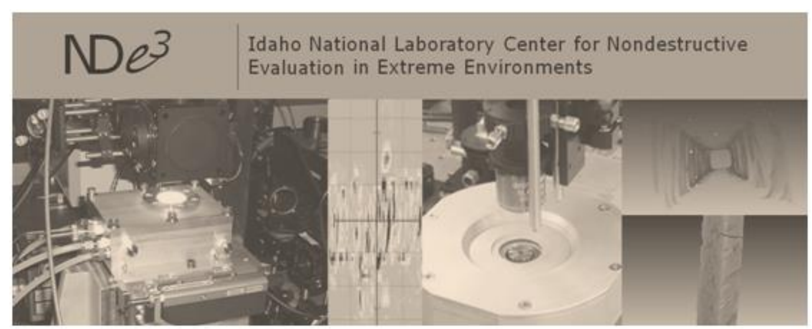
- Lou Lherbier & Dave Novotnak (Carpenter Technology)
- Myles Connor, James Robinson, Ron Horn (GE-Hitachi)
- Steve Lawler and Ian Armson (Rolls-Royce)
- Will Kyffin (N-AMRC)
- Dave Sandusky (X-Gen)
- Ben Sutton, Dan Purdy, Alex Summe (EPRI)

Together…Shaping the Future of Electricity

Monitoring and Control of the Hybrid Laser-Gas Metal-Arc Welding Process

Dennis C. Kunerth, Tim McJunkin, and Corrie Nichol
Idaho National Laboratory
Evgueni I. Todorov, Steve Levesque
Edison Welding Institute
Feng Yu and Dana Couch
Electric Power Research Institute

DOE-NEET-AMM

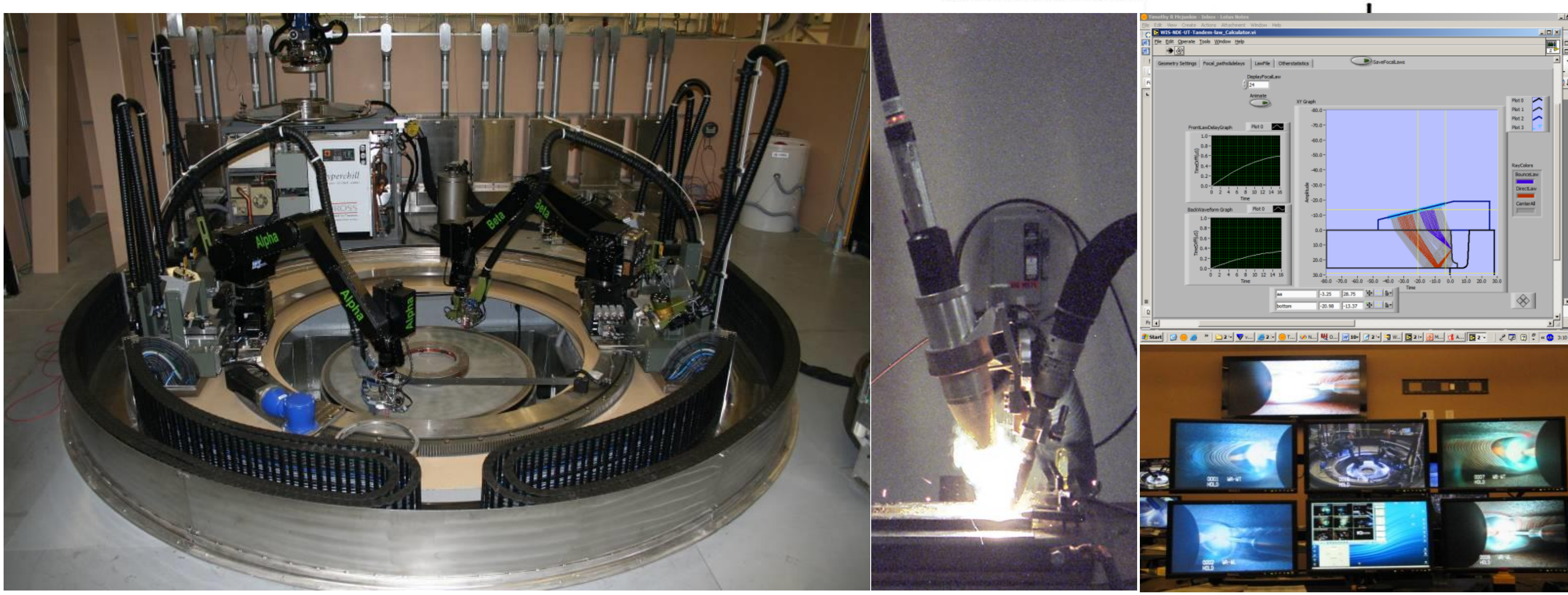


Date: September 2015

INL/MIS-14-33465

Outline

- Overview of Project
- INL Sensor and system development focusing on real-time ultrasonic inspection probe/methods
- EWI real-time Eddy-Current inspection
- Concluding



Enhanced technology for nuclear and industrial fabrication

- Advanced Manufacturing Methods (e.g. hybrid laser welding, spray forming).
- Efficiency through robotics, near real-time diagnostics, and intelligent systems.
- High throughput, minimized energy, and low waste processes.
- Remote capability in hazardous environments.

Building on the legacy of state of the art high temperature process research.

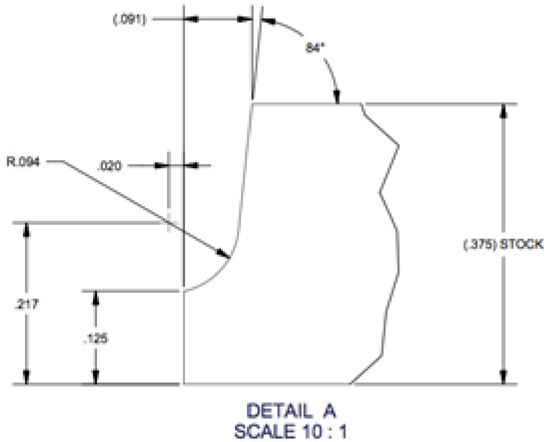
Towards effective real time feedback…

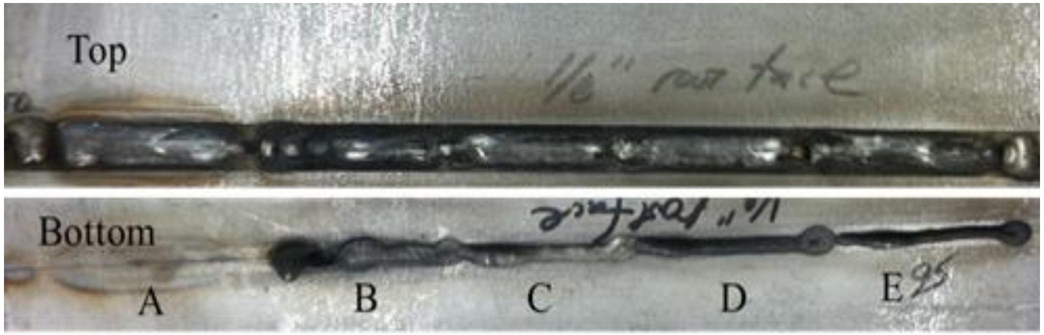
- With High Speed processes along with the potential for high productivity is the danger of high productivity of flawed welds
- Not necessarily detected by welder or system prior to post weld examination—possibly at an entirely different facility (i.e. radiography cave)
- Base goal: do in place evaluation of weldment in welding fixture
- Next goal: provide real time feedback is the ability to detect a flawed weld and shut it down to minimize the extent waste or repairs
- Ultimate goal: have a knowledge base so signature of a flaw or precursor to a flaw can be remedied without a start and stop
- Sensors tailored to producing near instantaneous feedback.
  - Weld electrical signals.
  - Ultrasonic methods
  - Electromagnetic (eddy current)

Choice of Welding Configuration / Lab Setup

- High through put welds Hybrid/Laser
  - Laser and Hybrid laser allow a high speed process.
  - Focused laser leading GMAW.
  - Parameter variations of Laser power source is a convenient feedback input to system
  - Feedback mechanisms to remedy lack of penetration or excessive heat leading to weld pool leaking out.
- Weld Joint and Material for Initial Research
  - Chose 316L – EWI desired non-magnetic material
  - 3/8” thick material
  - Started with V-groove preparation with vertical root face and have moved to a J-groove with vertical root face.
  - Bounded welding parameters with available laser.
- Current limitations
  - 4KW laser limits root face to approximate 1/8”

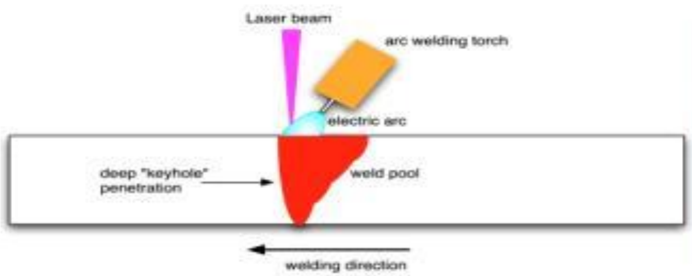
Joint Configuration

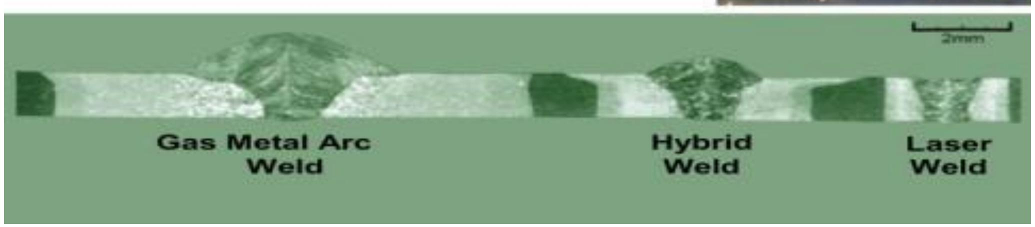




Laser Hybrid Welding Process

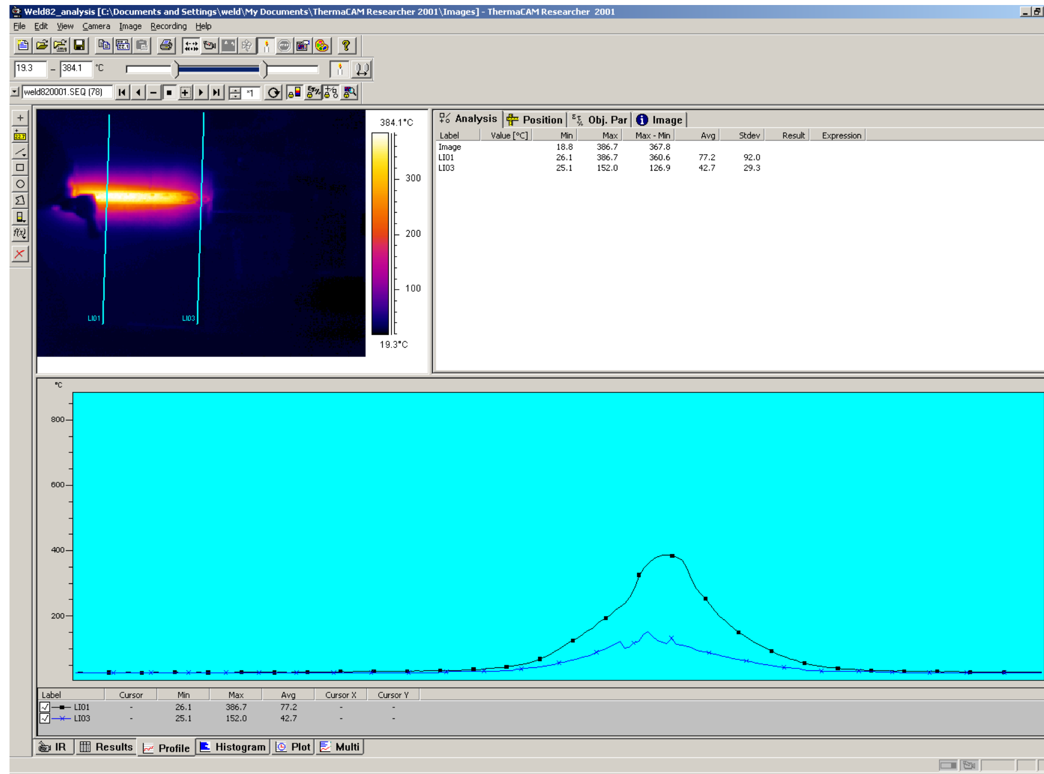
- Advantage
  - laser's penetrating power
  - Gas Metal Arc Welding (GMAW) bridges gaps mitigates tight fitup tolerance
  - Greatly increase welding speeds are achieved, but present new Challenges.
- Challenges
  - Fast feed rate make real time adjustments by welder more difficult. Automation is more important.
  - NDE can be optimized for inspection immediately after weld – i.e. not requiring moving part to radiography chamber to inspect.
  - Real time assessment and laser tracking correction based on NDE would be big a big plus to productivity.



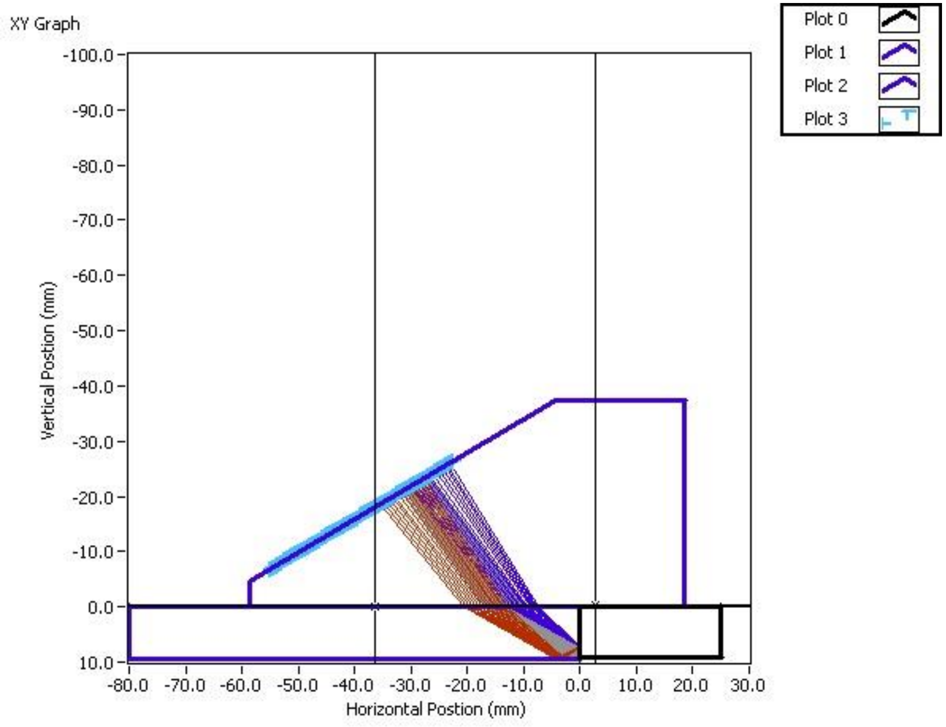


Heat Profile of Hybrid Laser Process

- Thermal Imaging Camera
- Relatively low temperature to the sides of the weld bead
  - Advantage of Laser/Hybrid
- INL and EWI using surface temperature as a design criteria for probes
- Less exotic coupling methods and wider choice of materials are possible in the design.

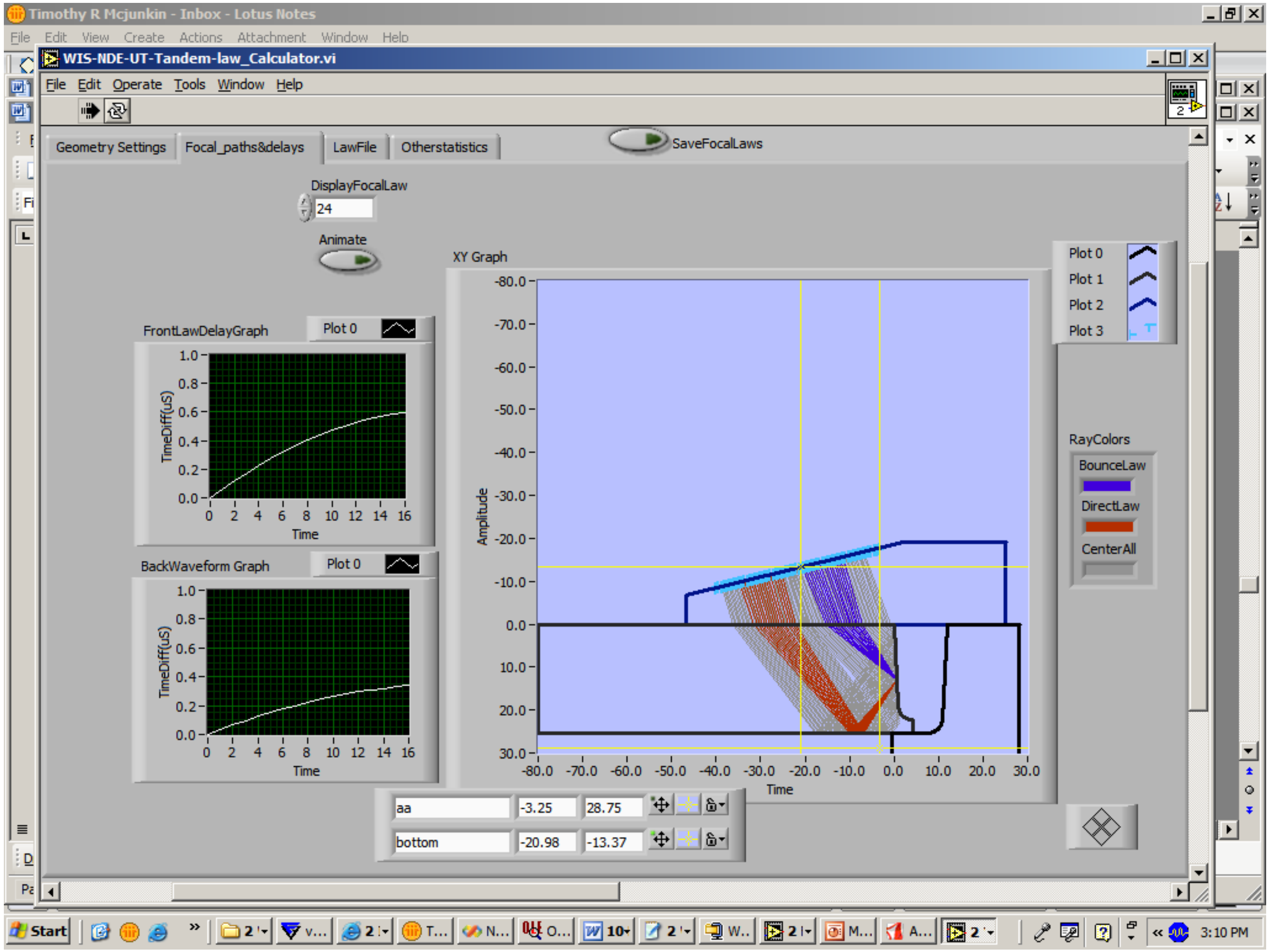


UT Phased Array Focal Laws

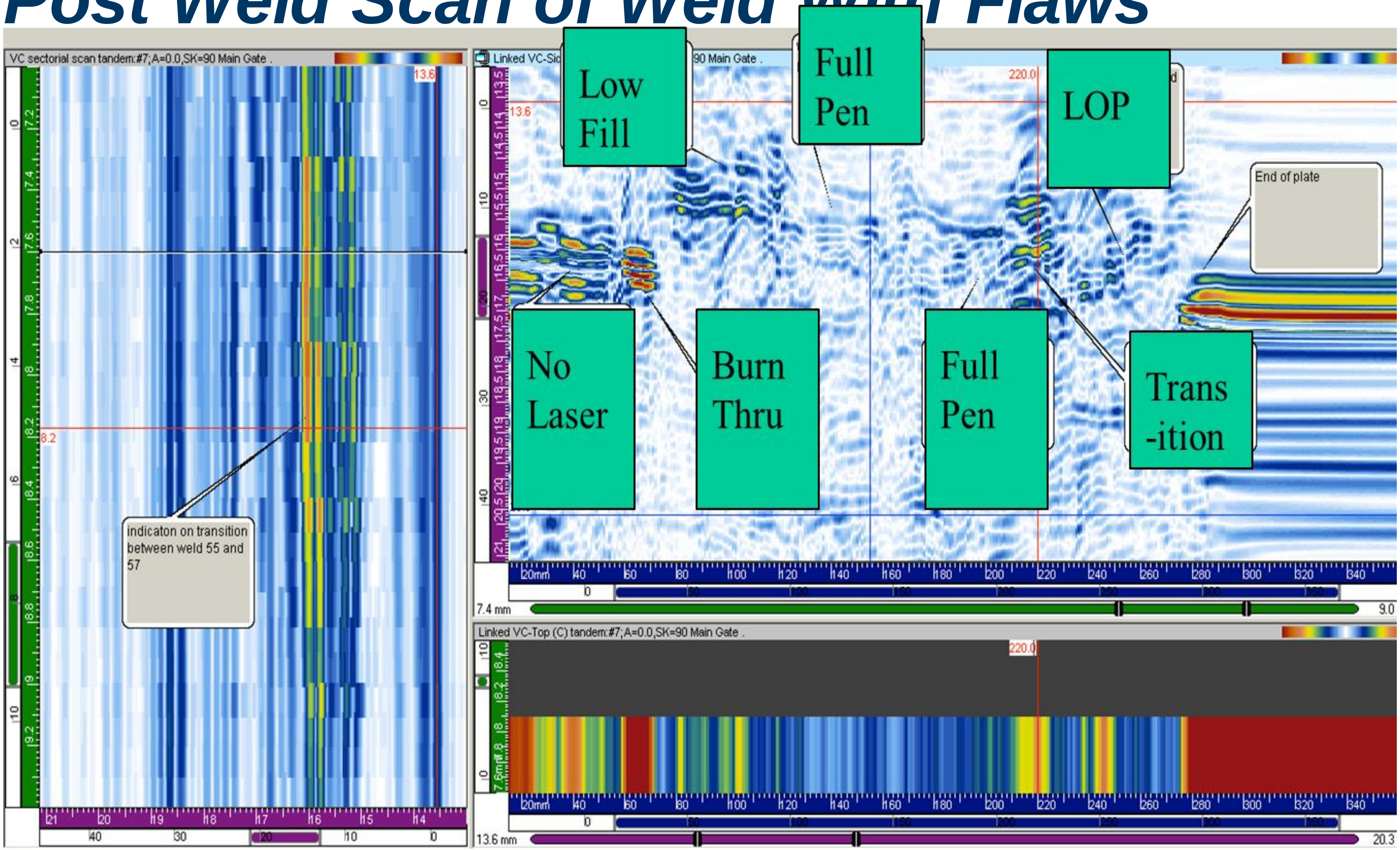


- Direct focus of transducer laws to the root and root face.
  - Detects a laser miss on the root face even when full penetration can be seen on the bottom surface
- Initial design used a commercial probe with modifications.

Adapted from Tandem (Pitch-catch) Find mid weld fusion defects

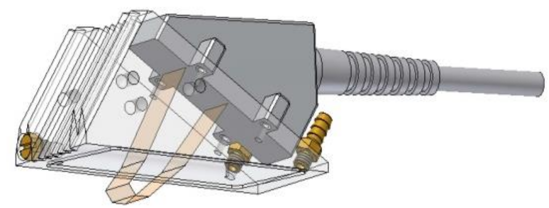


Real-Time Ultrasonics
Post Weld Scan of Weld With Flaws

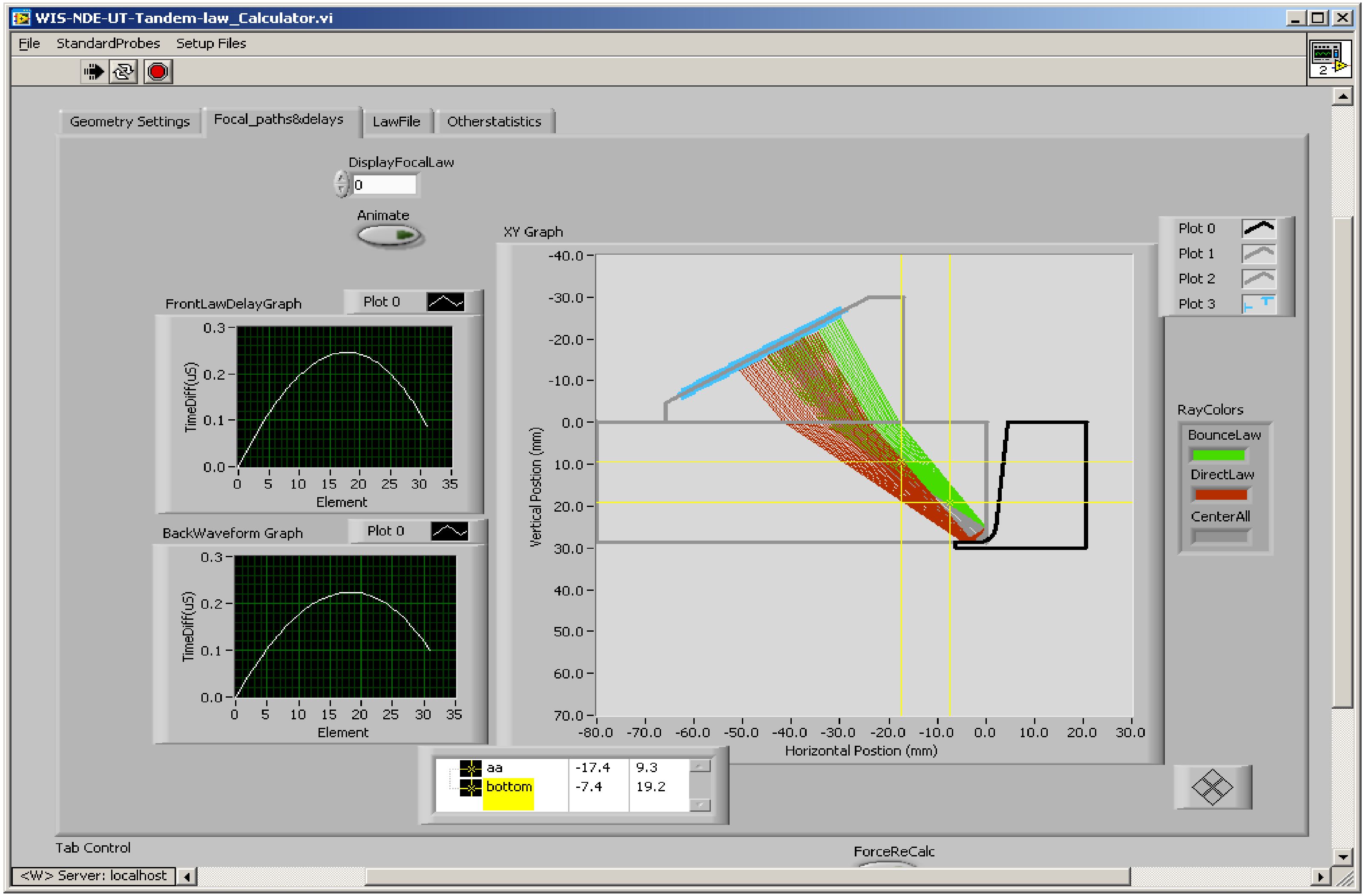


UT Probe Design

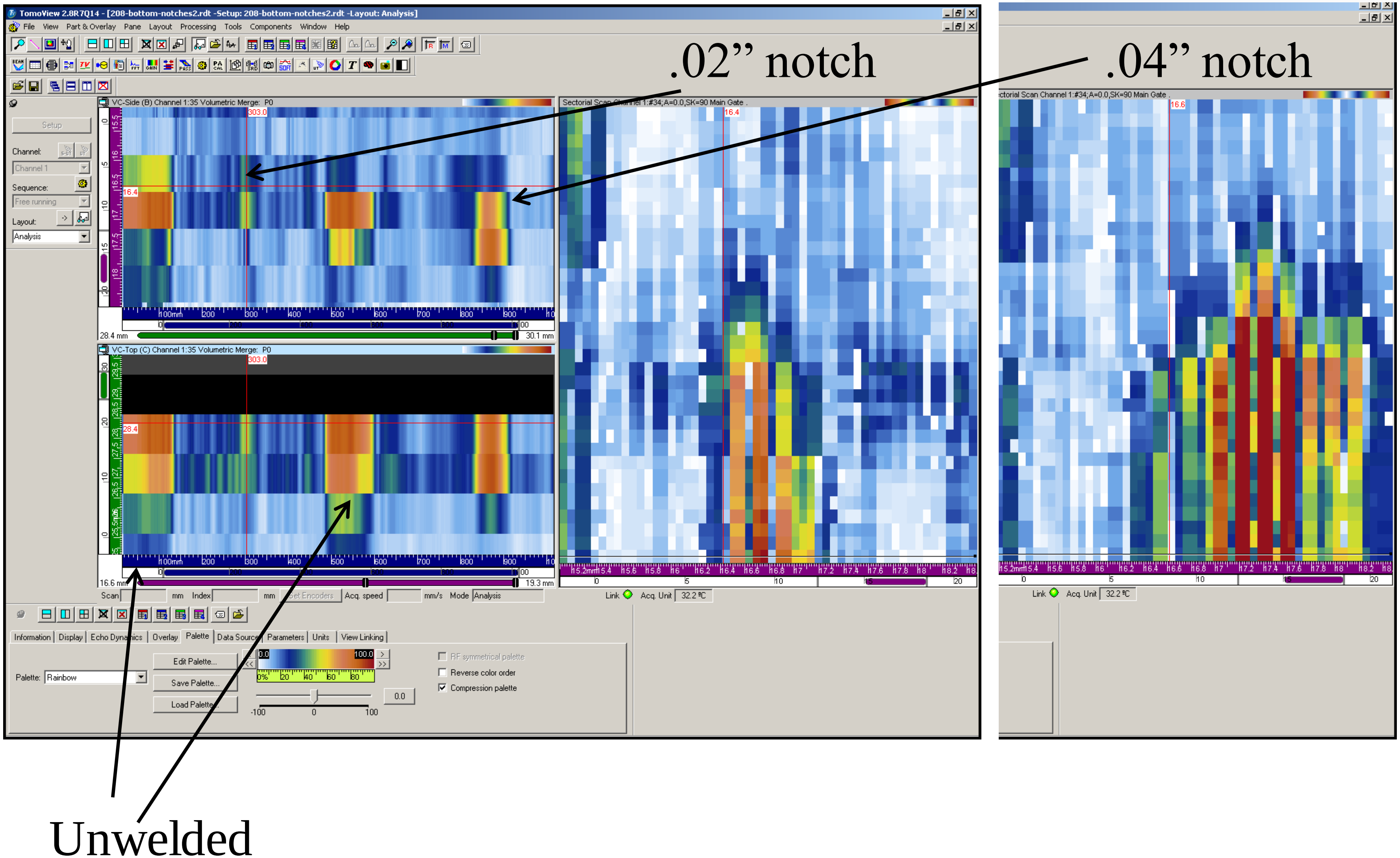
- Custom probe design
  - Shallow water path for coupling
  - Sound path designed to allow 10mm spacing to weld
  - Design viable for greater root thickness than current 3/8 inch plate
- Real-time testing completed in 2015
- Water cooled copper heat shield designed to protect probe material



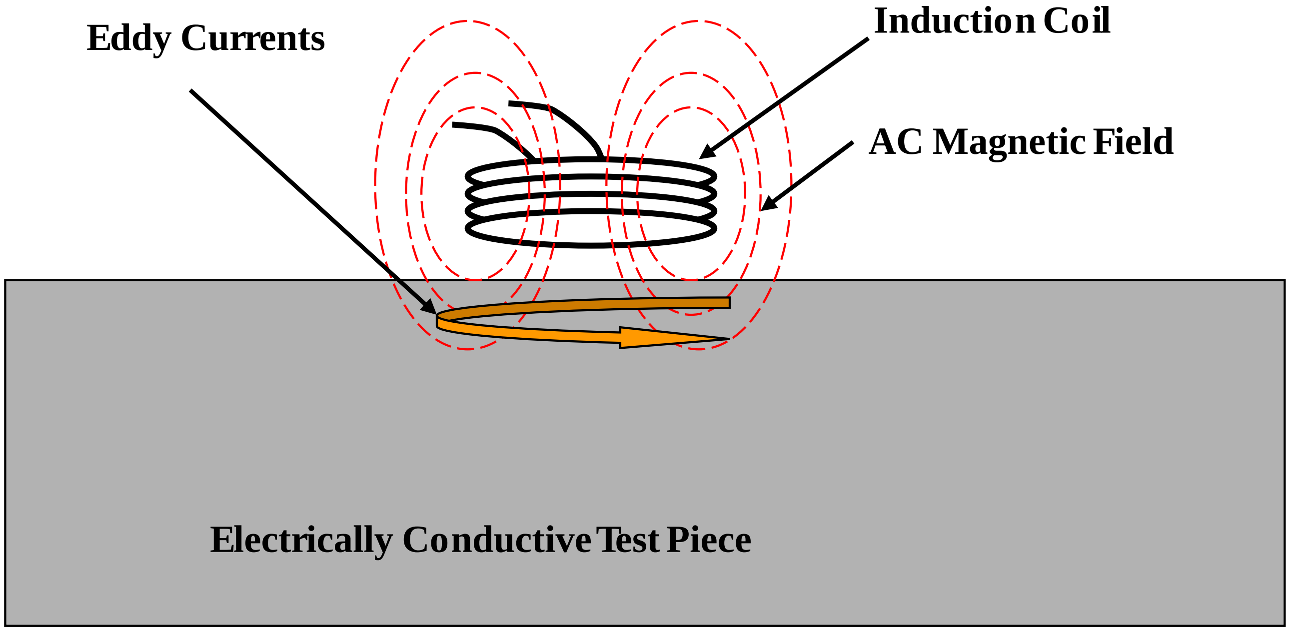
Focal Law Design for More Setback



EDM Notches Results



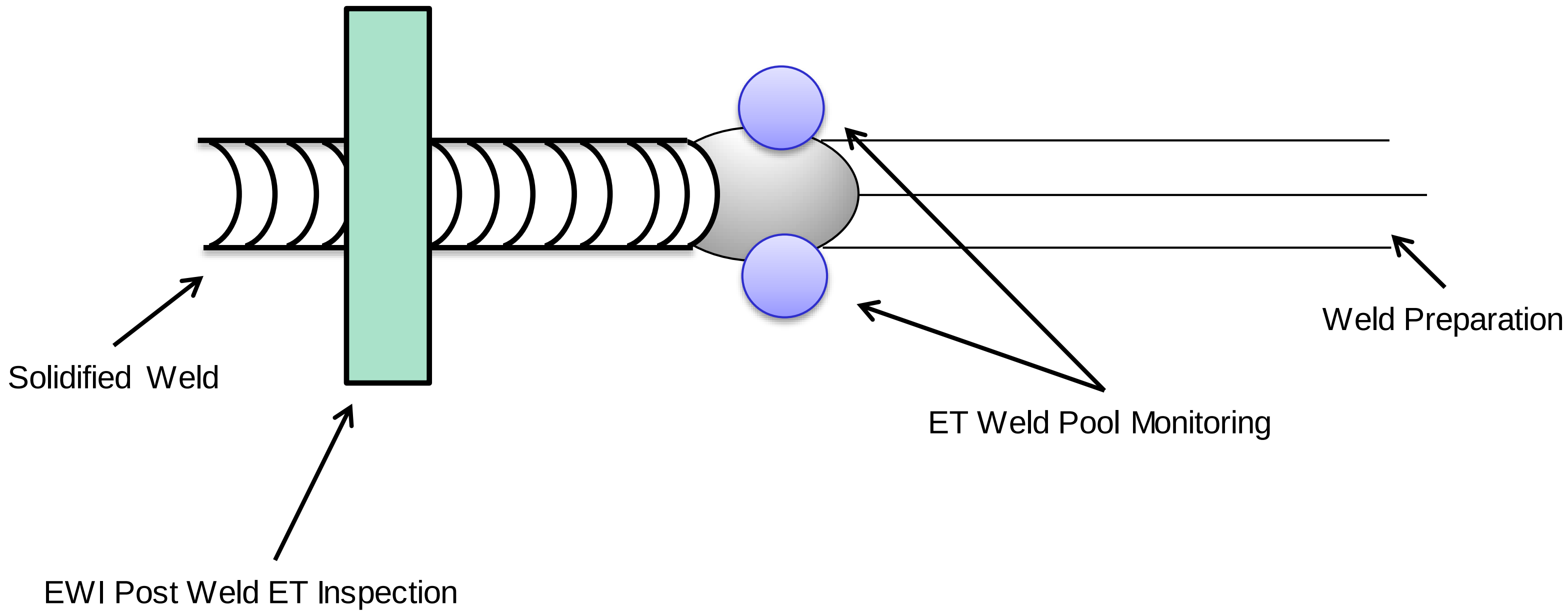
Eddy Current (ET) Inspection



Inspections Based on Electromagnetic Properties of the Test Material

Surface/Near Surface Inspection Due to Skin Effect and Limited Projection of Magnetic Field

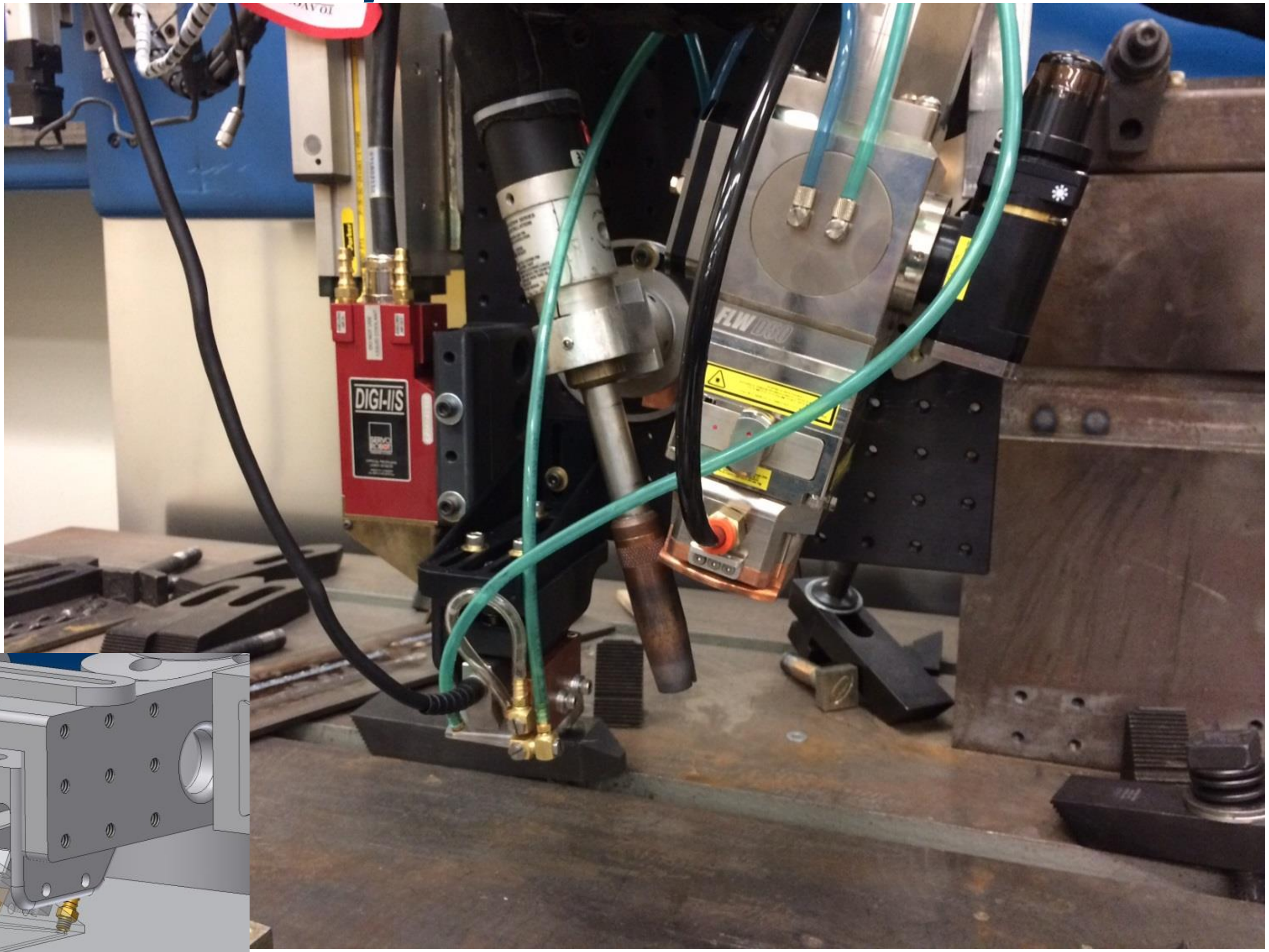
ET Weld Monitoring

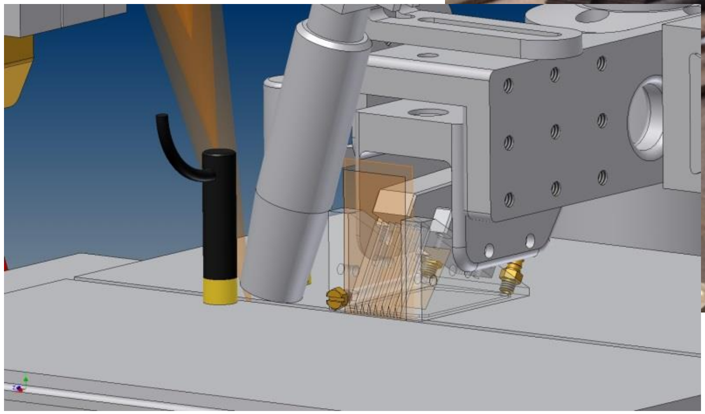


Side Beam Configuration – New Laser

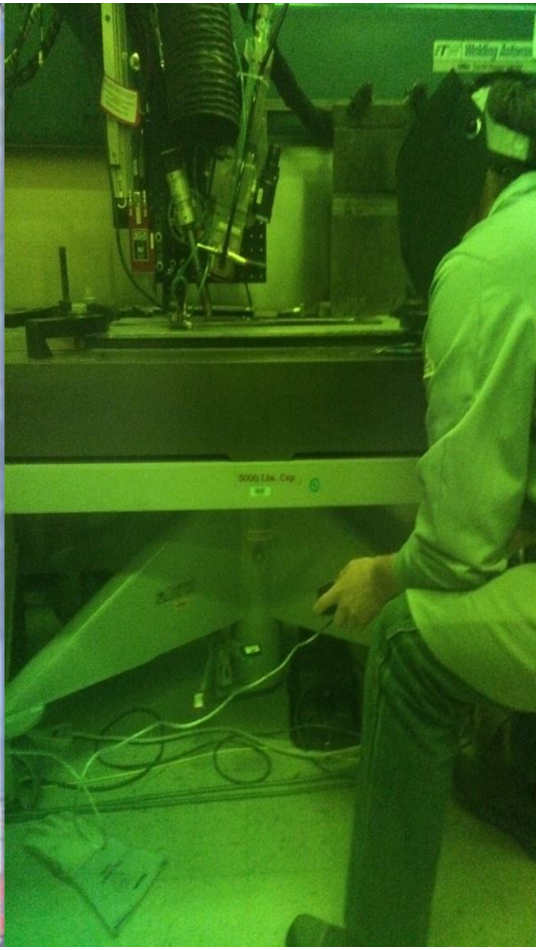
Longer welds for development/ demonstration

Sidebeam installed UT probe

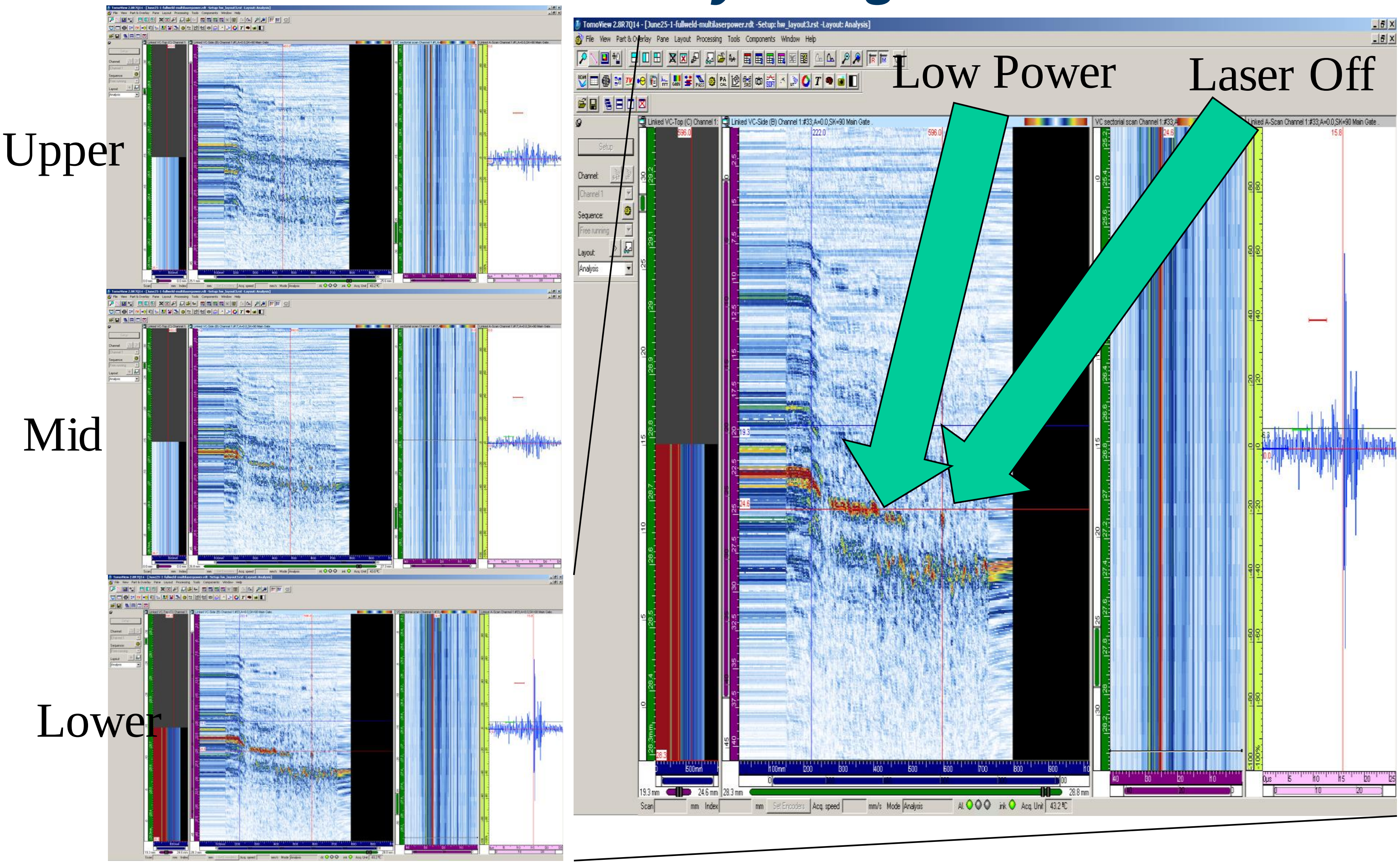




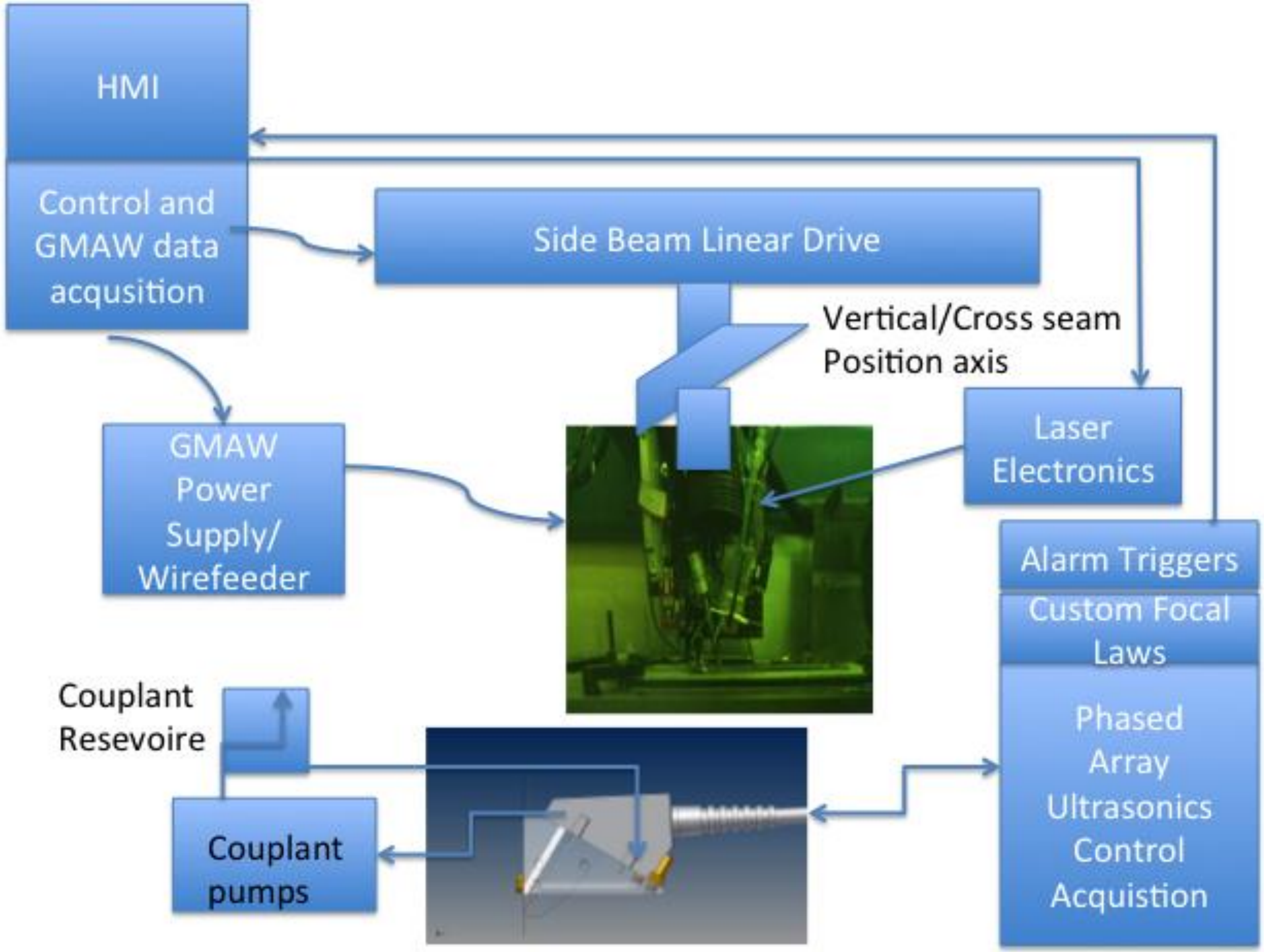
Results UT Sensor under test



Real-Time Data Summary – regions of root



System Diagram



Eddy Current Sensor Development for Monitoring and Control of Hybrid Laser/Gas Metal Arc Welding Process.

Advanced Methods for Manufacturing Workshop

29 September 2015

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Jacob Hay, jhay@ewi.org
Nancy Porter, nporter@ewi.org

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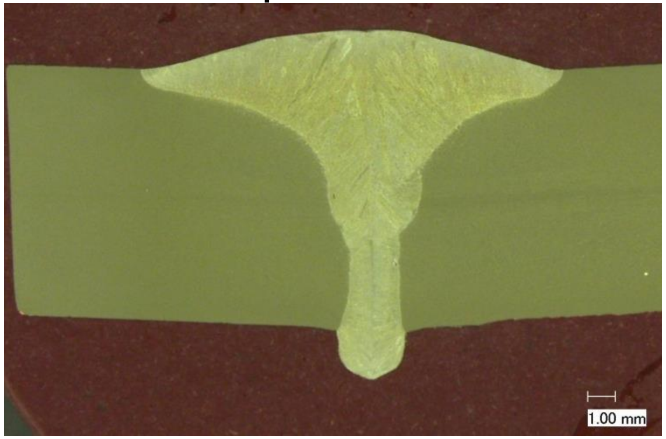
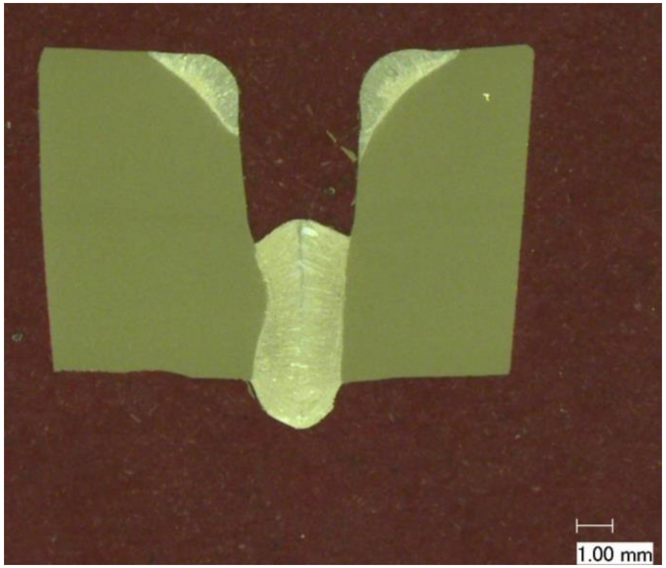
Background

Completed Weld



First Pass



- **Objectives**
  - Detecting surface and subsurface flaws in first, second and any subsequent layer
  - Only cap surface of each layer accessible
  - Narrow bead preparation - Limited access
  - Cap width may increase significantly for second (and subsequent) layers
  - Weld inspection done in one pass
  - Sensor follows weld head closely for real- or near-real time monitoring
    - High temperature components
    - Cooling features required
- **Approach**
  - Computer optimization modeling
  - Material selection and testing
  - Optimized design
  - Testing on actual weld system

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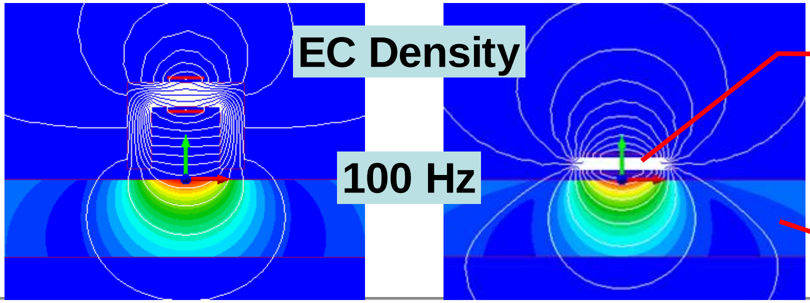
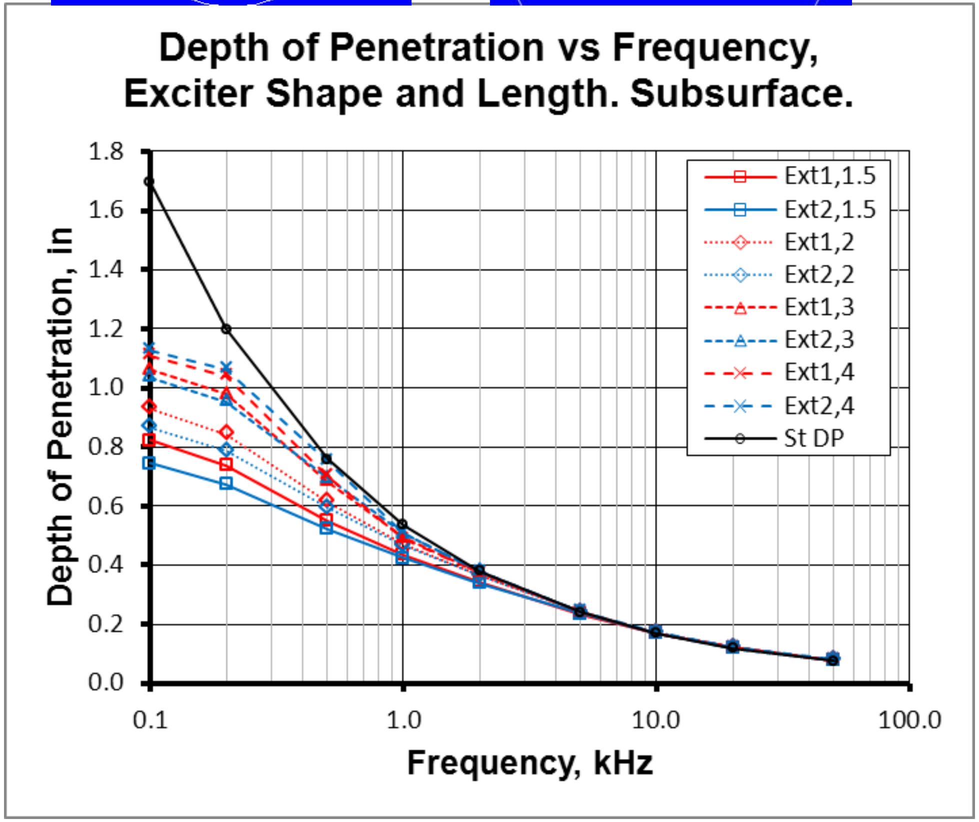
Depth of Penetration (DP) Optimization





- **2D translational symmetry models used**
- **DP, EC surface extent and EC density investigated vs exciter shape, length and frequencies**
  - 2 exciters considered – U-(1) and Plate-shaped (2)
  - Length – 1.5”, 2”, 3” and 4”
  - Frequencies – 0.1 to 50 kHz
  - Plate thickness – 1.25”
  - Plate material – 316L
- **Length affected DP for frequencies lower than 2 kHz and DP smaller than 0.365”**
- **Good DP with reasonable exciter dimension**
- **U-shape exciter selected**

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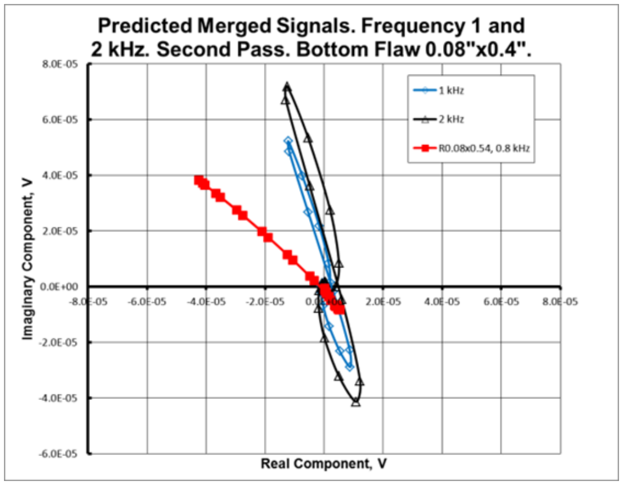
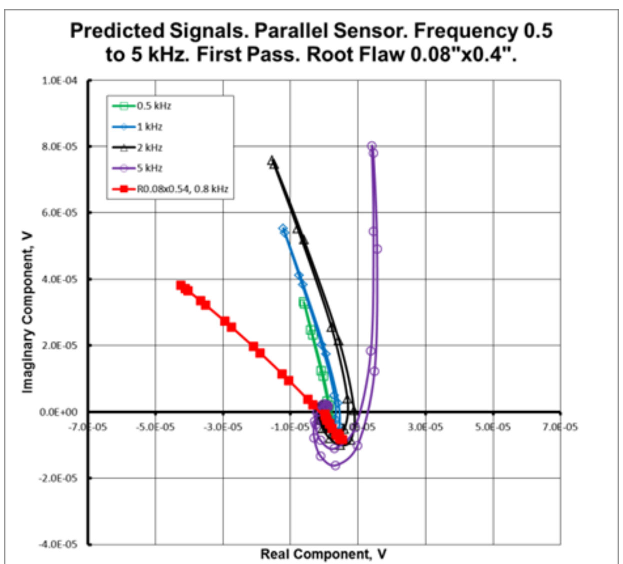
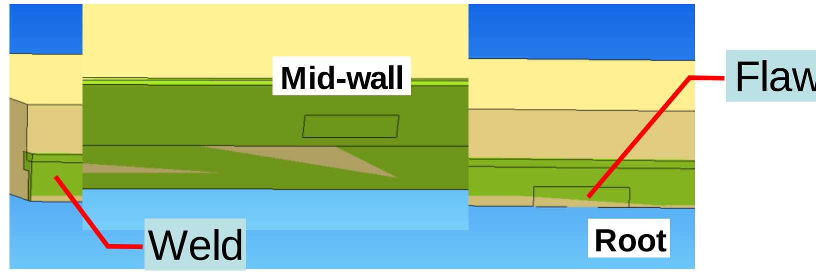
Interaction with Subsurface Planar Flaws. Summary.







Root

- Two receiver elements most promising – parallel (x) and normal (z)
- Surface and slightly subsurface pores larger than 0.06” expected to be detectable
- Planar flaws longer than 0.4” and height larger than 0.04” and 0.08” expected to be detected depending on depth
- Detection of planar flaws with height 1/16” would be in sensor range

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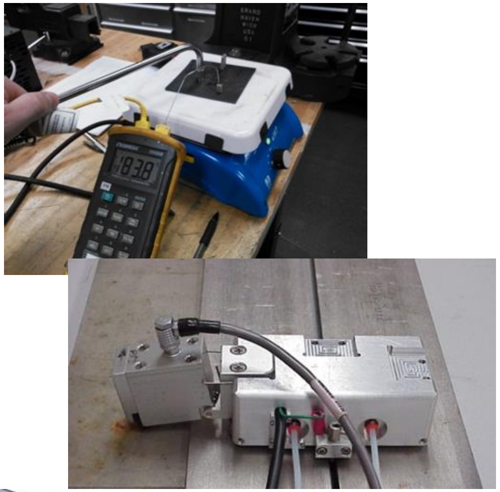
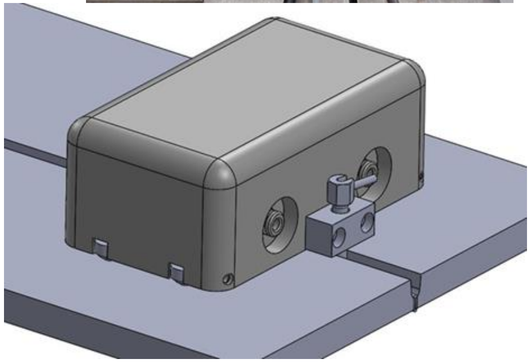
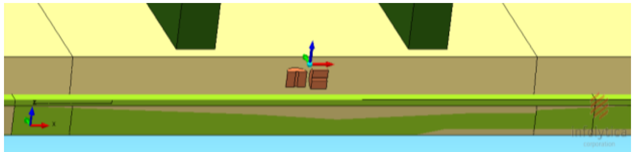
Design







- Thermal testing conducted. Selected materials performed up to 200ºC without any adverse effects.
- All wires and insulation rated to 200ºC
- Sensor designed to work with single receiver element (first pass) and array arrangement (cap pass)
- Each receiver element – X and Z field
- Air cooling lines available if necessary
- Design features built for sensor centering and sliding over surface
- Testing conducted without mechanical contact between surface and receiver element

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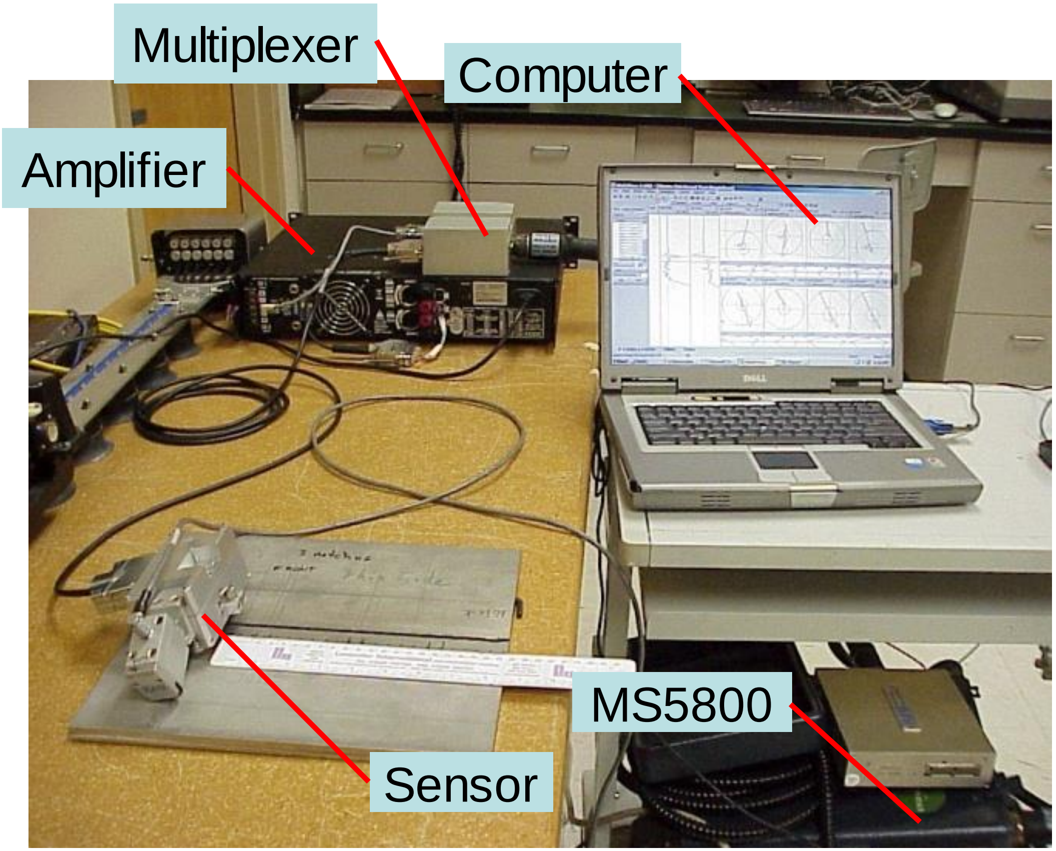
Laboratory Setup



- **Off-the-shelf equipment**
- **Single element**
  - Three frequencies F1-2.25 kHz, F2-4.5 kHz and F3-15.75 kHz
  - 12 processing channels with and without HP and BP filters and 2 orthogonal receivers
- **Array demonstrated at 14 kHz**

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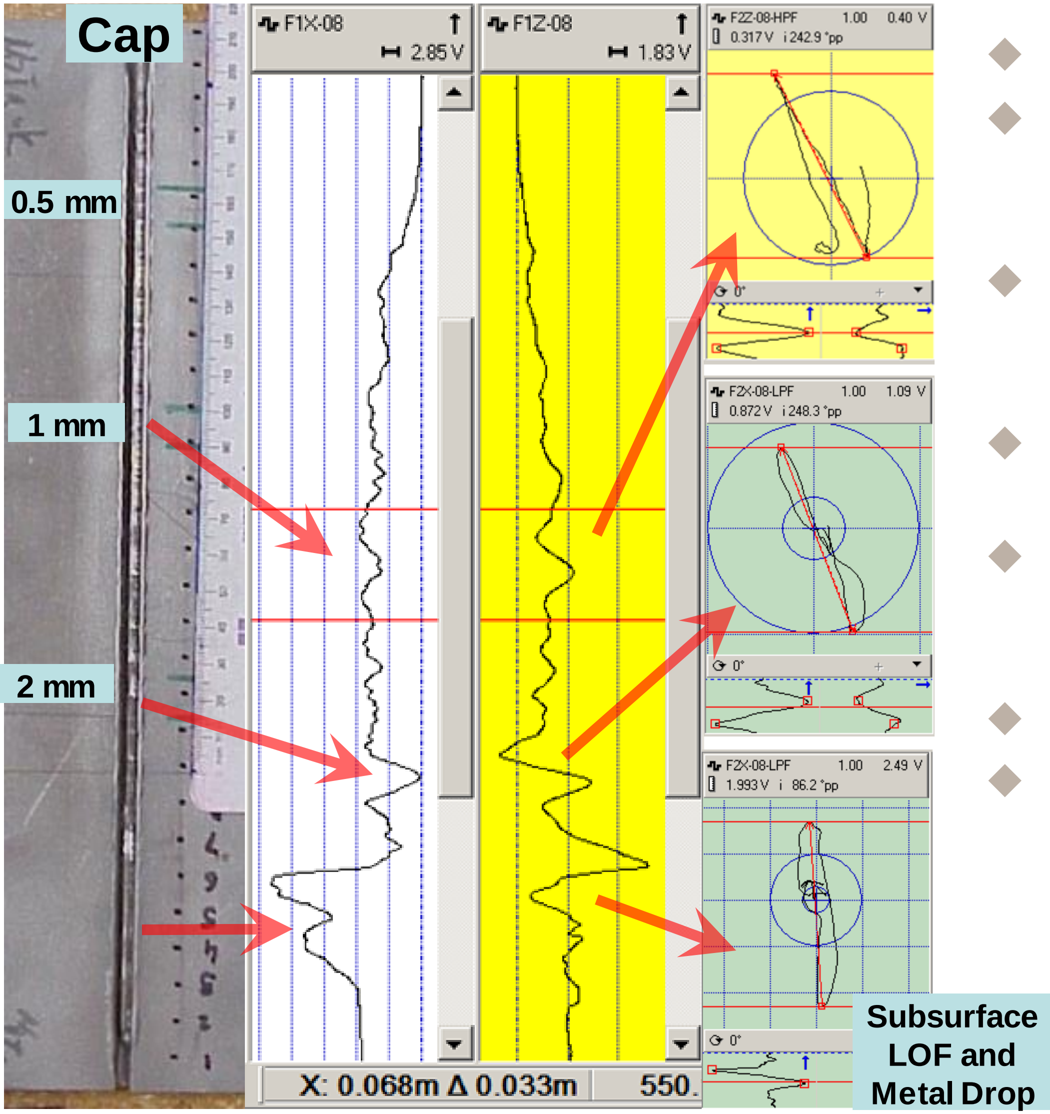
First Pass. Surface Flaws.



- Weld with root pass
- EDM notches 10 mm length and height 0.5, 1 and 2 mm at cap
- Long area with subsurface LOF at one specimen end
- Notches 1 and 2 mm detected
- Large area of LOF and root metal drop also detected
- Notch 0.5 mm missed
- Other natural features detected

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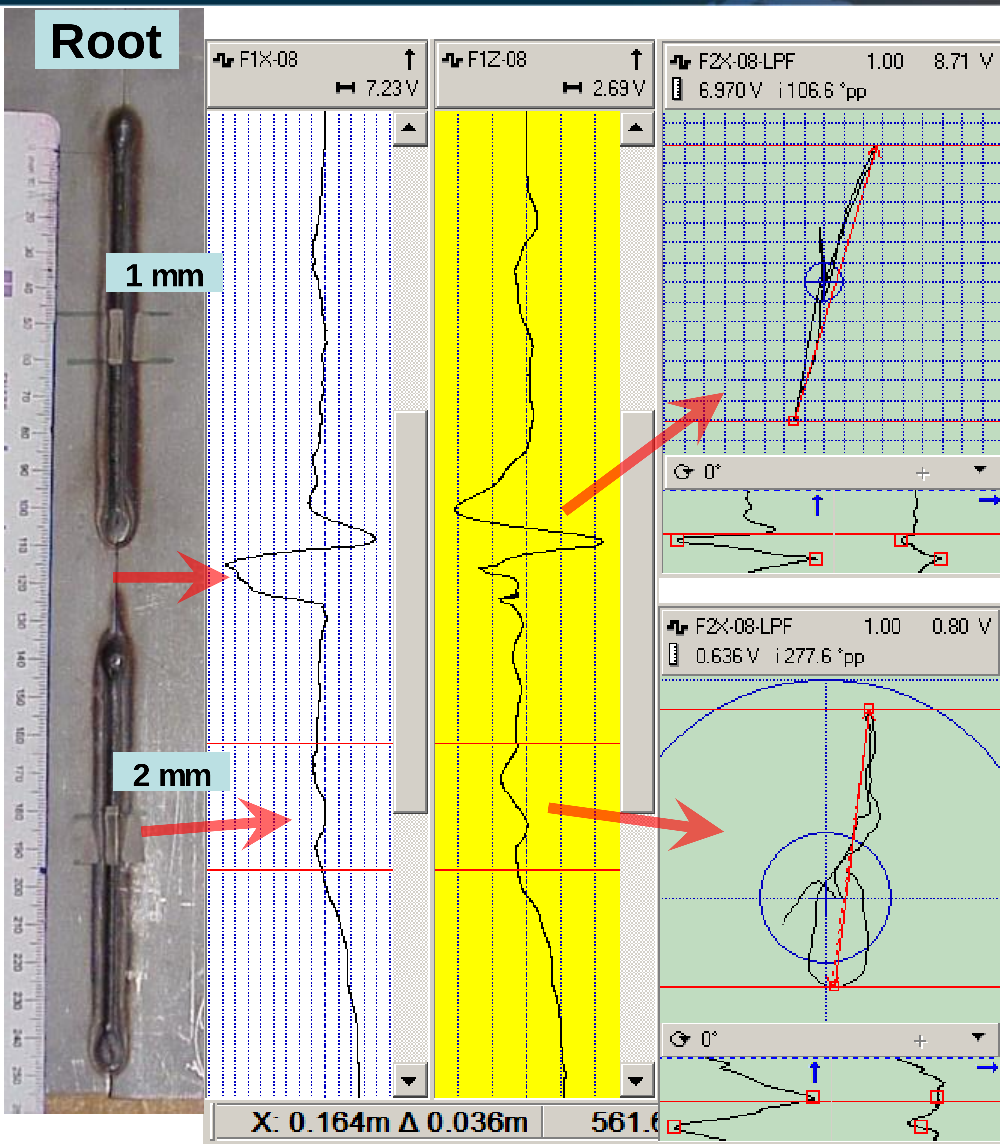
First Pass Subsurface Flaws.



- Weld with root pass
- EDM notches 10 mm length and height 1 and 2 mm at root
- Long area with surface and subsurface LOF at middle
- Notch 2 mm detected
- Large area of LOF and root metal drop also detected
- Notch 1 mm missed
- Other natural features detected

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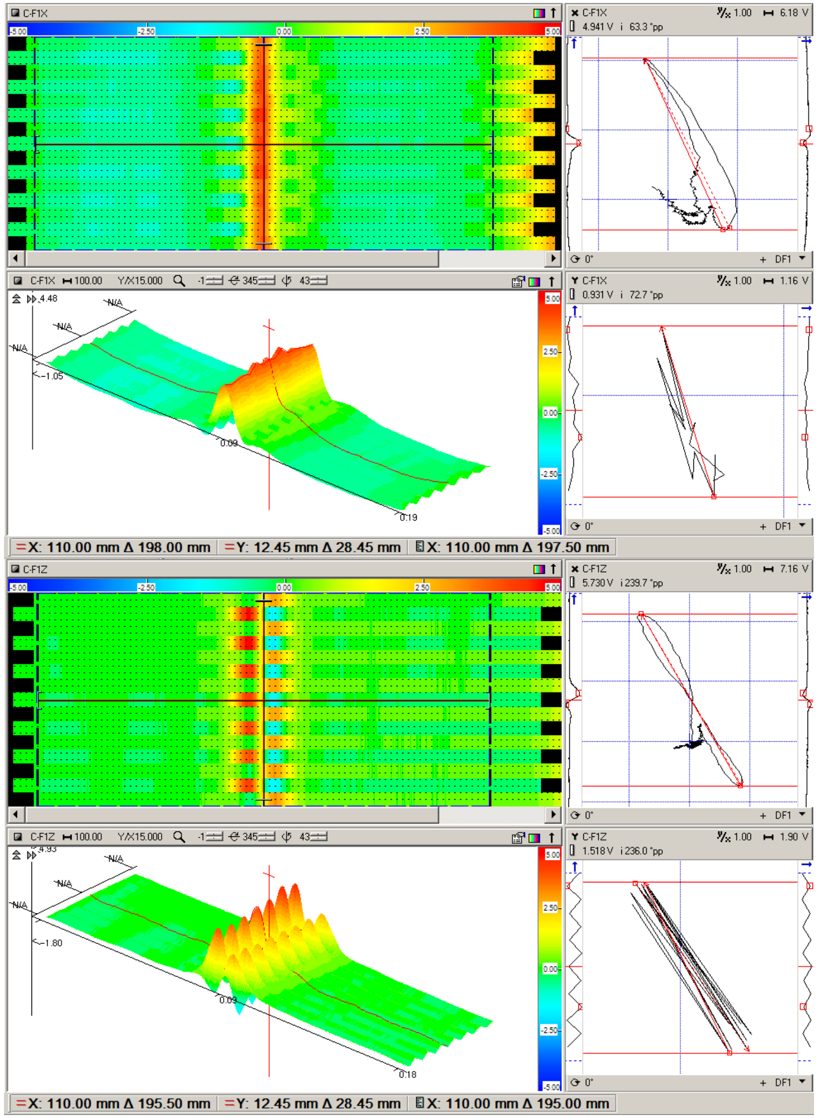
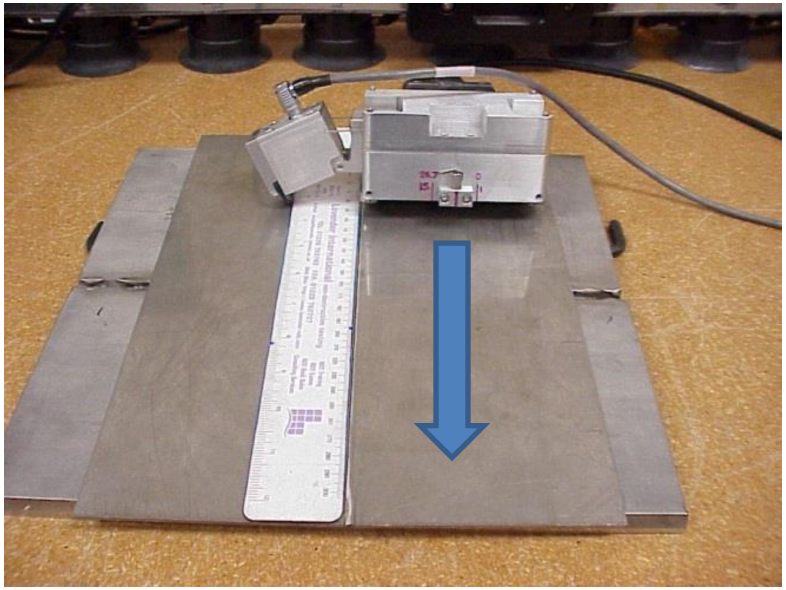
Array Inspection





- Array demonstrated with subsurface flaw under 1.8 mm thick sheet
- Frequency 14 kHz

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Conclusions

- Multipurpose eddy current sensor for weld monitoring designed and integrated
- Laboratory tests indicated very good sensitivity for surface and subsurface implanted and natural features in first weld pass
- Trials will conducted at INL to verify and demonstrate performance during welding on root and cap pass later this year

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EWI is the leading engineering and technology organization in North America dedicated to developing, testing, and implementing advanced manufacturing technologies for industry. Since 1984, EWI has offered applied research, manufacturing support, and strategic services to leaders in the aerospace, automotive, consumer electronic, medical, energy, government and defense, and heavy manufacturing sectors. By matching our expertise to the needs of forward-thinking manufacturers, our technology team serves as a valuable extension of our clients' innovation and R&D teams to provide premium, game-changing solutions that deliver a competitive advantage in the global marketplace.

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Conclusions/Path Forward

- Satisfactory Results Out of Both EWI/INL probes on post weld inspections
  - EWI filed for provisional patent
  - INL evaluating intellectual property
- UT Probe system has undergone evaluation under welding conditions and performed satisfactorily
  - Water coupling work per conceptual design
  - Focal laws design provided expected mechanism to determine depth of laser penetration
  - Auto-Tuning of focal plane during setup would beneficial for more robust detection

Conclusion Path/Forward (more)

- Project extended to November 2015:
  - Support a combined demonstration with EWI with INL laser welding system
  - Provide opportunity for live evaluation of EWI Sensor additional evaluation of INL sensor
- To do list:
  - Submit draft publication
  - Explore commercialization opportunities

Thank you--Questions

Georgia Institute of Technology

Self-Consolidating Concrete Construction for Modular Units

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Kimberly Kurtis (Co-PI)
Larry Kahn (Co-PI)
Giovanni Loreto (Researcher)
School of Civil and Environmental Engineering (CEE) – Georgia Institute of Technology

Bojan Petrovic (Co-PI)
Nuclear and Radiological Engineering) – Georgia Institute of Technology

Industry partner:
Jurie van Wyk (Westinghouse Electric)
Bernd Laskewitz (Westinghouse Electric)

1. Intro
Objectives and outcomes

- Development of a self-consolidating concrete mixtures so that concrete placement can be made into steel plate composite (SC) modular structures without the need for continuous concrete placement.

Task 1: Development of SCC with Shear-Friction Capacity for Mass Placement

- SCC mixtures to ensure sufficient shear capacity across cold- joints (self-roughening), while minimizing shrinkage and temperature increase during curing to enhance concrete bonding with the steel plates.

Task 1: Development of SCC with Shear-Friction Capacity for Mass Placement
Task 2: Assessment of Cold Joint Shear-Friction Capacity

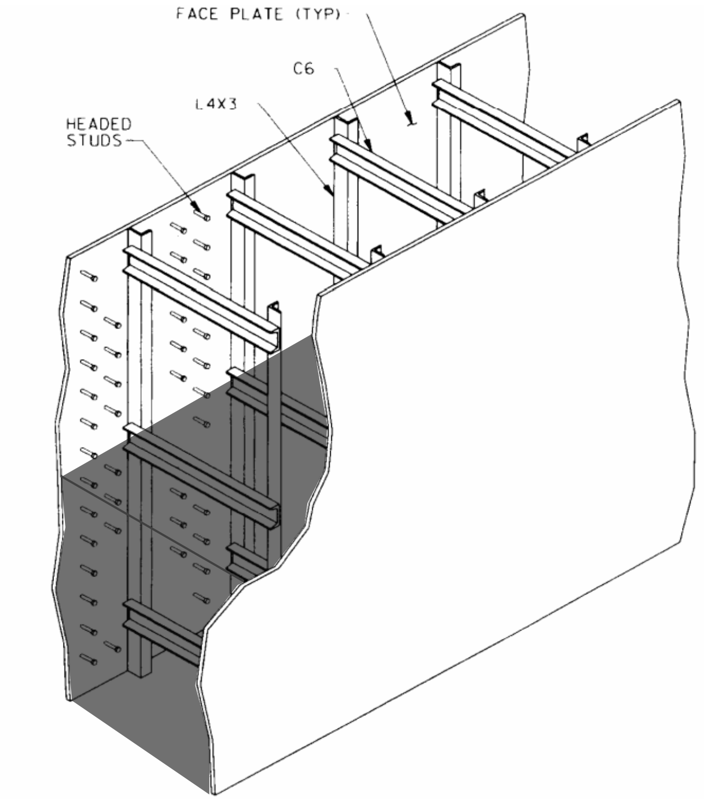
- SCC mixtures featuring a self-roughening capability to produce adequate shear friction between cold joints and to produce draft provisions addressing shear-friction, for consideration in the AISC N690-12 Appendix N9 code used for the design of SC modular structures.

Task 3: Assessment of Shear and Flexural Performance
Task 4: Validation through Full-Scale Testing and Modeling
Task 5: Draft Code Requirement for Shear Friction Design of Cold Joints

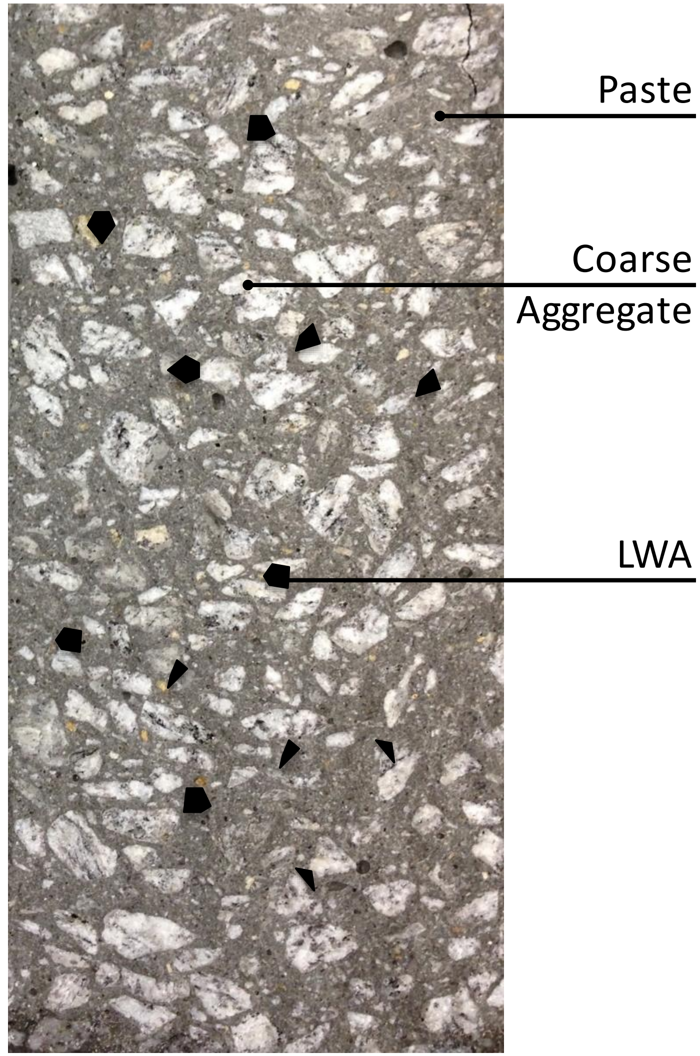
1. Intro

Objectives

- Development of a self-consolidating concrete mixtures so that concrete placement can be made into steel plate composite (SC) modular structures without the need for continuous concrete placement.



1. Intro
Objectives



2. Development of SRC Mix Design
Strategies

Mix Component	67M
Cementitious (lb/yd^3)	
Cement Type II	617
Fly Ash, Class F	459
Total Powder	*1076*
Water (lb/yd^3)	343
w/cm	*0.319*
Coarse Aggregates (lb/yd^3)	
# 67	981
# 89	305
Total Coarse	*1286*
Fine Aggregates (lb/yd^3)	
Natural sand	679
Manufactured sand	679
Total Fine	*1357*
Total Aggregates	*2796*
Admixures (fl oz./cwt)	
HRWR	0.18
TOT	4063

2. Development of SRC Mix Design
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TOT	4063

- Smaller aggregates and controlled gradation curve
- Use of #67 and #89 coarse aggregates
- Substitute 5%, 10% and 15% in volume of coarse aggregate with LWA

2. Development of SRC Mix Design
Proprieties and tests

Self-Consolidating Concrete

Self-Roughening Concrete

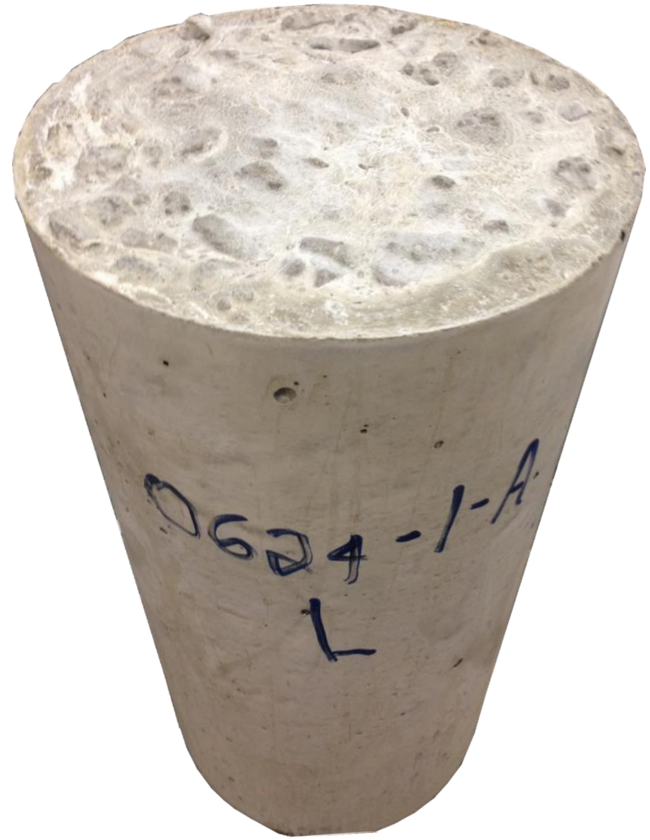
Fresh SCC proprieties

- Flowability: flows easily at suitable speed into formwork (T20 = 4-5sec; Flow Slump = 24-26”)
- S Groove test (good self-healing ability)
- Hardened Visual Stability Index (VSI = 0)

Hardened SRC proprieties

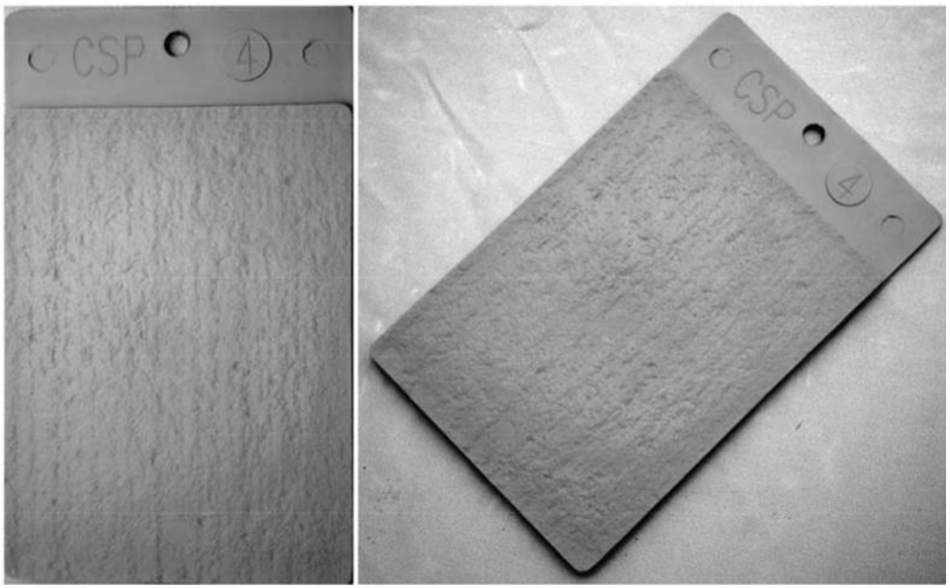
- Compressive strength: 6-7ksi
- Shrinkage: <250 $\mu\varepsilon$

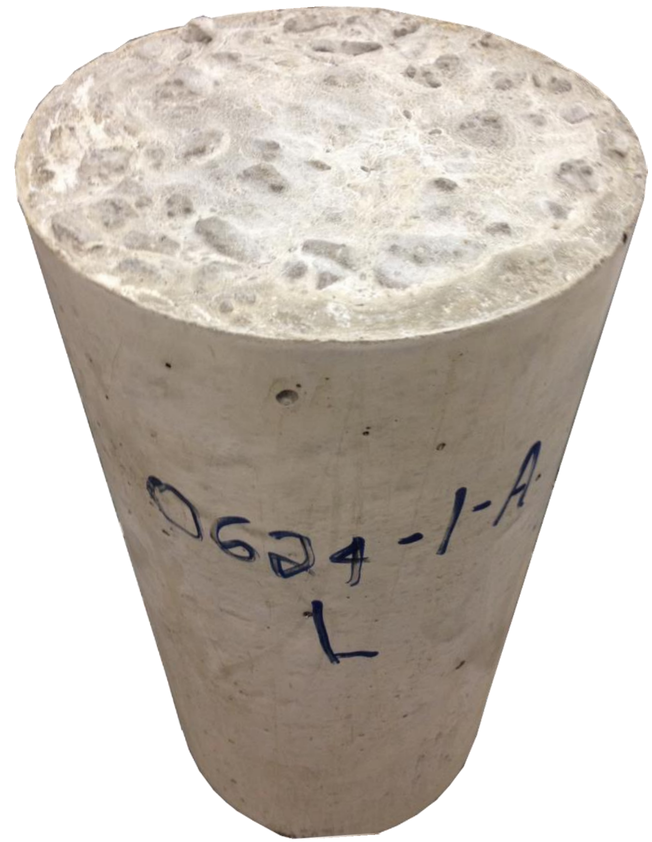
2. Development of SRC Mix Design
Measurements of Roughness



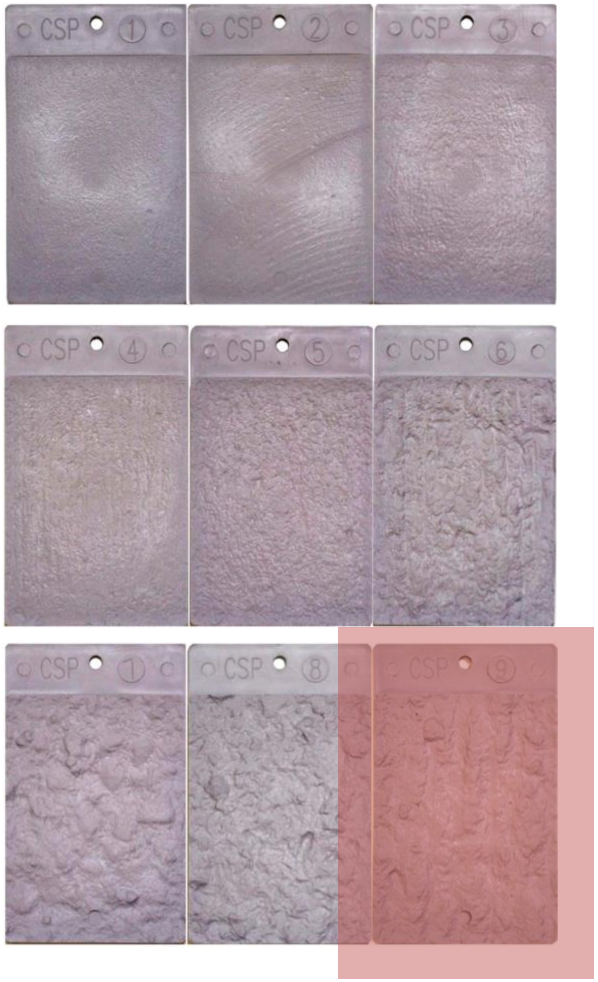
2. Development of SRC Mix Design
Roughness

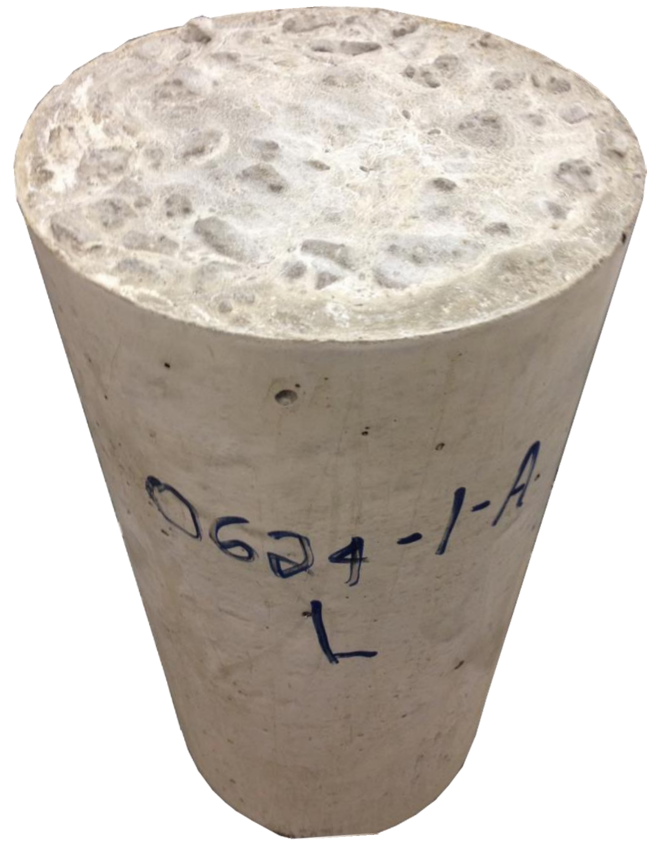
ICRI's CSPs





2. Development of SRC Mix Design
Roughness

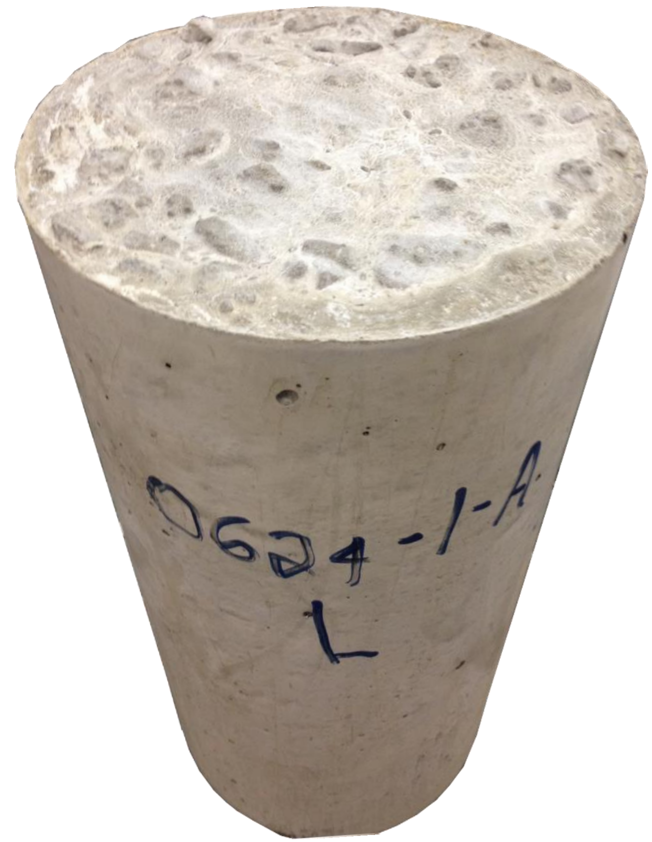




2. Development of SRC Mix Design
Measurements of Roughness

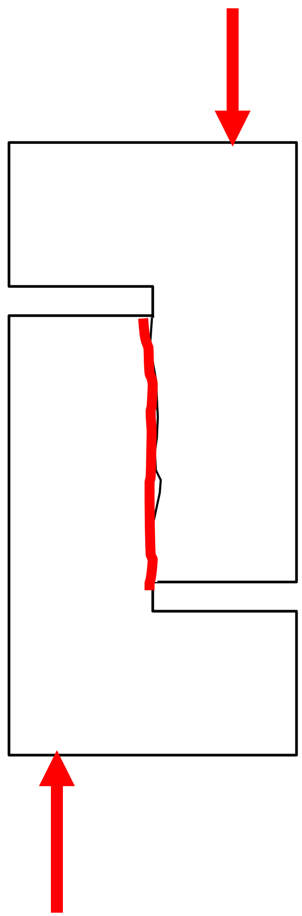
ACI 318-11 (11.6.9):

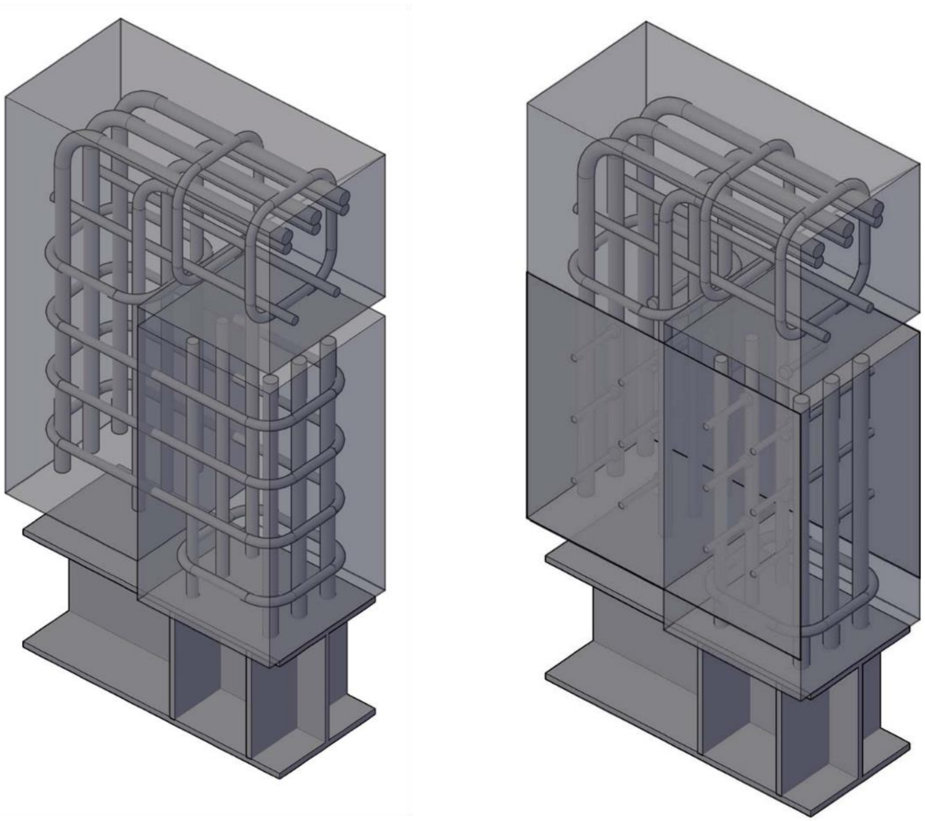
"…when concrete is placed against previously hardened concrete, the interface for shear transfer shall be clean and free of laitance. If μ is assumed equal to **1.0**λ, interface shall be roughened to a full amplitude of approximately 1/4 in."



3. Assessment of Cold Joint Shear Friction Capacity

Mechanical tests for shear friction characterization





Laboratory test

Kahn, L., Mitchell, A. D. (2002) “Shear friction test with high-strength concrete” ACI Structural Journal, 99 (1).

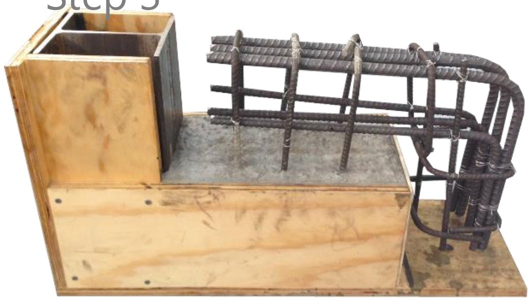
3. Assessment of Cold Joint Shear Friction Capacity

Mechanical tests for shear friction characterization

Step 1

Step 2

Step 3

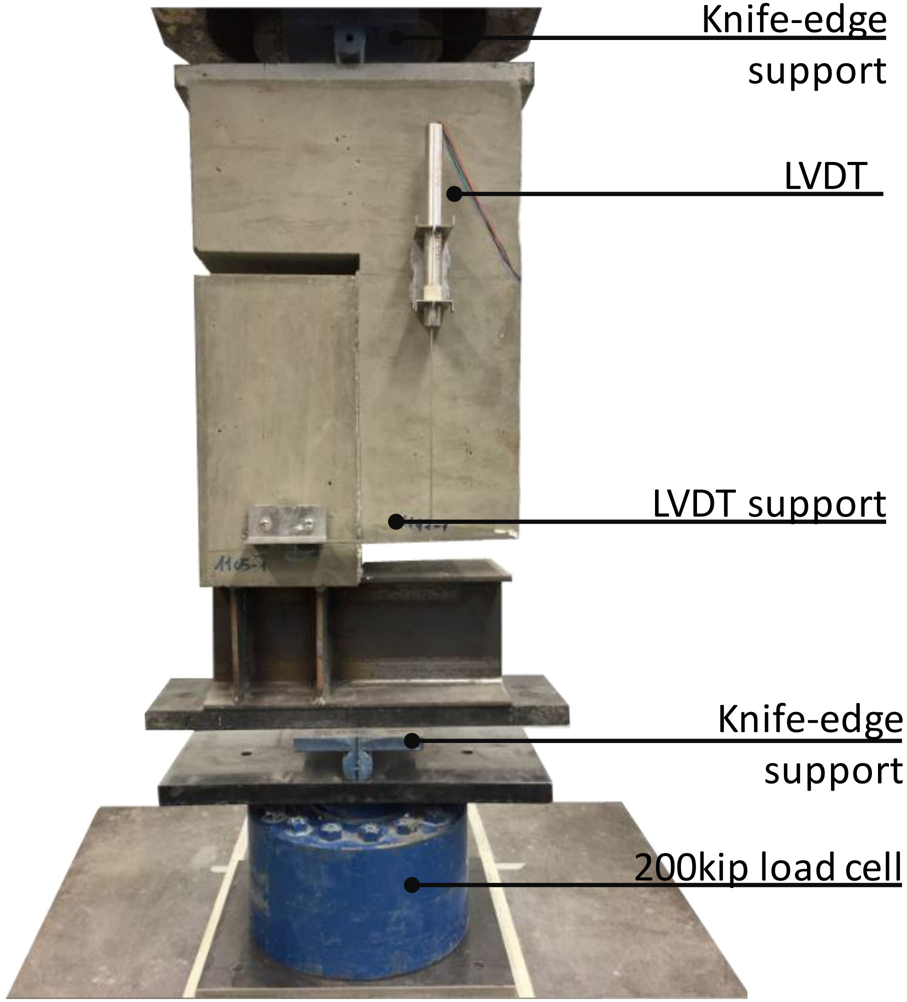


Step 4

Step 5

3. Assessment of Cold Joint Shear Friction Capacity

Mechanical tests for shear friction characterization



3. Assessment of Cold Joint Shear Friction Capacity

Failure modes

Internal Reinforcement
ρ=0.75%

External Steel Plate
ρ=0.25%
t=0.031 in.
(22 gage)

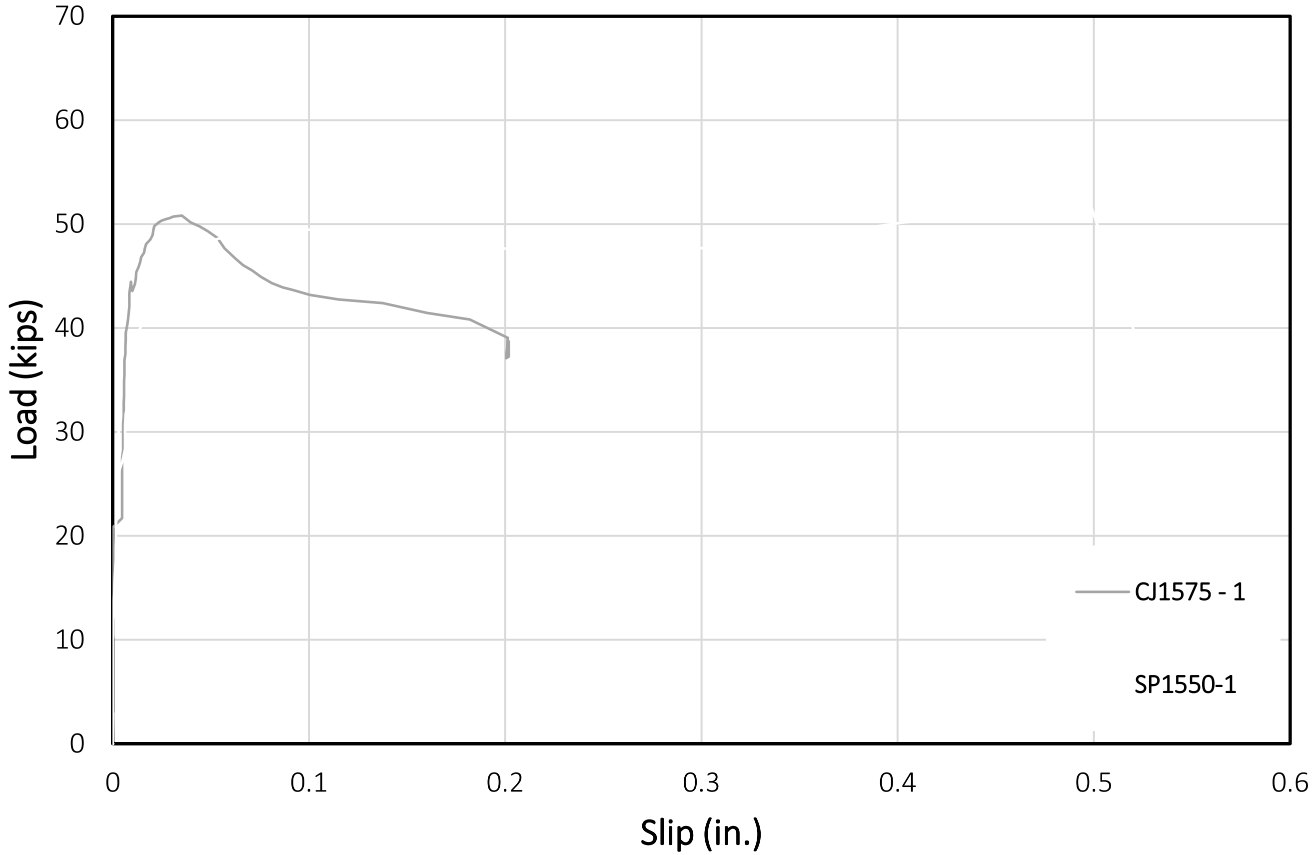
External Steel Plate
ρ=0.50%
t=0.063 in.
(16 gage)

External Steel Plate
ρ=0.75%
t=0.094 in.
(13 gage)

External Steel Strips
ρ=0.75%
t=0.375 in.

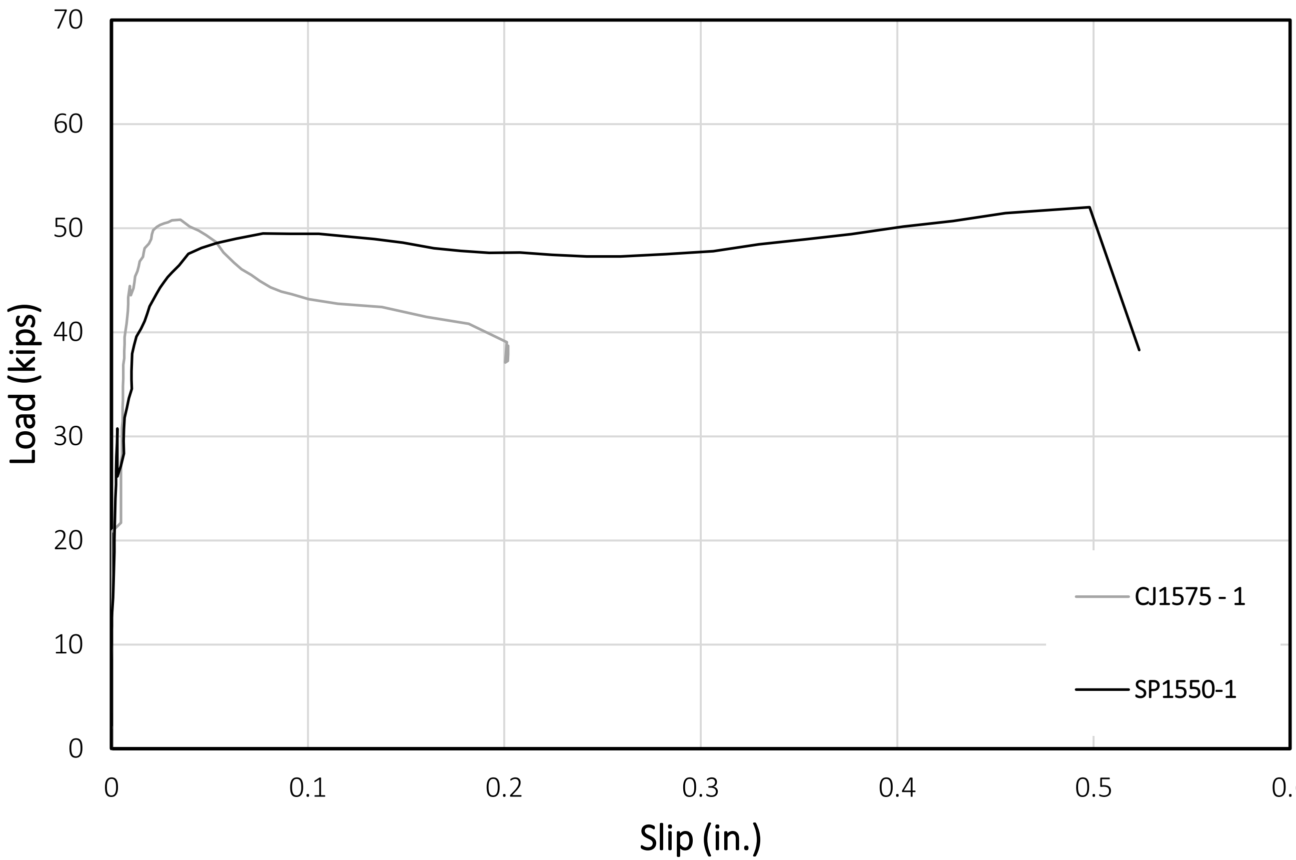
3. Assessment of Cold Joint Shear Friction Capacity

Test Results – Internal Reinforcement



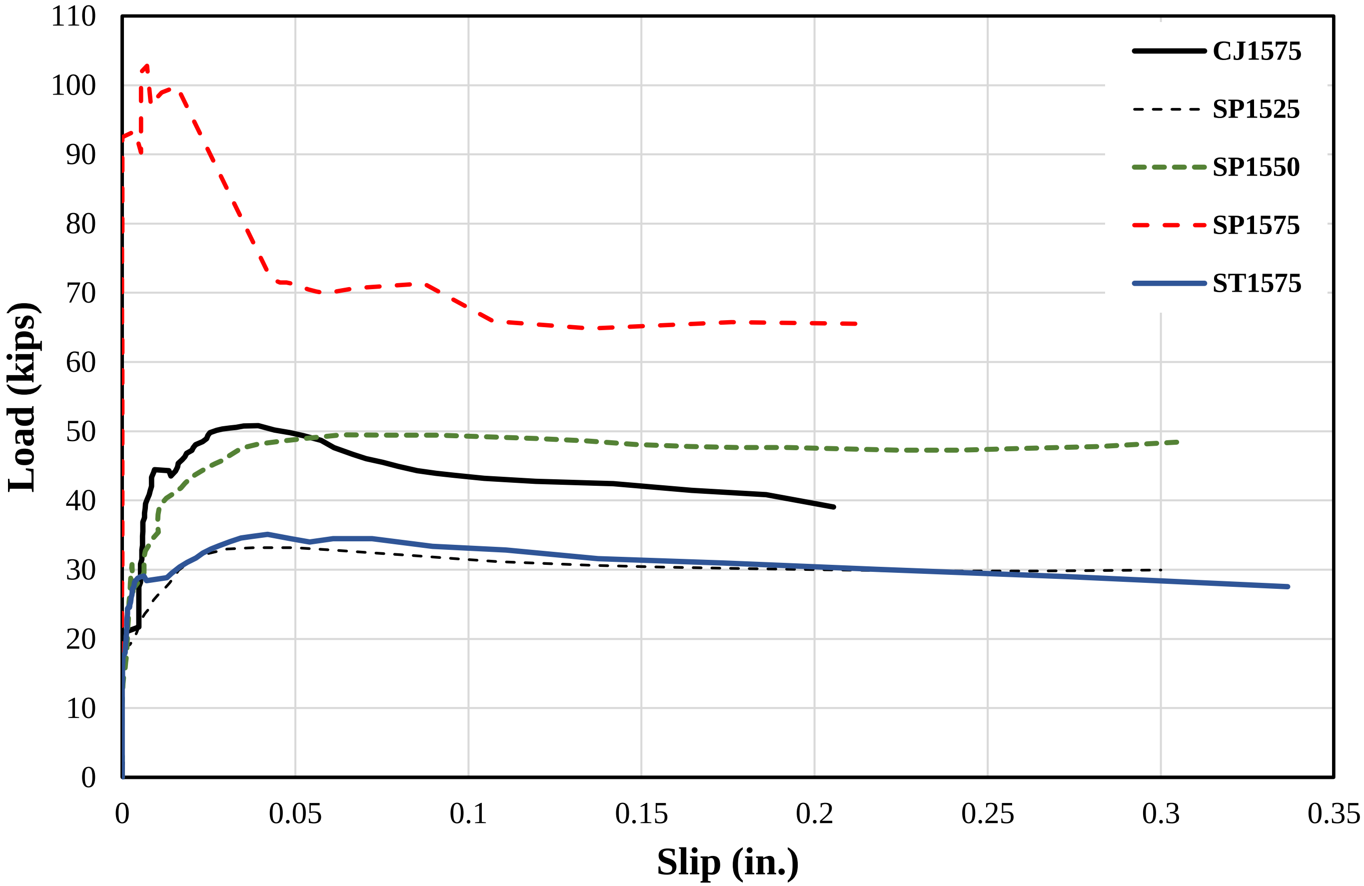
3. Assessment of Cold Joint Shear Friction Capacity

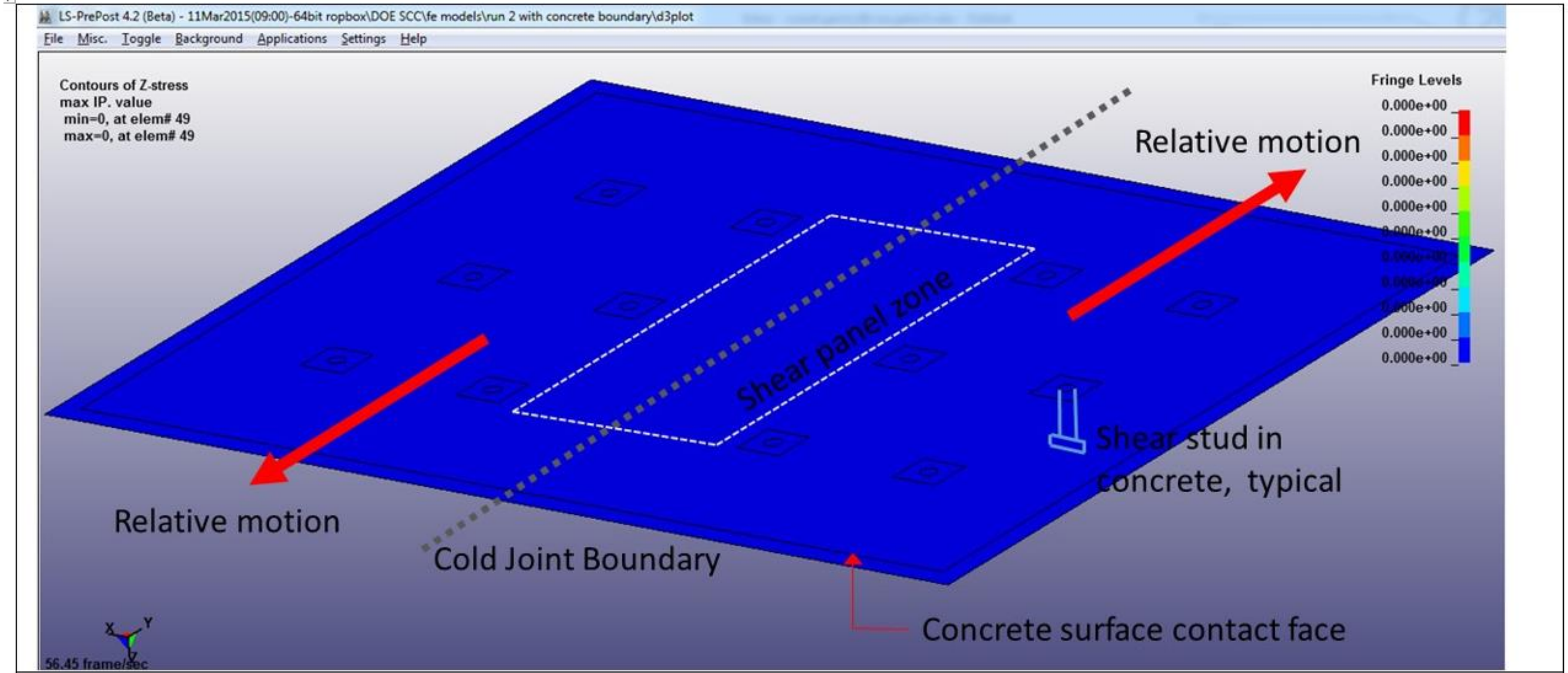
Test Results – External Steel Plate



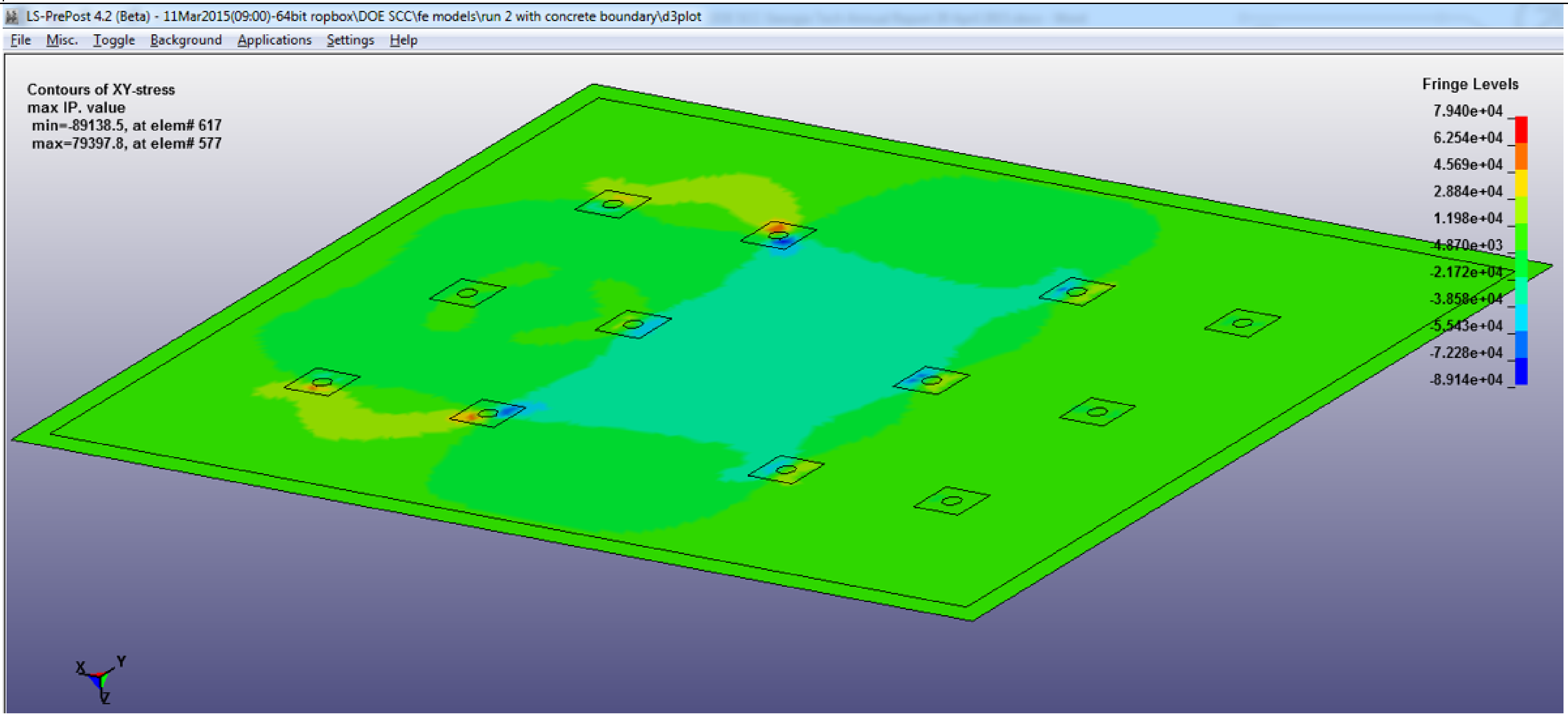
3. Assessment of Cold Joint Shear Friction Capacity

Test Results – Comparison among sets

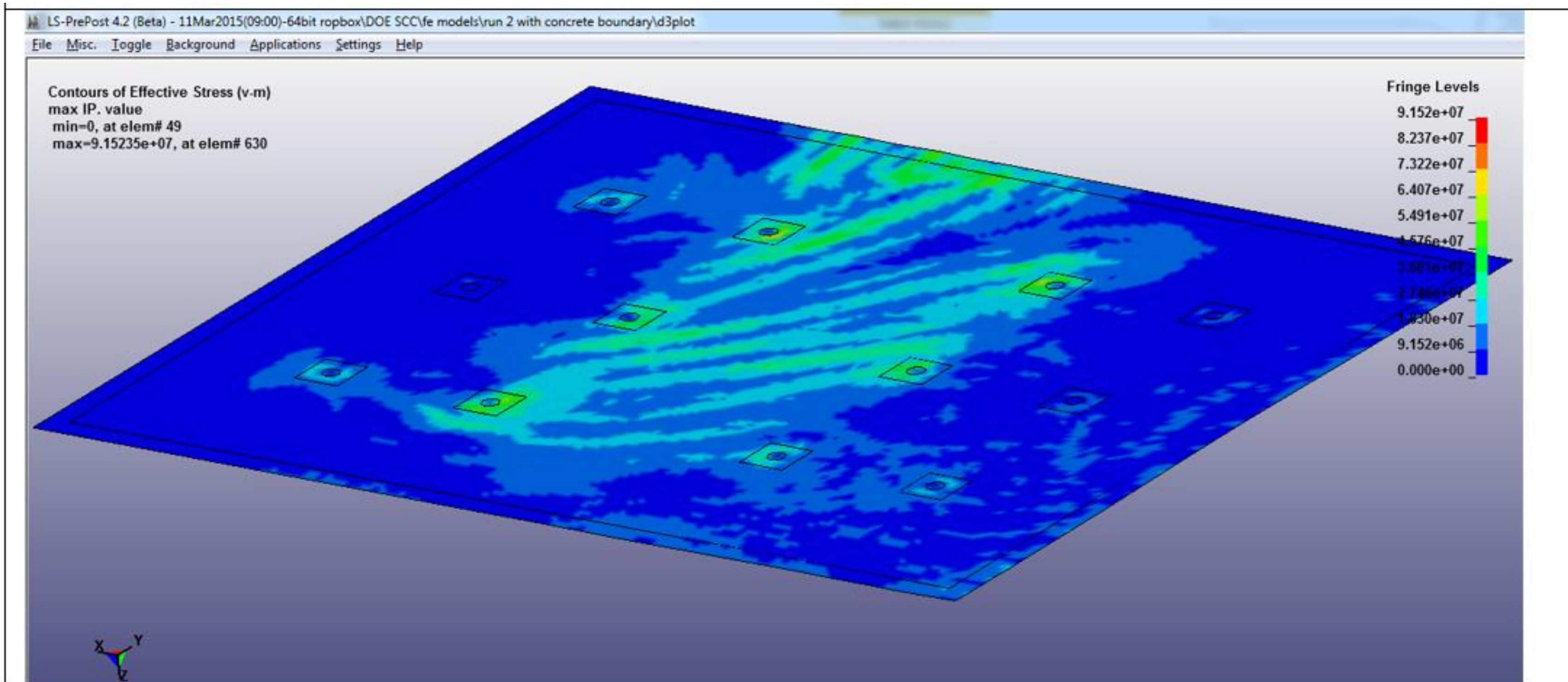




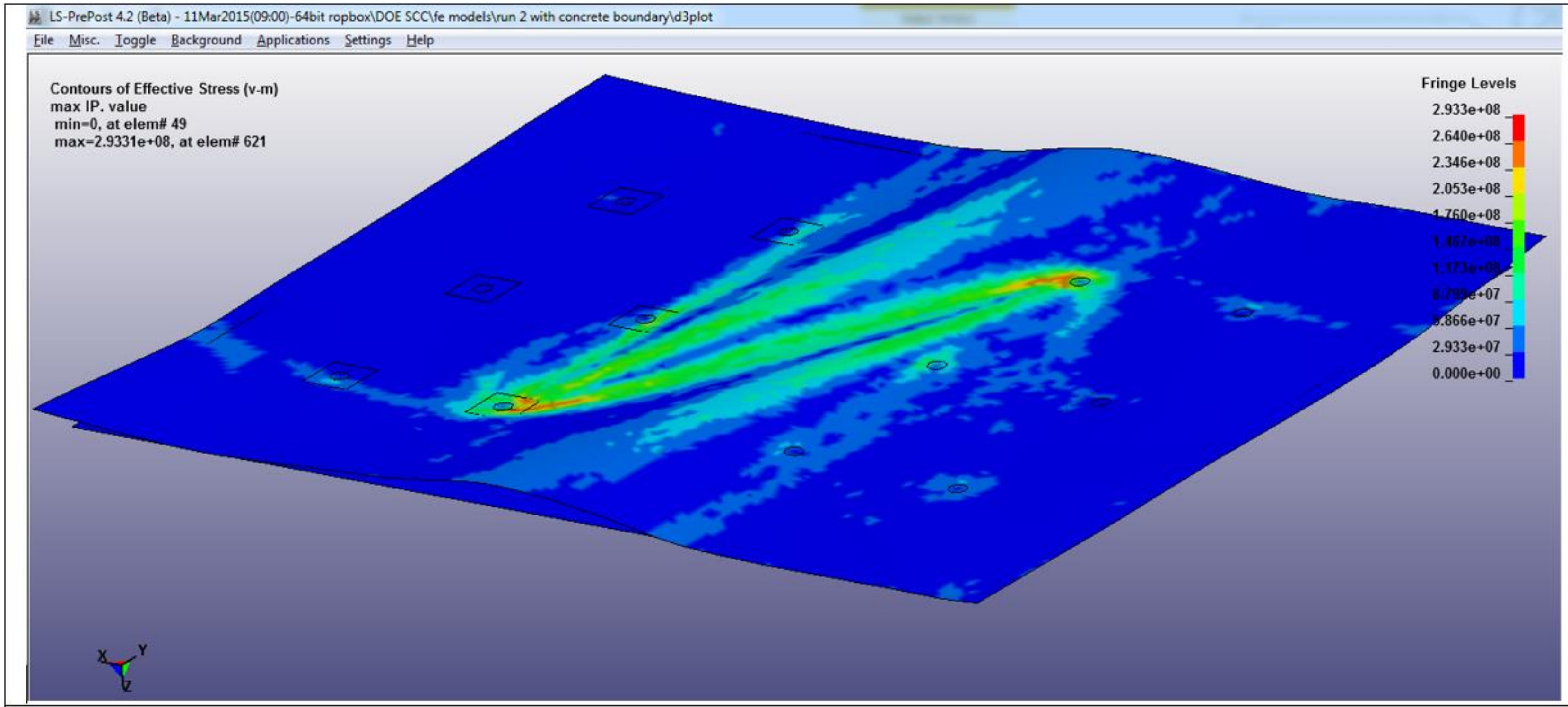
(a) Non-linear finite element model in LS-DYNA explicit. This initial model approximate the geometry of specimen SP 15 50-1 but with fewer Nelson studs.



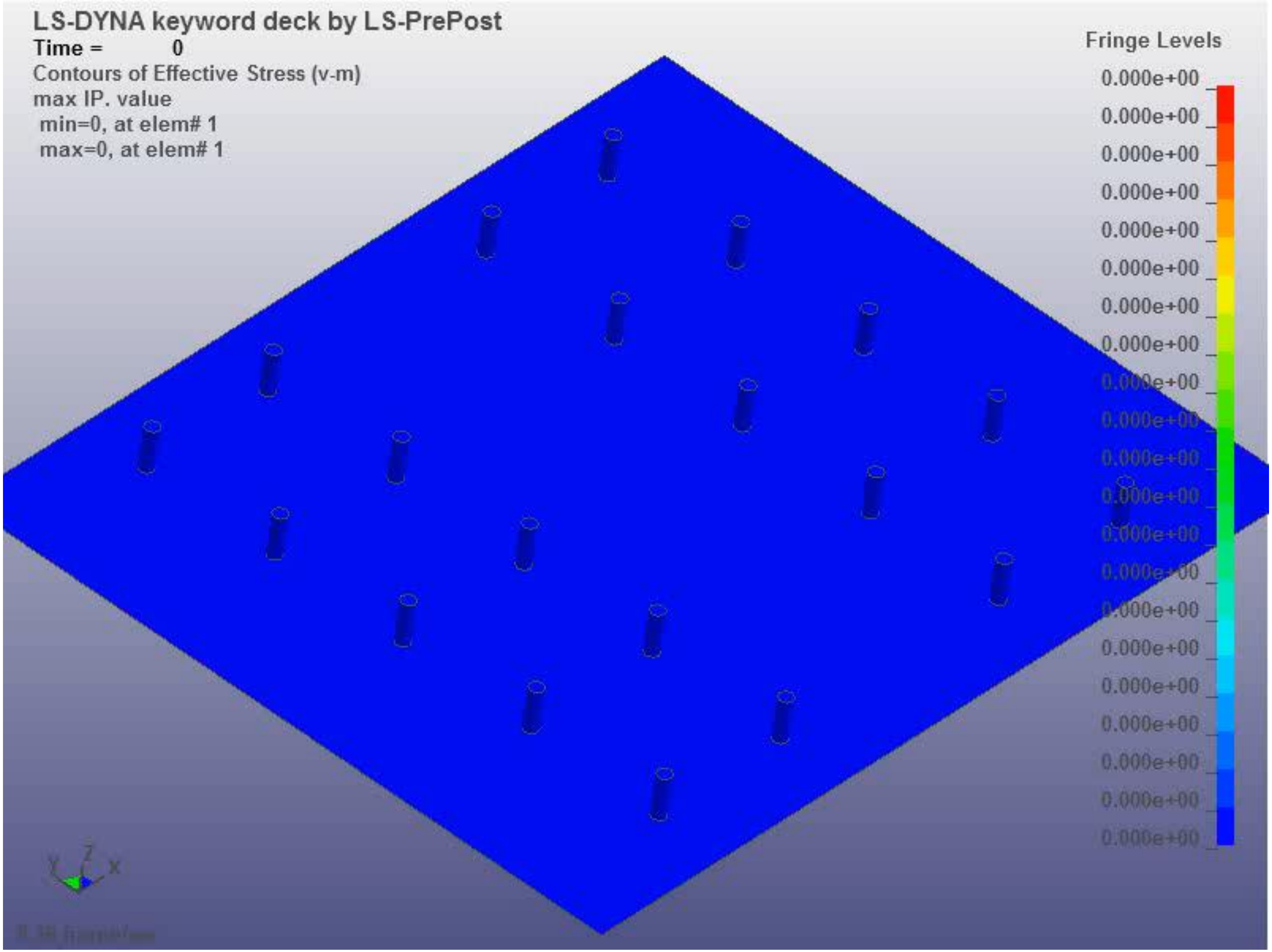
(b) Initital loading. Constant shear in the panel zone. In-plane shear stresses shown (all stresses in Pa).



(d) Onset of buckling. Panel zone shear dramatically reduced. Principle tensile stresses align with buckling of plate steel. Buckling is elastic, that is, steel plate does not yield before the bucking initiates. Model also predicts the lifting of the edge of the steel plate.



(e) Buckling progresses. Steel plate begins to yield in the vicinity of two studs (see red on stress contour). Buckling distortion as the plate pulls away from the concrete visible.


LS-DYNA keyword deck by LS-PrePost
Time = 0
Contours of Effective Stress (v-m)
max IP. value
min=0, at elem# 1
max=0, at elem# 1
Fringe Levels
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
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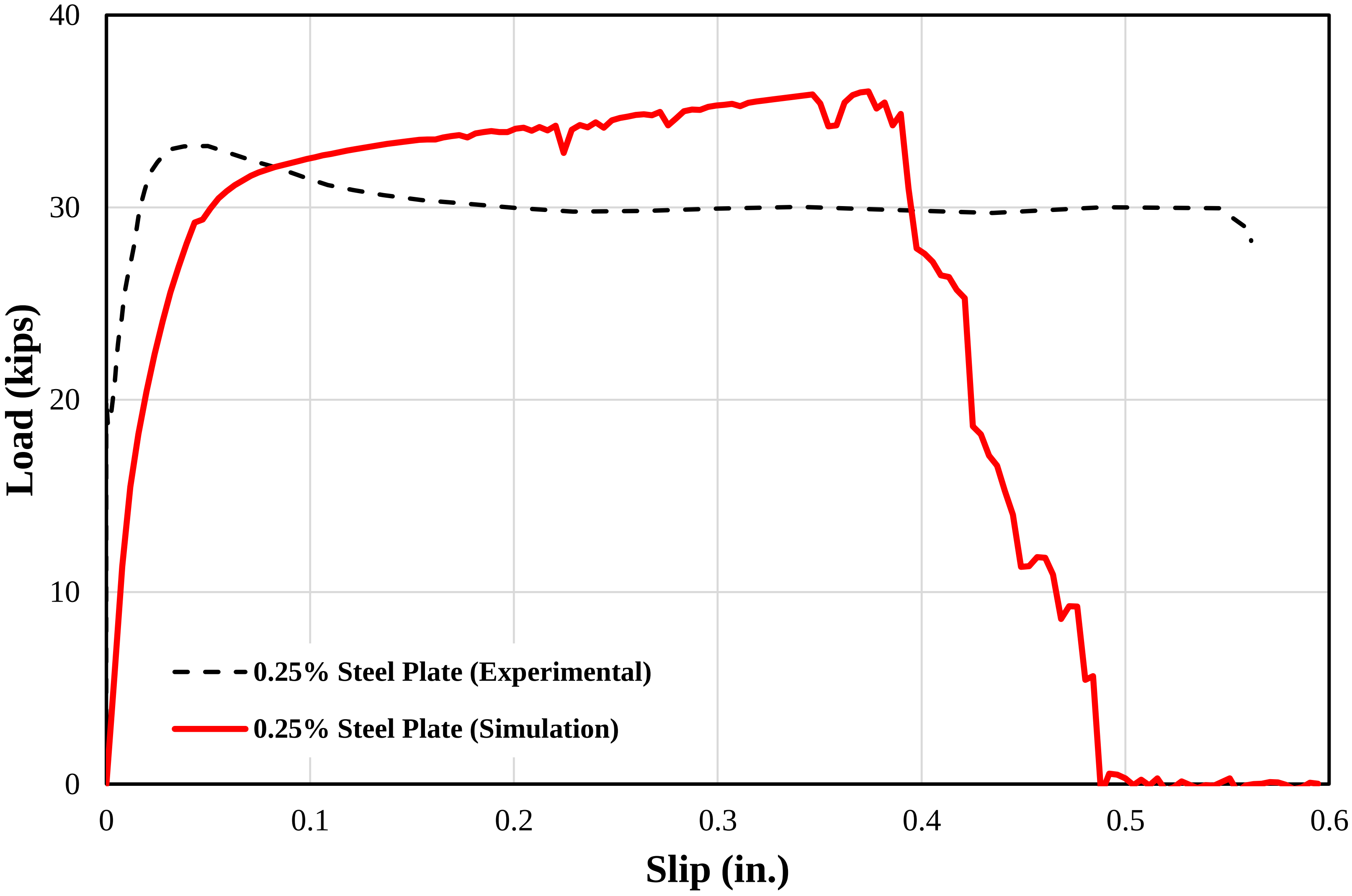
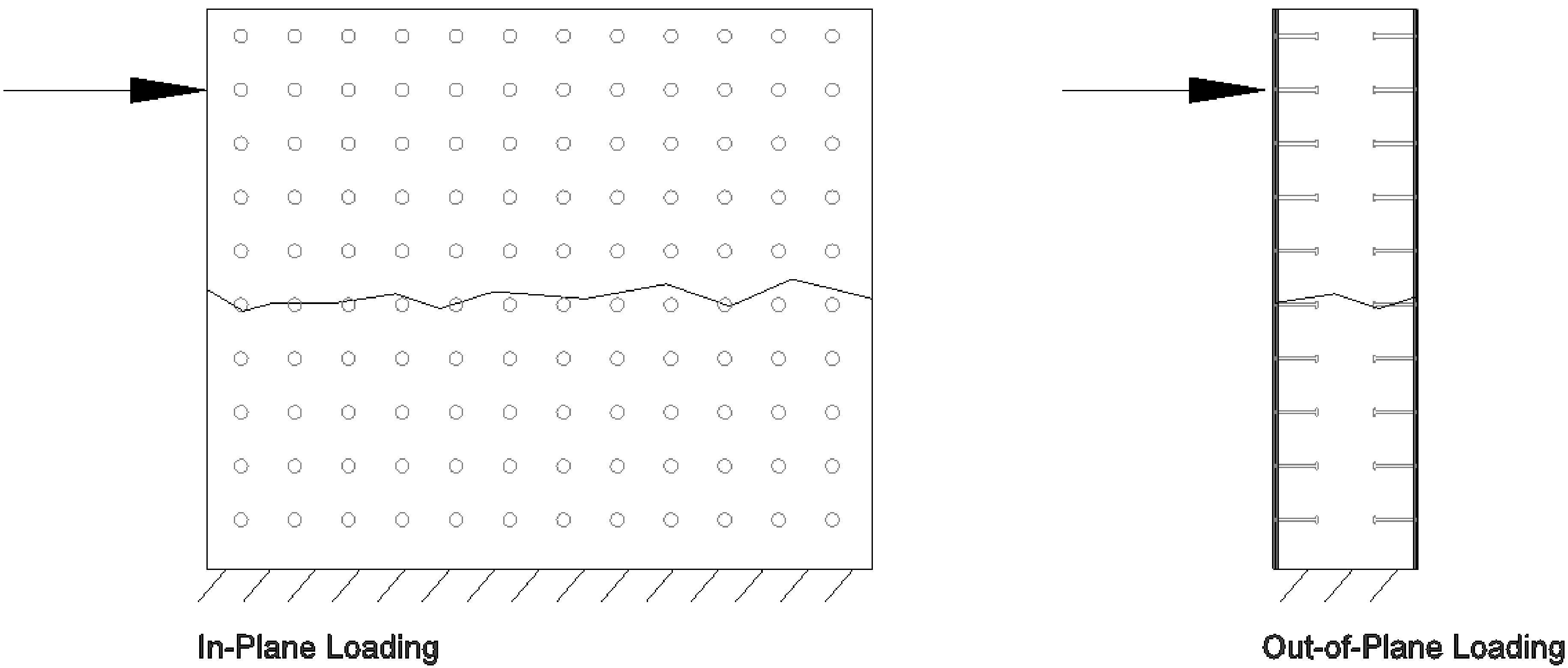
Y
Z
X


40
30
20
10
0
Load (kips)
0
0.1
0.2
0.3
0.4
0.5
0.6
Slip (in.)
0.25% Steel Plate (Experimental)
0.25% Steel Plate (Simulation)

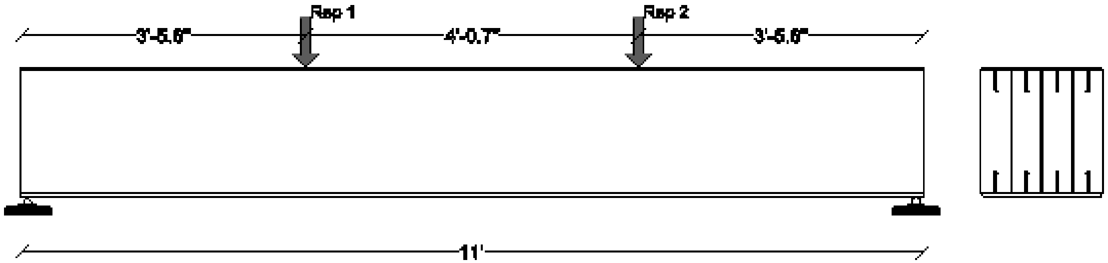
4. Assessment of Shear and Flexural Performances

Specimens preparation

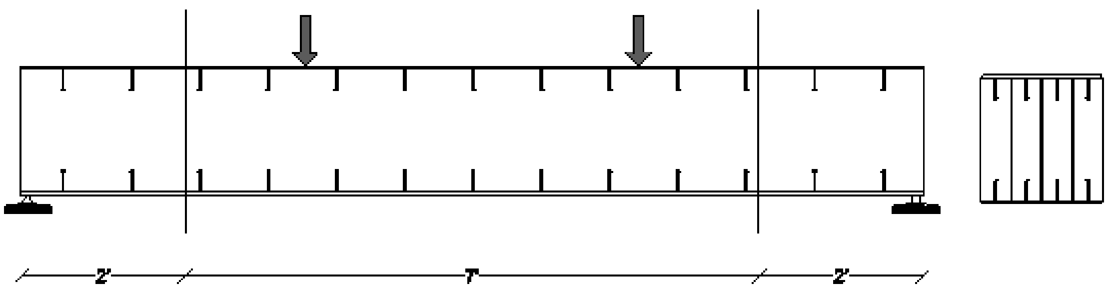


Task 3

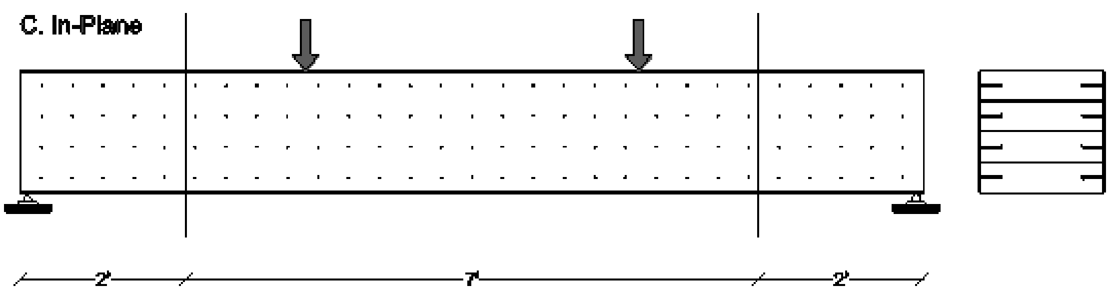
A. Control - No cold joint 1 in-plane and 1 out-of-plane

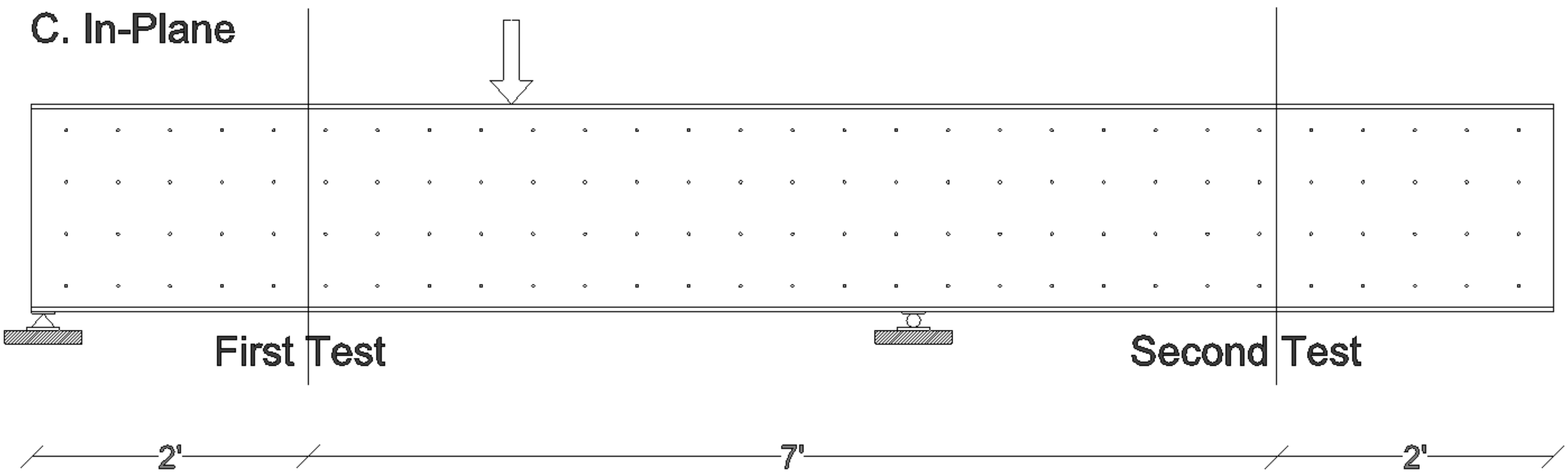


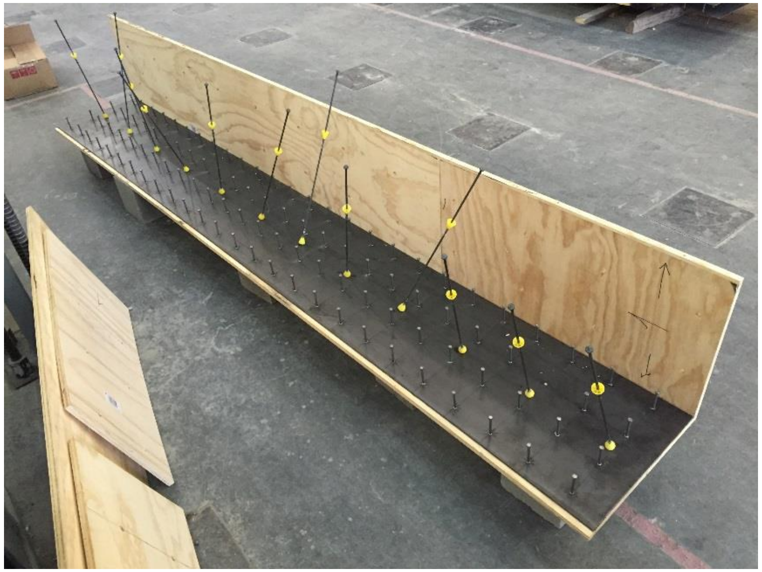
B. Out-of-Plane



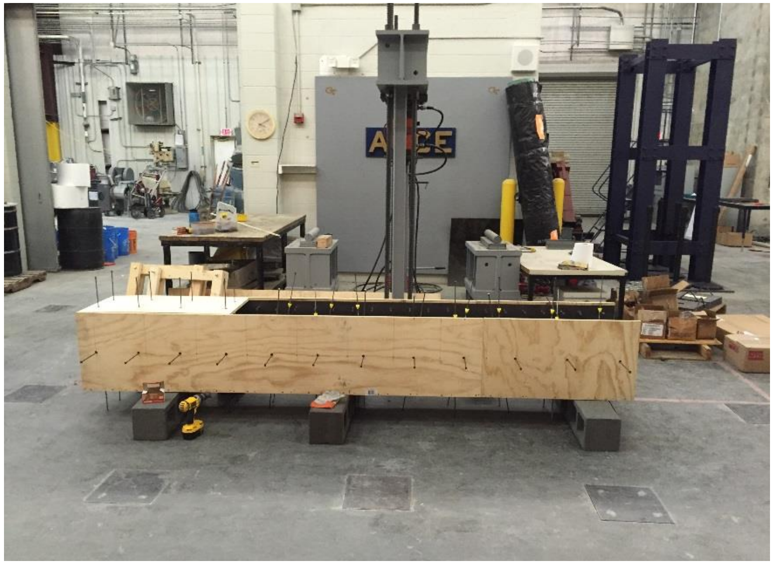
C. In-Plane

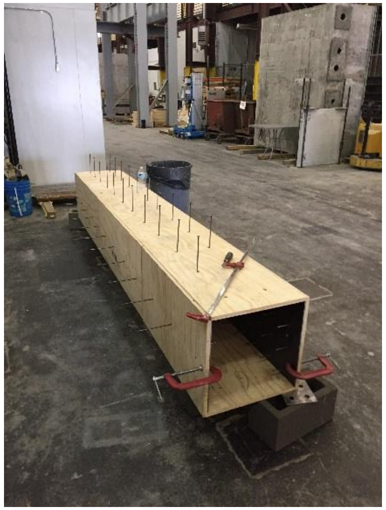


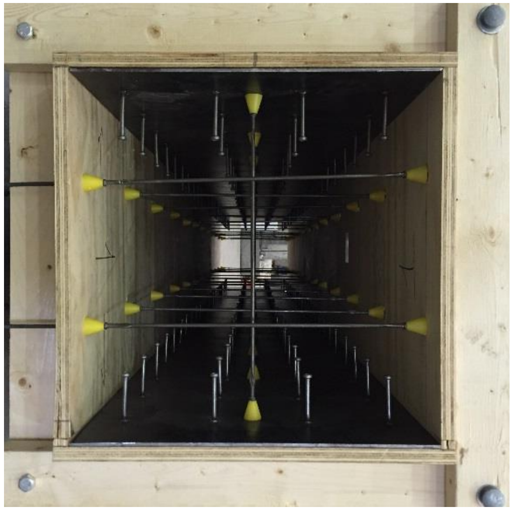

C. In-Plane
First Test
Second Test
2'
7'
2'

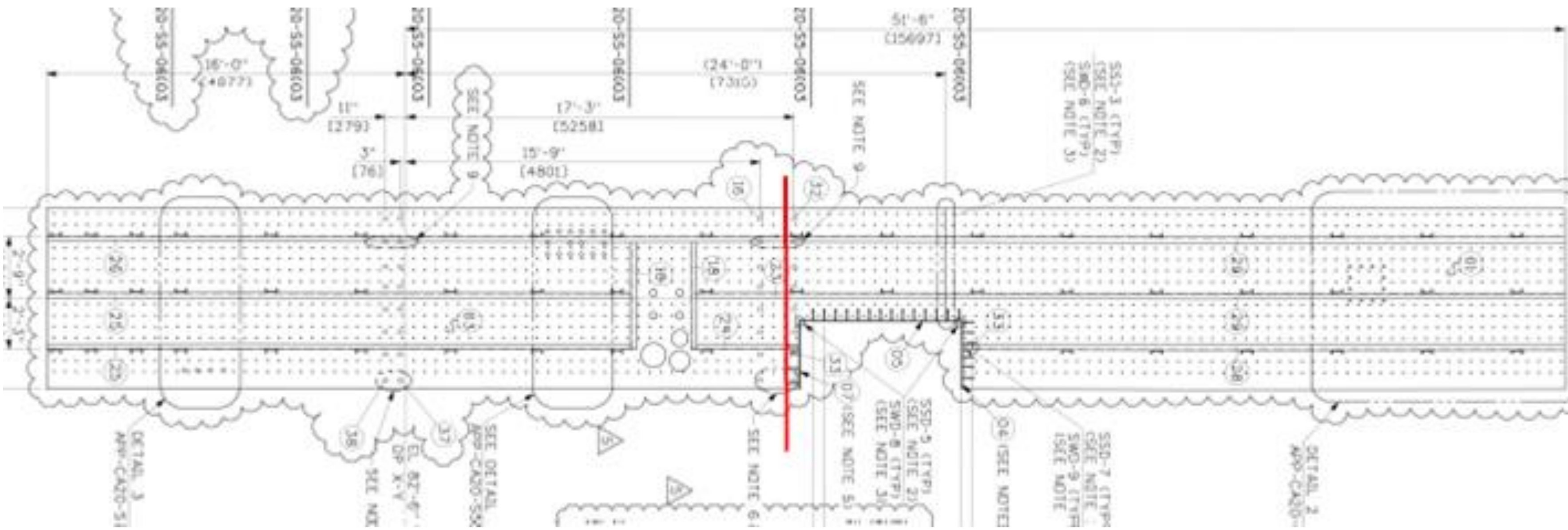








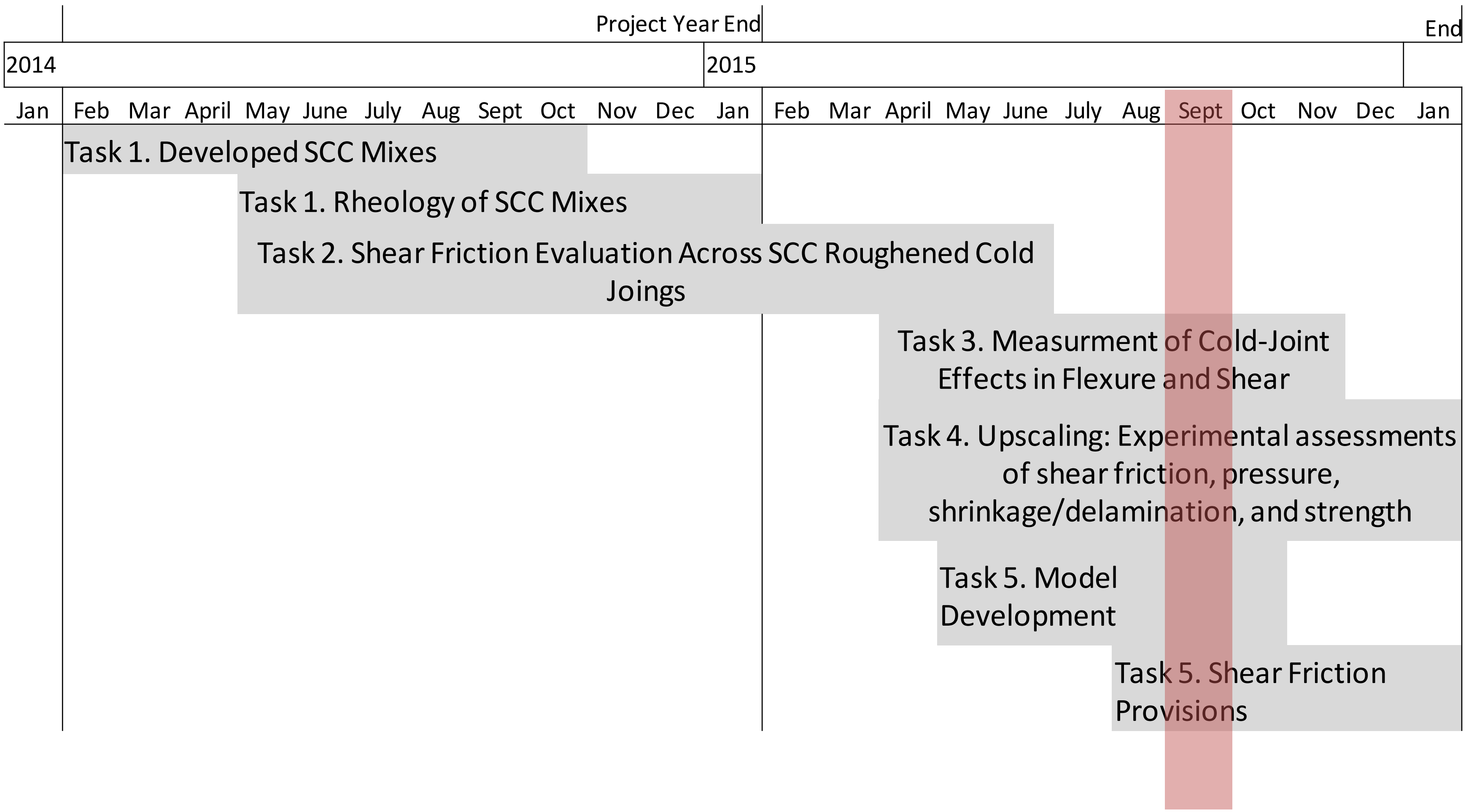

5. Validation through Full-scale Test and Modeling
Model



6. Conclusions and Outlooks
And future developments

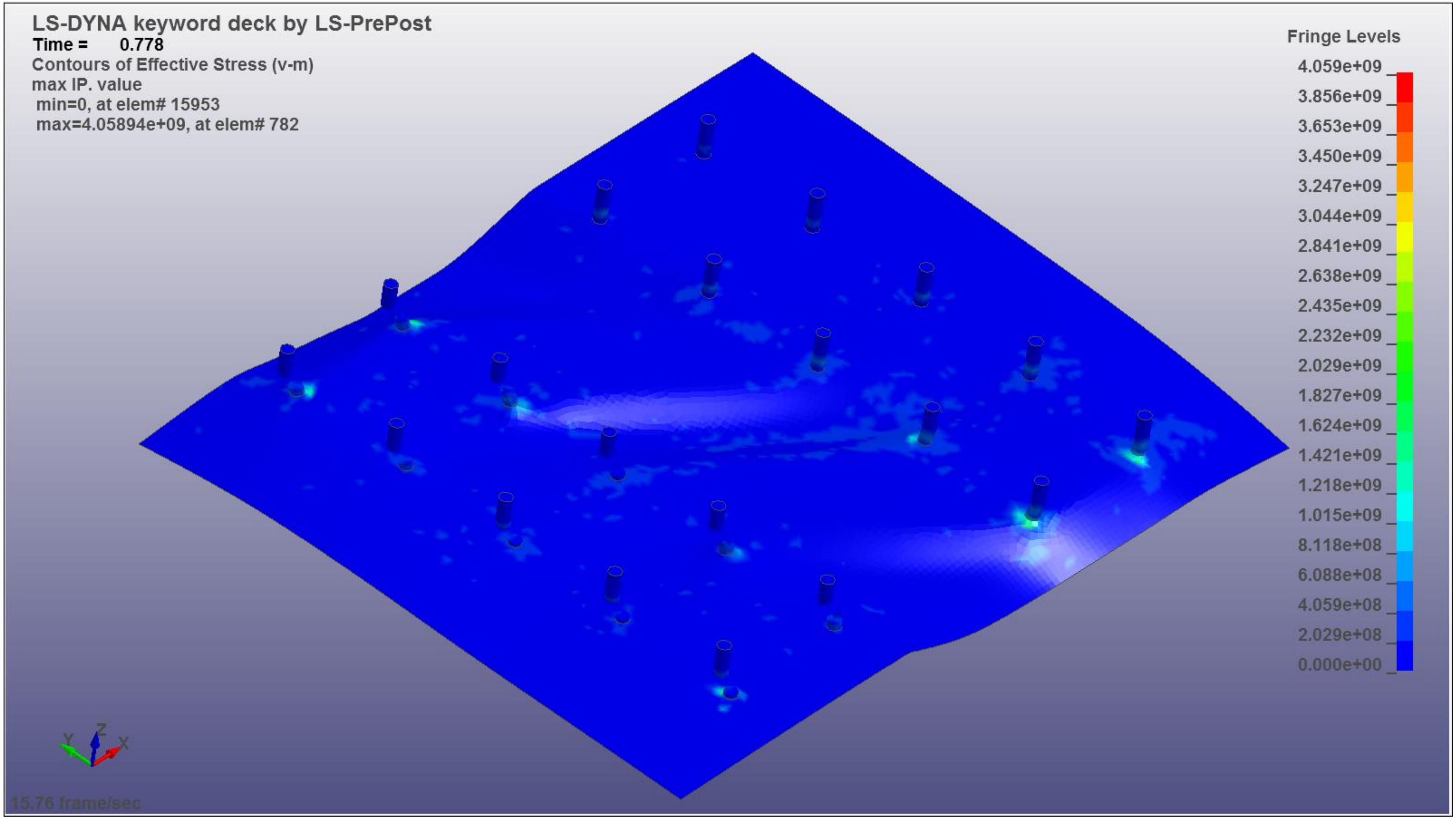
1. Task 2 test results demonstrate the ability of SC construction to transfer in-plane forces across the cold-joint boundaries.
2. Results show that SC construction is more ductile than conventional internally-reinforced concrete.
3. The test results do not conclusively demonstrate the relationship between LWA percentage and cold-joint shear capacity.
4. Non-linear FEA models are promising and may be used for parametric studies of joint behavior – but further calibration is needed.
5. Task 3 specimens will validate in-plane shear behavior and provide better guidance on the out-of-plane behavior of cold-joint behavior in SCC.
6. The Task 4 specimen will be a tremendous challenge and we are working closely with Westinghouse to procure the test article from CBI in a cost-effective and timely manner.

Timeline


Project Year End
End
2014
2015
Jan Feb Mar April May June July Aug Sept Oct Nov Dec Jan Feb Mar April May June July Aug Sept Oct Nov Dec Jan
Task 1. Developed SCC Mixes
Task 1. Rheology of SCC Mixes
Task 2. Shear Friction Evaluation Across SCC Roughened Cold Joings
Task 3. Measurment of Cold-Joint Effects in Flexure and Shear
Task 4. Upscaling: Experimental assessments of shear friction, pressure, shrinkage/delamination, and strength
Task 5. Model Development
Task 5. Shear Friction Provisions

“This material is based upon work supported by the Department of Energy [DE-NE0000667 NEET]”

Thank you. Questions?

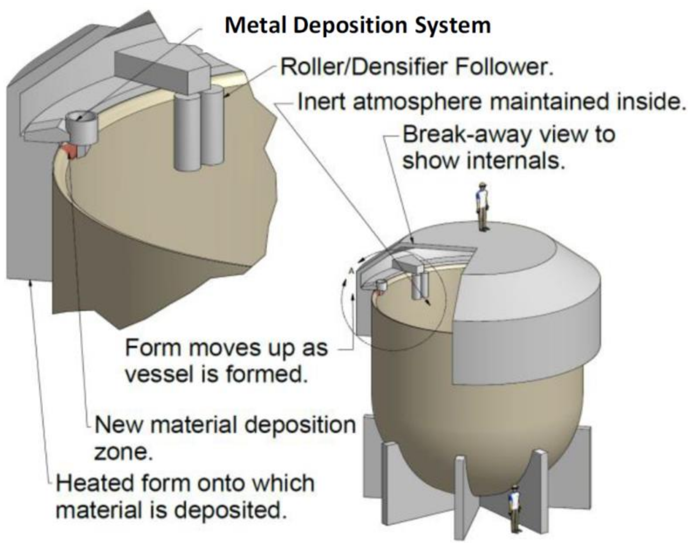

LS-DYNA keyword deck by LS-PrePost
Time = 0.778
Contours of Effective Stress (v-m)
max IP. value
min=0, at elem# 15953
max=4.05894e+09, at elem# 782
Fringe Levels
4.059e+09
3.856e+09
3.653e+09
3.450e+09
3.247e+09
3.044e+09
2.841e+09
2.638e+09
2.435e+09
2.232e+09
2.029e+09
1.827e+09
1.624e+09
1.421e+09
1.218e+09
1.015e+09
8.118e+08
6.088e+08
4.059e+08
2.029e+08
0.000e+00
Y
Z
X
15.76 frame/sec

Advanced Onsite Fabrication of Continuous Large-Scale Structures

Corrie I. Nichol, Ph.D.

AMM Workshop

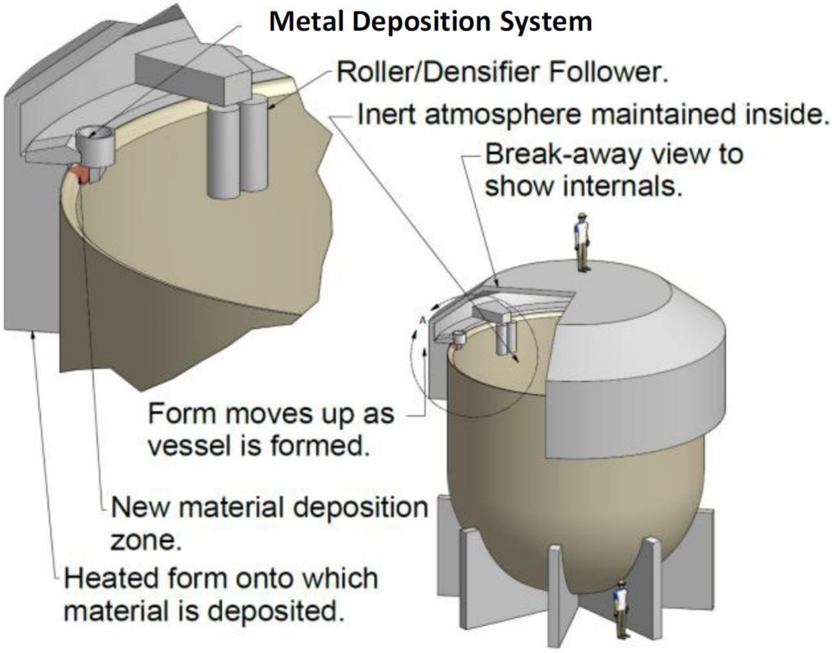
29 Sept., 2015



Idaho National Laboratory

Concept Overview

- Cross between 3-D printer and Concrete Slip-Forming
- Structure built on-site from small format raw materials
- Form moves up as vessel is formed
- Material is fully densified by roller follower

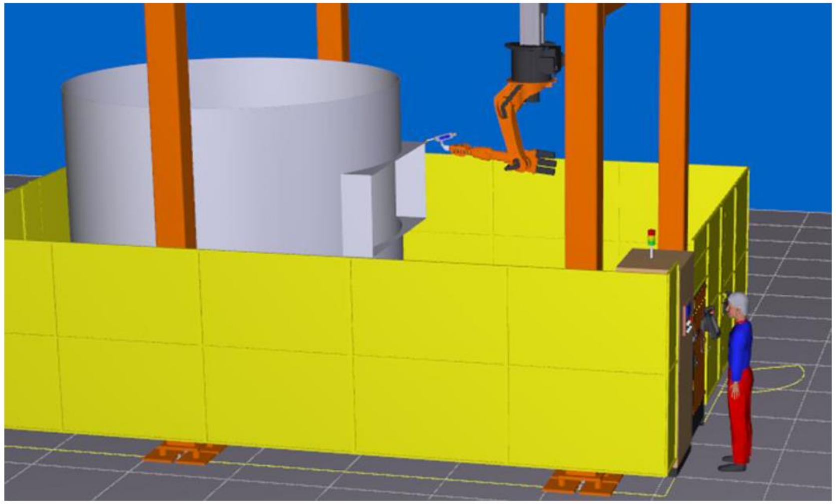


Potential Benefits

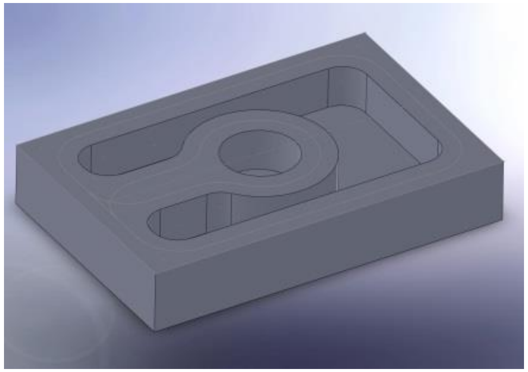
- Potential multi-material composite construction, multi stress-state end product.
  - Corrosion resistant cladding, high strength steel alloy interior.
  - Residual compressive stresses to reduce corrosion cracking.
- Material transported to site in small form factor. (No component size site limitations.)
  - Site access to large navigable water-ways for component transport not required.
- Welds largely eliminated.
  - Residual weld stresses/weld flaws eliminated.
  - Weld inspection burden reduced.
- Domestic large vessel fabrication.
  - Ultra-heavy forging companies are no-longer in the U.S.

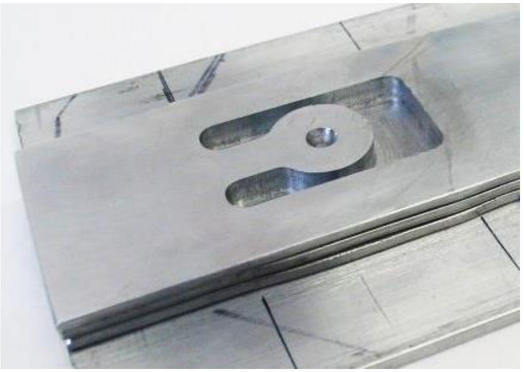
Participants and Relevant Capabilities

- Dr. Corrie Nichol, INL - Robotics
- Timothy McJunkin, INL - NDE
- Dr. Alan McLelland, NAMRC (UK) Large Scale RP



- Supporting rapid prototyping processes:
  - Arc-based additive manufacturing process
  - Friction stir additive manufacturing



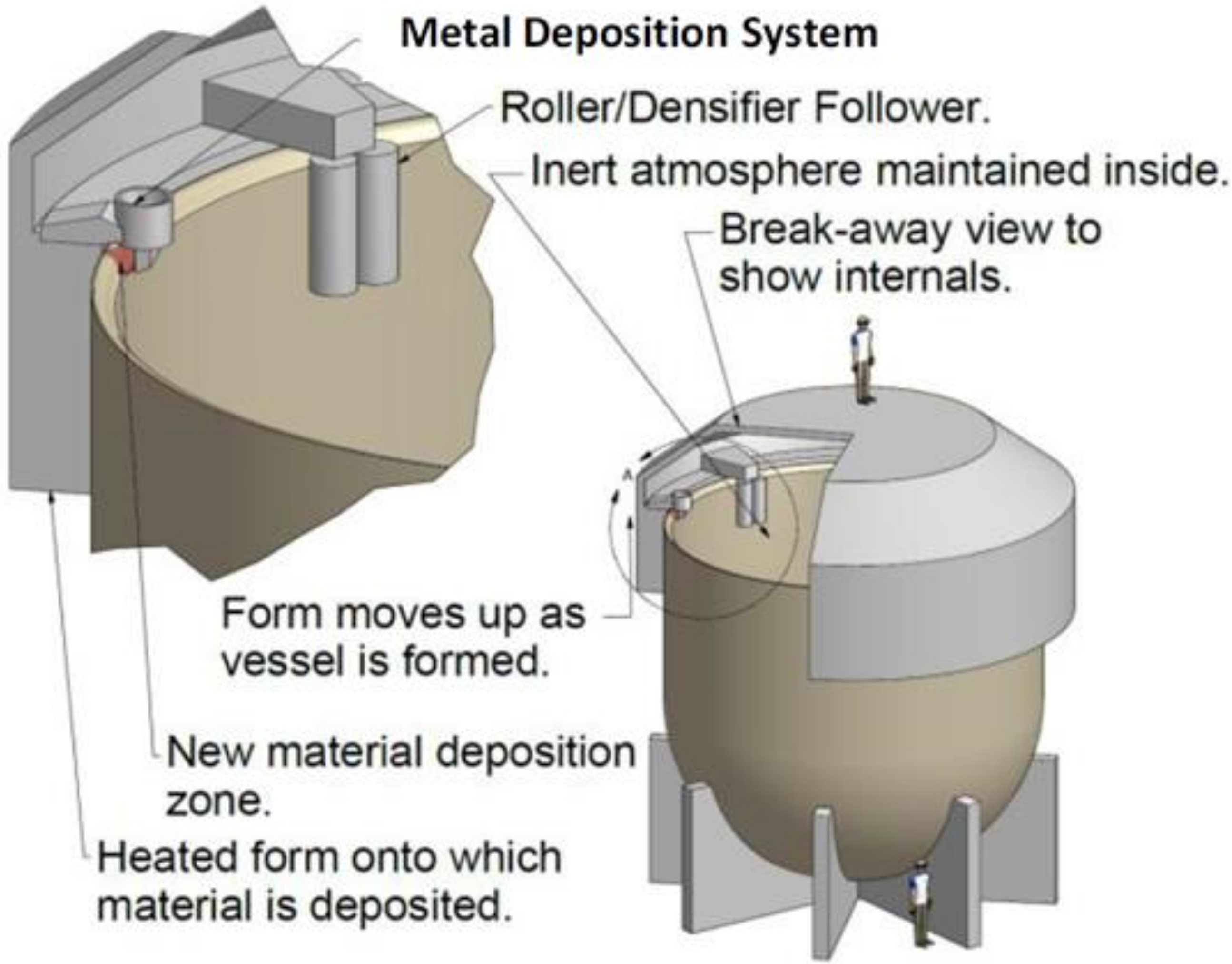


Project Proof-of-Concept Tasks

- Additive manufacturing processes and specific energy for material deposition.
- Development of robotic spray deposition device.
  - Deposition process control
  - Deposition on heated form
  - Post-deposition deformation and residual stress
- NDE for inspection of deposited materials during/after deposition
  - Elevated temperature environment
- Process modeling for energy consumption, force required for densification step, etc.

Relevance and Outcomes/Impacts

- Fabrication of large-scale structures in new locations.
  - SMR
  - Chemical Processing
- Domestic fabrication of large-scale structures.
- Novel fabrication techniques and material composites for improved vessel performance.
- Advance the state-of-the-art of large-scale advanced manufacturing.


Metal Deposition System
Roller/Densifier Follower.
Inert atmosphere maintained inside.
Break-away view to
show internals.
Form moves up as
vessel is formed.
New material deposition
zone.
Heated form onto which
material is deposited.

2015 DOE-NEET:

Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing (AM)

Xiaoyuan Lou (loux@ge.com)

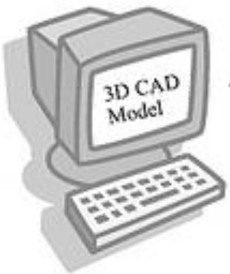
Ceramics and Metallurgy Technologies
GE Global Research, Niskayuna, NY

2015 DOE AMM Workshop, Arlington, VA
Sep. 29, 2015

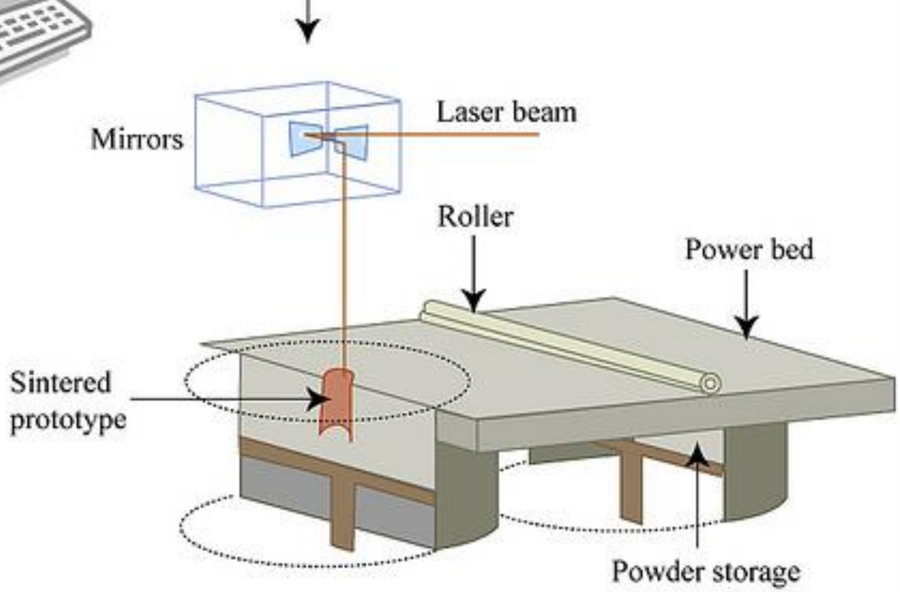
This material was prepared with the internal support from General Electric Company.

Additive Manufacturing for Nuclear Overview

Additive Manufacturing (3D Printing)

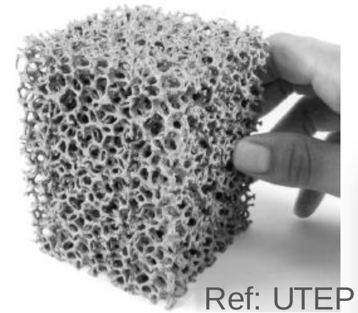


Direct Material Laser Melting (DMLM)

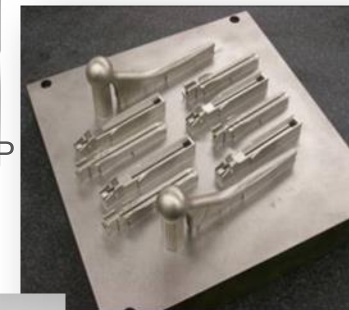


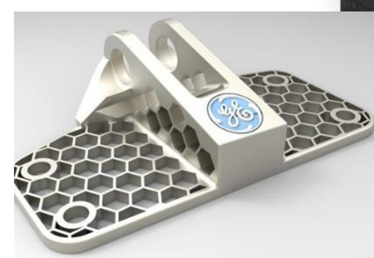
from metalbot.org

Ref. Within Labs, UK



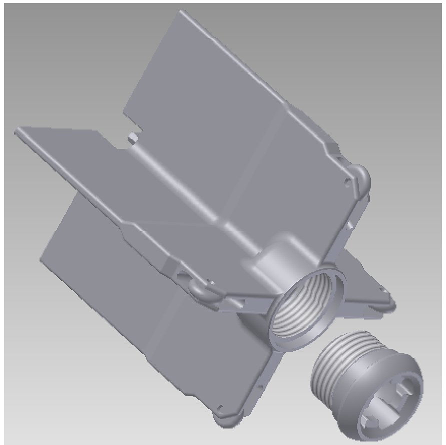
Ref: UTEP





Post Processing (HIP, Heat Treat, Surface Finishing, Machining, etc.)

Value of Additive/3D Manufacturing for Nuclear

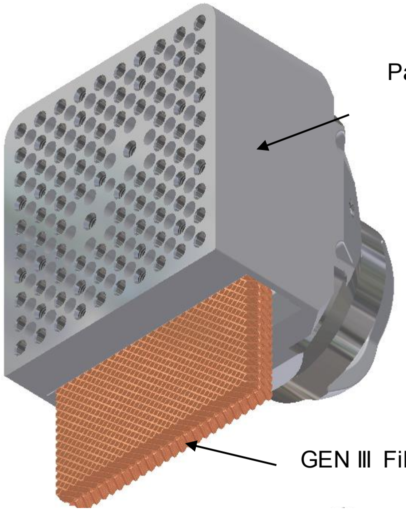


Speed of Delivery: Fast turnaround time

- Quick response to emergent needs and custom designs during outage interval
- Rapid prototyping
- Short design-to-commercialization period

Design for Performance: Fewer manufacturing limitations allow new designs for next generation reactor

- Design-driven manufacturing as opposed to manufacturing-constrained design
- Complex/expensive parts including hardfacing



Equivalent or Better Wrought Properties: Eliminating welding in a complex structure

Enhanced chemistry control: Powder atomization → Low Cobalt

Current Technical Gaps

High cost and high/unknown risk:

At this time, additively manufactured components generally have much higher manufacturing cost and higher or unknown risk in the reactor environment

No nuclear specified research on AM materials/processes:

Existing AM processes for most common materials, including stainless steel and Inconel alloys, have not been developed for nuclear needs.

- ❑ Stress corrosion cracking (SCC)
- ❑ Corrosion fatigue (CF)
- ❑ Irradiation resistance

Lack of specification/qualification

Need to address processing and material variability prior to codifying the material for nuclear use.

Goals of this Program – Addressing the Gaps

Lowering the overall component life cost:

Understanding and utilizing the non-equilibrium microstructure by laser process to improve the nuclear specified material properties

- ❑ Eliminating post treatment cost from HIP
- ❑ Replacing high performance alloys and welding/cladding operations
- ❑ Improving service life and reduce asset management costs.

Evaluating nuclear specified properties:

In addition to common mechanical properties, the program will evaluate the following properties for AM 316L stainless steel under various post heat treatments:

- ❑ Stress corrosion cracking (SCC)
- ❑ Corrosion fatigue (CF)
- ❑ Irradiation resistance

Developing nuclear specification for AM materials

- ❑ Understanding process variability in terms of nuclear properties
- ❑ Contributing to the development of nuclear specification for AM

Technical Concepts

Non-equilibrium Microstructure by Laser Process

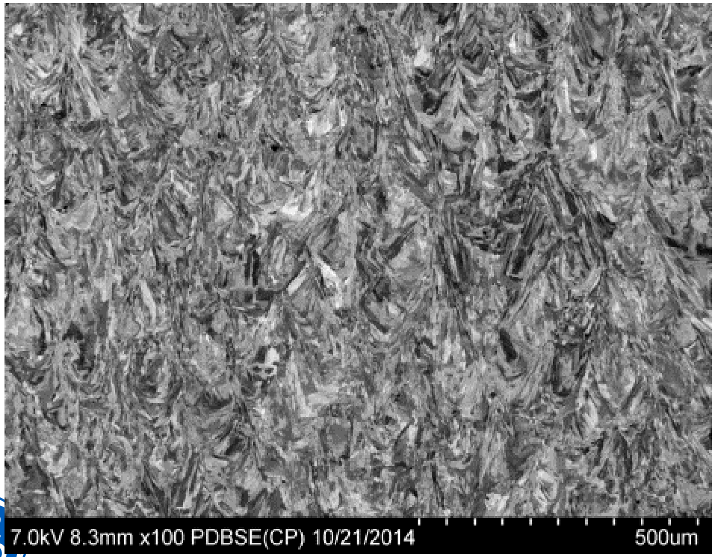
Direct metal laser melting process:

1. high local temperature
2. extremely fast cooling rate

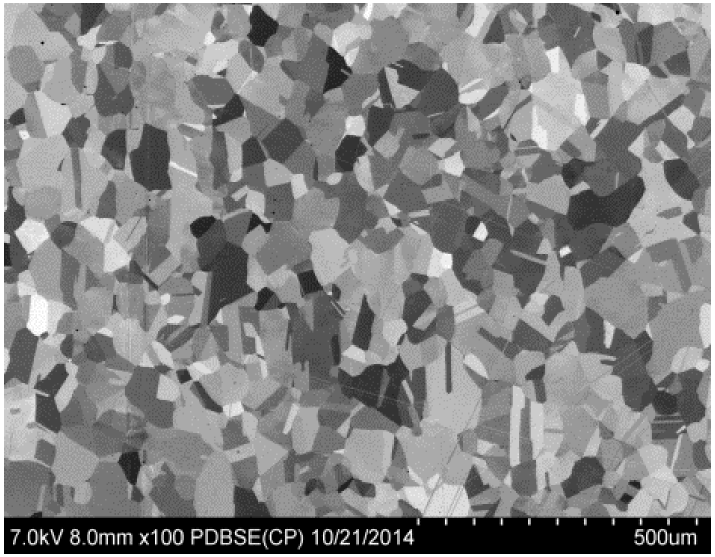
- ❑ ultrafine nanostructure
- ❑ minimum elemental segregation
- ❑ supersaturated solution
- ❑ non-equilibrium phases
- ❑ less diffusion controlled phase transformation

Non-equilibrium structure can produce desirable effects on material's properties

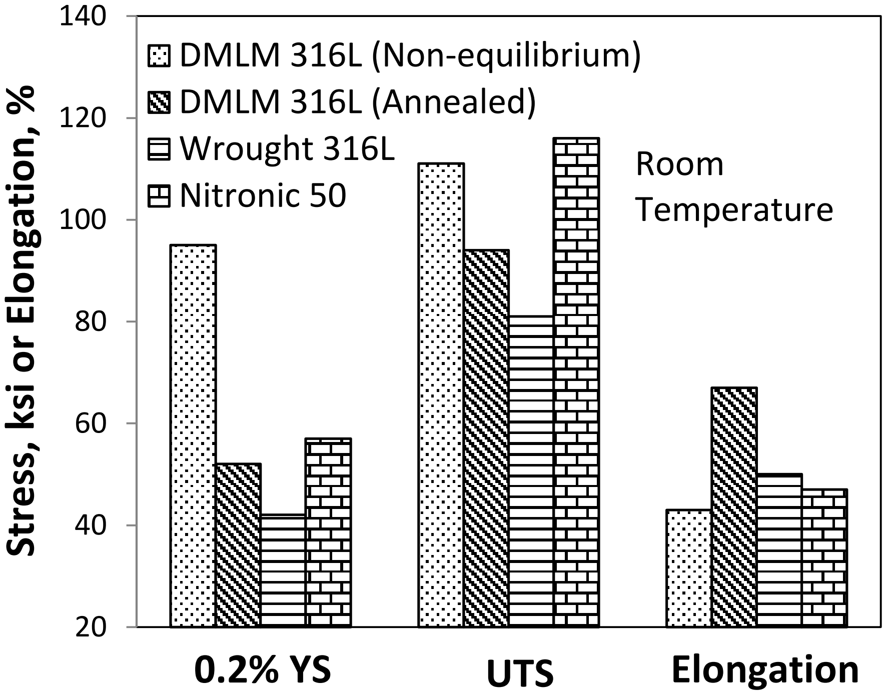
Non-equilibrium structure

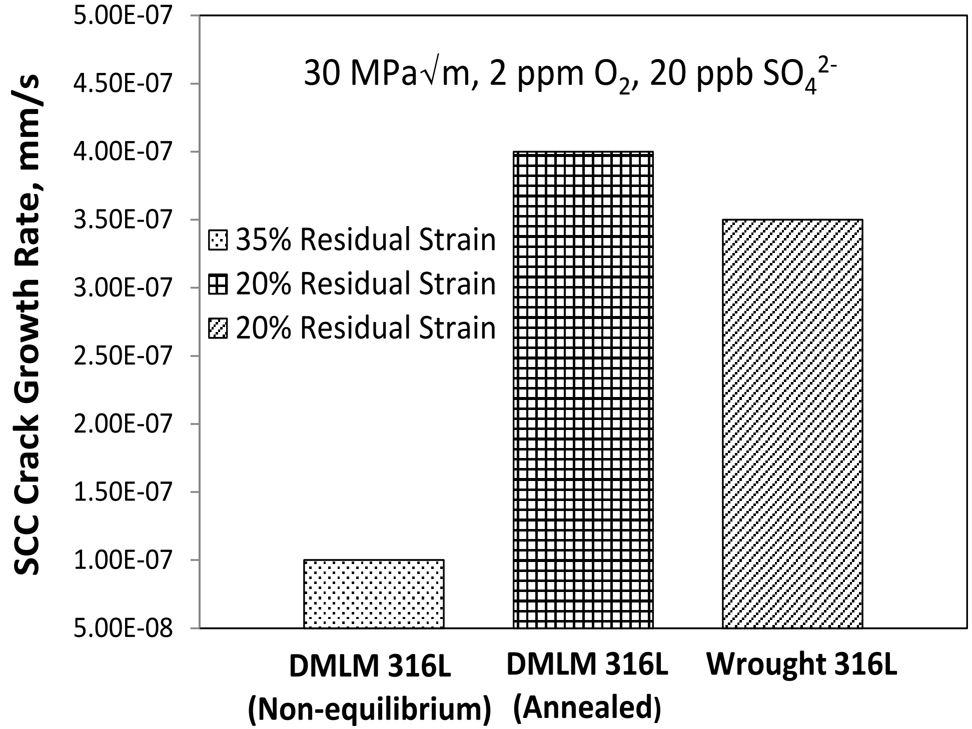


Annealed structure



Mechanical and SCC Properties

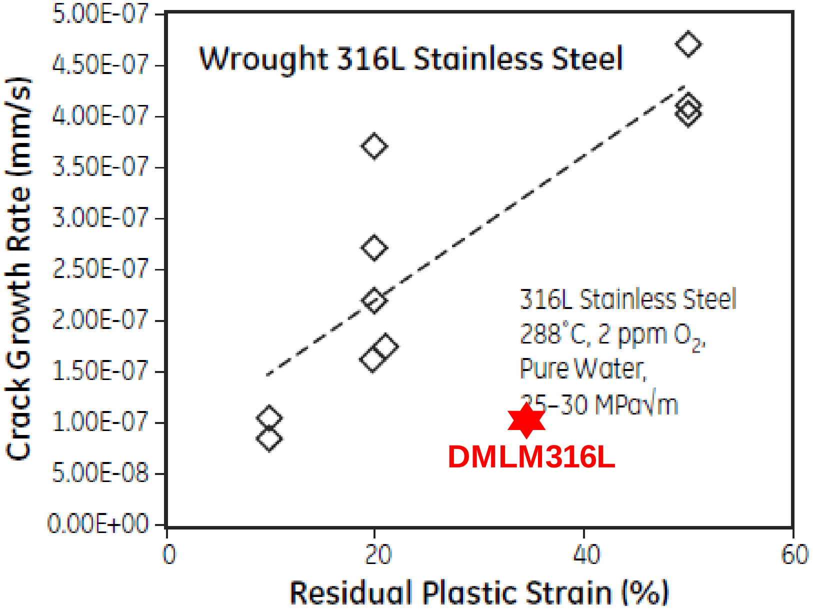




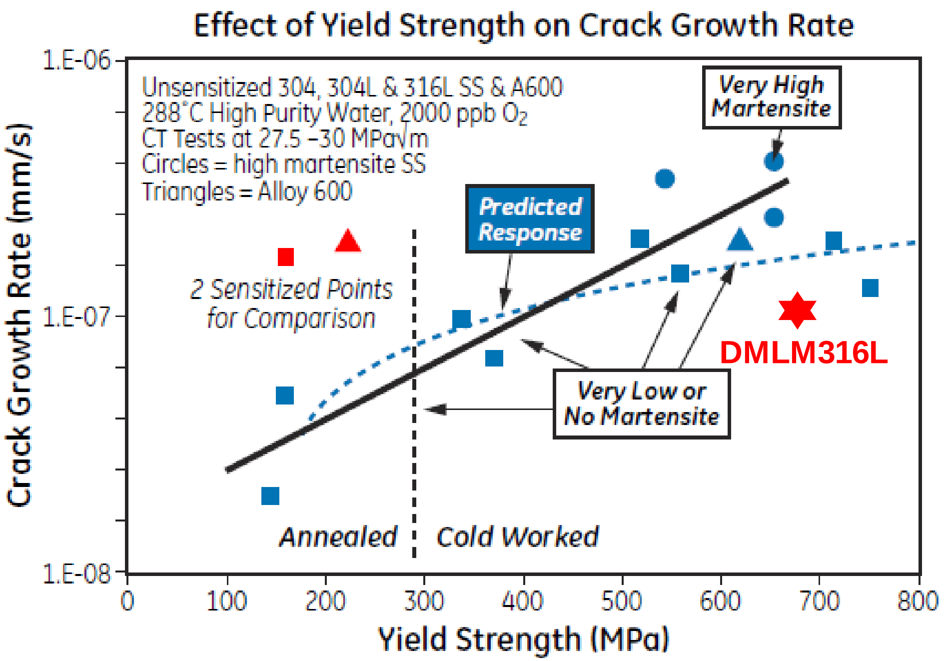
- Non-equilibrium DMLM 316L stainless steel shows higher strength, reasonable ductility and lower stress corrosion crack susceptibility in high temperature water
- Mechanical properties are very close to Nitronic 50 alloy

Stress Corrosion Cracking of Austenitic Stainless Steel

Residual Strain vs. SCC



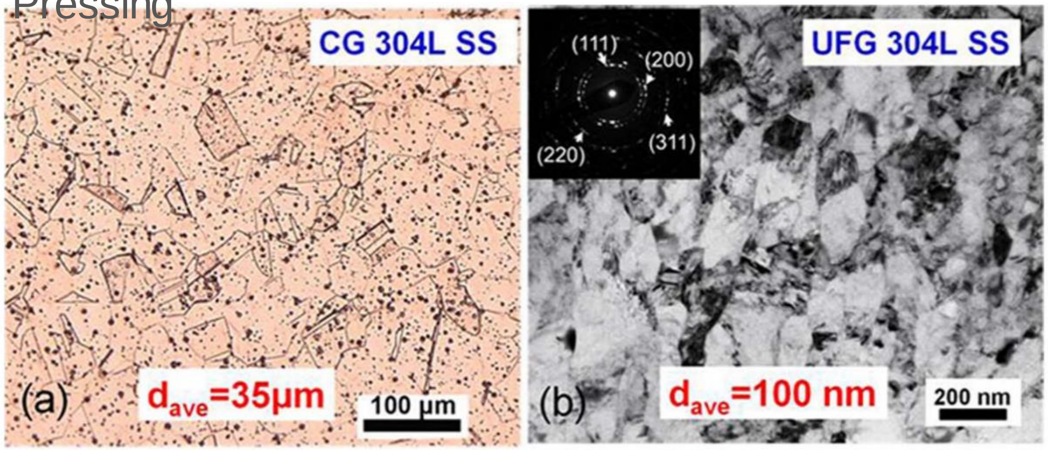
Yield Strength vs. SCC

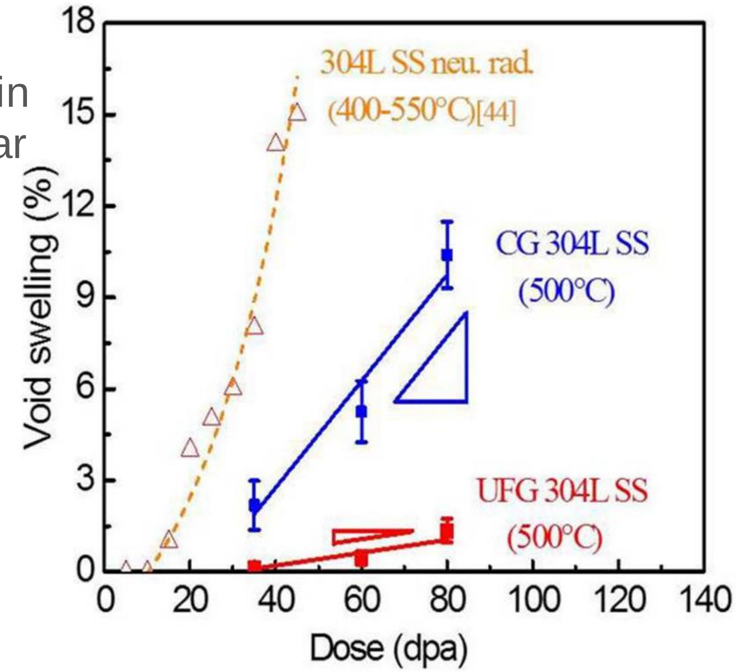


- ❑ For conventional austenitic stainless steel, SCC susceptibility generally increases with strength/cold work.
- ❑ The SCC behavior of non-equilibrium DMLM 316L vs. annealed DMLM 316L stainless steel is contradictory to the conventional theory, which is due to its unique microstructure.

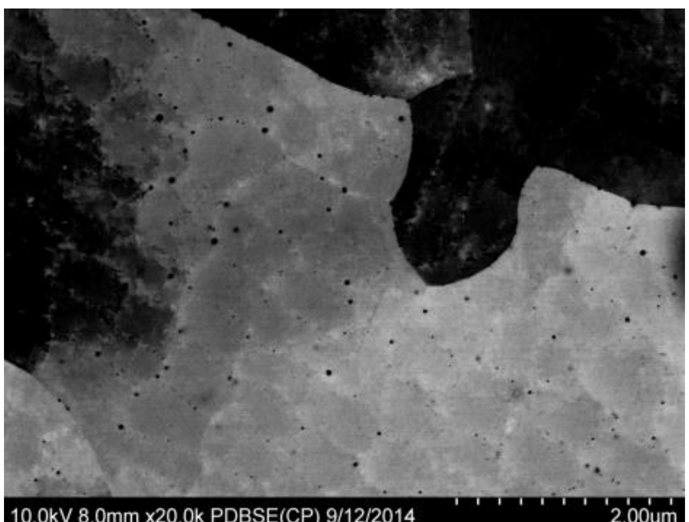
Irradiation Resistance of Nanostructured Austenitic Stainless Steel

Irradiation comparison: Coarse grain vs. ultrafine grain austenitic stainless steel by Equal Channel Angular Pressing





C.Sun, et al., Scientific Reports 5, Article number: 7801 (2015)



Understanding and controlling the nanostructure and ultrafine precipitates in DMLM stainless steel can lead to super irradiation resistant stainless steel

Program Outline

Teams, Approaches, Deliverables

Understanding and controlling the DMLM non-equilibrium microstructure to improve material's nuclear performance:

high strength, high SCC resistance, high irradiation tolerance

Program Team

GE Global Research

- 40 years of experience in environmental degradation of nuclear materials
- Industrial leader of advanced manufacturing and material technology

Oak Ridge National Lab

- Laser melting process development

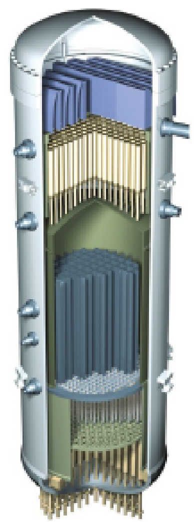
University of Michigan

- Leading lab for irradiated material research
- Environmental cracking of irradiated materials

GE-Hitachi Nuclear

- New component by DMLM
- Regulatory and commercialization plan for additive manufacturing

2-Year, $850K Program to Develop Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing



Program Objectives:

- *Understand and control the non-equilibrium nanostructure during laser additive manufacturing process to develop a SCC and irradiation resistant super 316L stainless steel*
- *With the improved performance, the technology can save life cycle cost and deployment schedule with improved plant reliability*
- *Evaluate SCC and irradiation resistance of 316L stainless steel by additive manufacturing*
- *Develop a plan for regulatory approval and commercialization*

Technical Approaches

- Understand the correlation between laser process, non-equilibrium nanostructure, and SCC/irradiation resistance
- Perform stress corrosion cracking, corrosion fatigue and irradiation tests
- Component fabrication to demonstrate the time and overall cost saving

Technical Challenges

- It may take some time to reproduce GE's material at Oak Ridge National Lab.
- Surface roughness may add another fact to IASCC crack initiation

Program Deliverables

- A novel concept and technology for additive manufacturing in nuclear application
- Technical database about SCC and irradiation resistance of additively manufactured material
- A plan for regulatory approval and commercialization

Anticipated Benefits of the Proposed Technology

An improved additive manufacturing process for stainless steel nuclear components that

- Rapidly fabricates custom designed parts
- Saves overall life cycle cost and plant management cost
- Improves the reliability of nuclear power plant

GE Global Research's world class nuclear research facility for materials degradation

- 50+ fully instrumented high temperature water SCC testing systems for crack initiation and growth study
- 14 high temperature electrochemistry systems
- All stages of alloy processing capabilities, from melting to hot/cold working to heat treatment
- State-of-the-art materials characterization facility

Program Scope

Program Activities		GRC	ORNL	UM	GEH	Year 1				Year 2			
						Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	**Laser Process Development for Improved Material Properties**					■	■	■	■	■	■	■	■
1.1	Correlation between laser process, microstructure and properties	●	●			▬	▬	▬	▬				
1.2	Optimize 316L stainless steel with improved nuclear performance	●	●							▬	▬	▬	▬
1.3	Nuclear component fabrication and evaluation	●	●		●					▬	▬	▬	▬
Task 2	**Microstructure and Mechanical Characterization**					■	■	■	■	■	■	■	■
2.1	Microstructure characterization	●	●			▬	▬	▬	▬	▬	▬	▬	▬
2.2	Tensile property	●	●			▬	▬	▬	▬				
2.3	Fracture resistance	●				▬	▬	▬	▬				
Task 3	**Environmental Degradation Evaluation**					■	■	■	■	■	■	■	■
3.1	Stress corrosion crack growth	●				▬	▬	▬	▬	▬	▬	▬	▬
3.2	Corrosion fatigue crack growth	●				▬	▬	▬	▬	▬	▬	▬	▬
Task 4	**Irradiation Resistance Evaluation**					■	■	■	■	■	■	■	■
4.1	Irradiation effects - microhardness and IASCC susceptibility			●		▬	▬	▬	▬	▬	▬	▬	▬
4.2	Irradiation effects - microstructure characterization			●		▬	▬	▬	▬	▬	▬	▬	▬
Task 5	**Material Specification for Nuclear, Plan for Regulatory Approval and Commercialization**	●			●					■	■	■	■

Periodic Material-Based Seismic Base Isolators for Small Modular Reactors

NEET-1 Annual Meeting
September 29, 2015

Research Team

Y. L. Mo – University of Houston

Yu Tang – Argonne National Laboratory

Robert Kassawara – Electrical Power Research Institute

K. C. Chang – National Center for Research on Earthquake Engineering, Taiwan

Project Monitoring Team

Alison Hahn (Krager) (Project Manager)

Jack Lance (Technical POC)

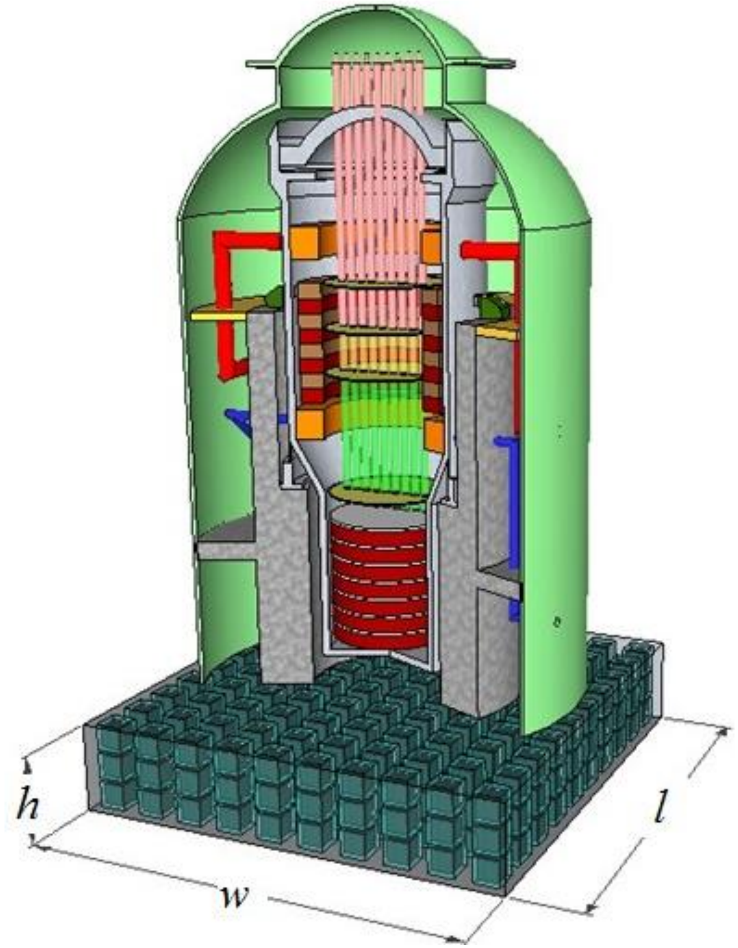
Project overview

Purpose:

To develop a periodic foundation that can completely obstruct or change the energy pattern of the earthquake before it reaches the structure of small modular reactors (SMR).

Scopes:

(1) Perform comprehensive, analytical study on periodic foundations.
(2) Design a SMR model with periodic foundations.
(3) Verify the effectiveness of periodic foundations through shake table tests.
(4) Perform finite element simulation of SMR supported by periodic foundations.



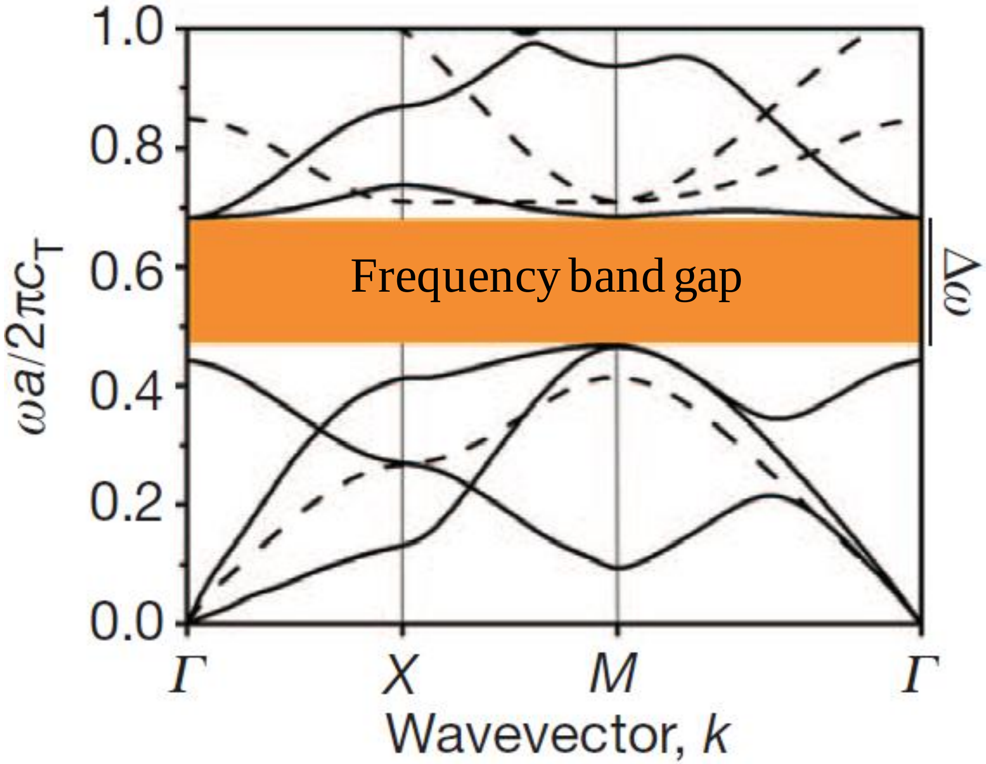
Project schedule

Task	2014	2015				2016				2017		
	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep
1	Review of previous work and literature											
2		Theoretical study on periodic foundations										
3			Design of 3D periodic foundation									
4					Experimental study of periodic foundations							
5							Experimental data analysis and numerical simulation of periodic foundations					
6											Preparation of final report	

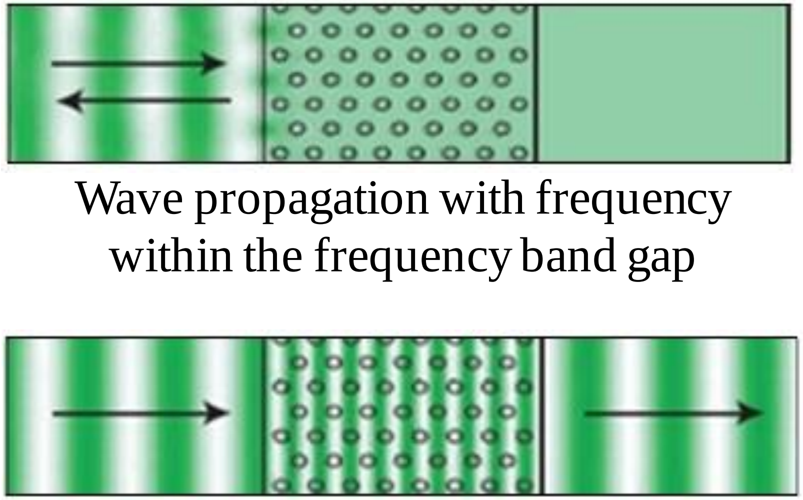
Wave propagation in phononic crystal

Phononic crystal is a novel composite developed in solid-state-physics.

Typical dispersion curve [1]



Wave Propagation [2]



Wave propagation with frequency within the frequency band gap

Wave propagation with frequency outside of the frequency band gap

[1] Maldovan, M. (2013). Sound and heat revolutions in phononics. *Nature*, *503*(7475), 209-217.

[2] Thomas, E. L., Gorishnyy, T., & Maldovan, M. (2006). Phononics: Colloidal crystals go hypersonic. *Nature materials*, *5*(10), 773-774.

Calculating dispersion curve

Governing equation of motion for a continuum body with isotropic elastic material

$$\rho(\mathbf{r})\frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla\left\{\left[\lambda(\mathbf{r}) + 2\mu(\mathbf{r})\right]\left(\nabla \cdot \mathbf{u}\right)\right\} - \nabla \times \left[\mu(\mathbf{r})\nabla \times \mathbf{u}\right] \qquad \text{Eq.1}$$

Where: $\mathbf{r}$ is coordinate vector
$\mathbf{u}(\mathbf{r})$ is displacement vector
$\rho(\mathbf{r})$ is the density
$\lambda(\mathbf{r})$ and $\mu(\mathbf{r})$ are the Lamé constant

Periodic boundary condition equation:

$$\mathbf{u}(\mathbf{r} + \mathbf{a}, t) = e^{i\mathbf{K}\cdot\mathbf{a}}\mathbf{u}(\mathbf{r}, t) \qquad \text{Eq.2}$$

Where: $\mathbf{K}$ is the wave vector
$\mathbf{a}$ is unit cell size

Calculating dispersion curve

Applying the periodic boundary condition (Eq.2) to the governing equation, (Eq.1), the wave equation can be transferred into eigen value problem as follow:

$$\left(\mathbf{\Omega}(\mathbf{K}) - \omega^2 \mathbf{M}\right).\mathbf{u} = 0 \qquad \text{Eq.3}$$

Where: $\mathbf{\Omega}$ is the stiffness matrix
$\mathbf{M}$ is the mass matrix

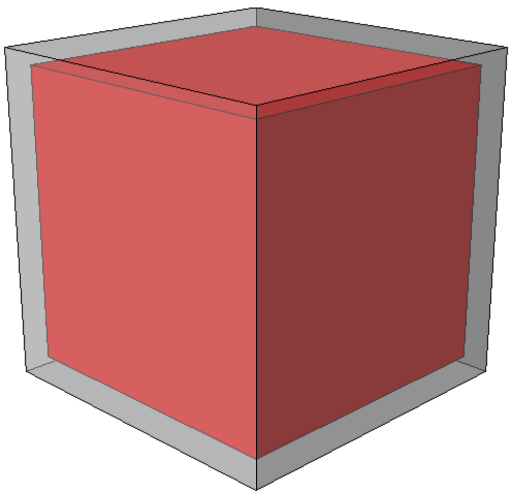
For each wave vector (**K**) a series of corresponding frequencies (ω) can be obtained.

Calculating dispersion curve

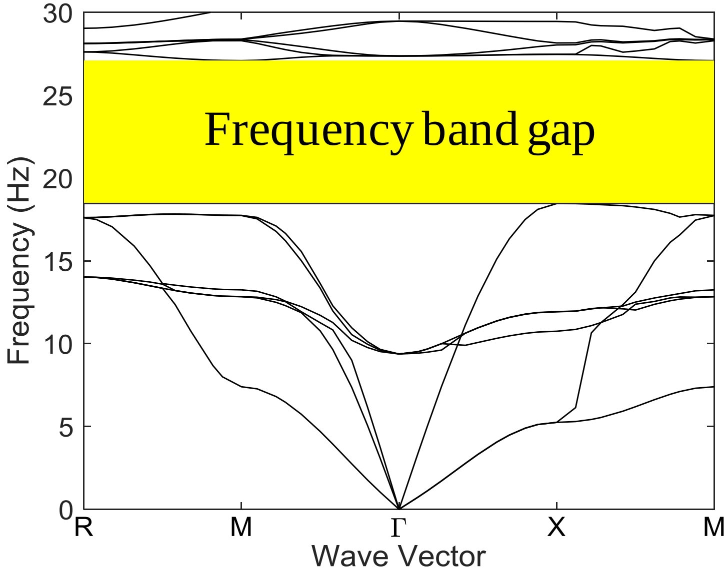
Eigen value problem:

$$\left(\mathbf{\Omega}(\mathbf{K}) - \omega^2 \mathbf{M}\right).\mathbf{u} = 0$$

Infinite number of unit cells condition



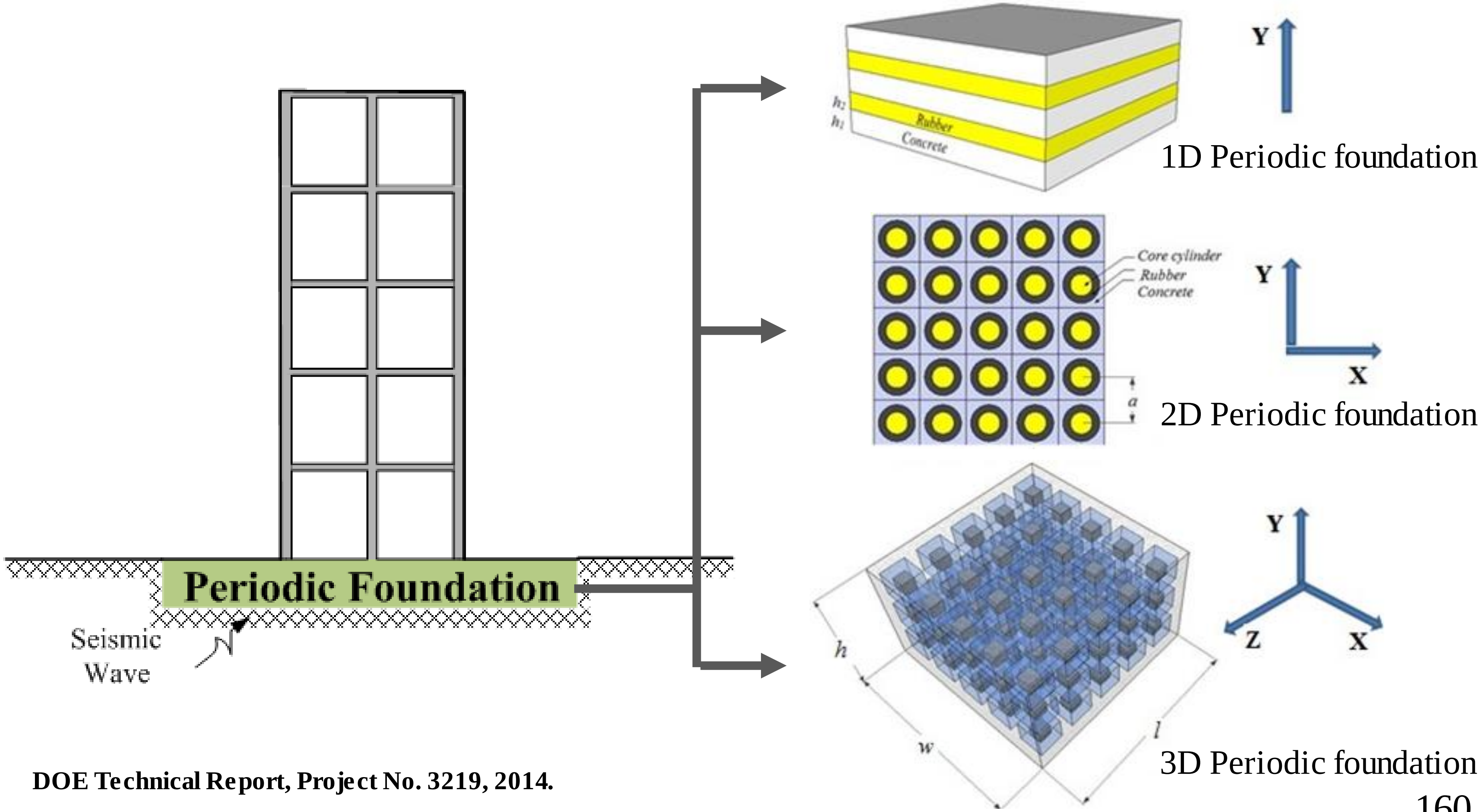
Typical two-component 3D periodic foundation



Typical dispersion curve

Application of phononic crystal

In civil engineering field



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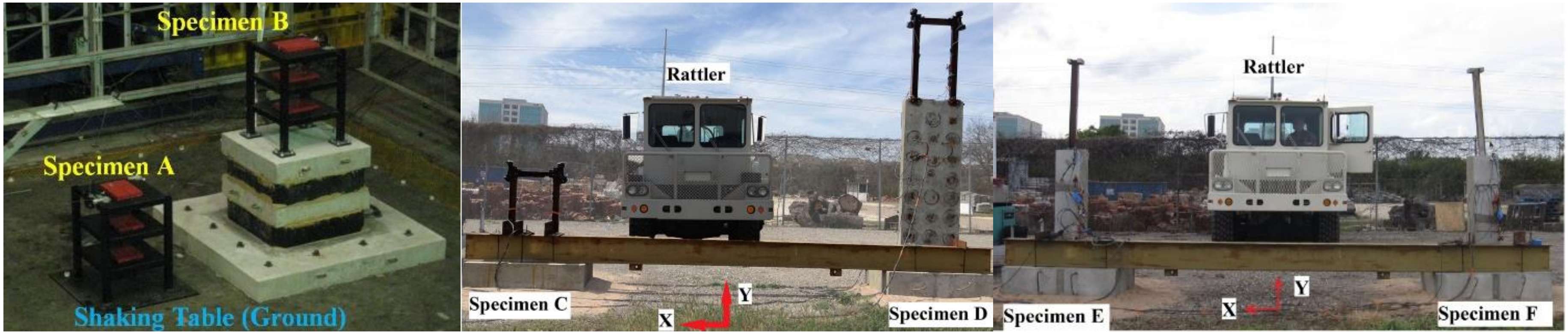
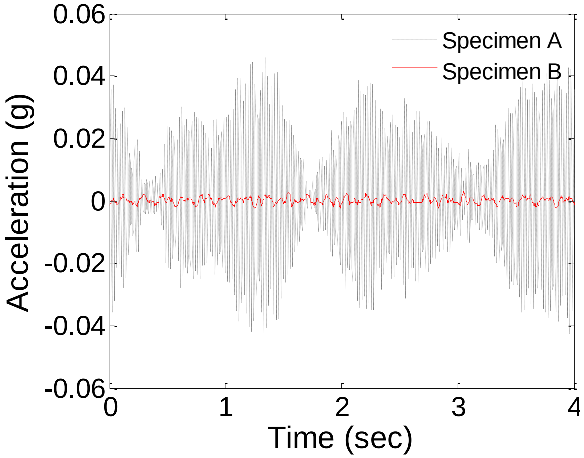
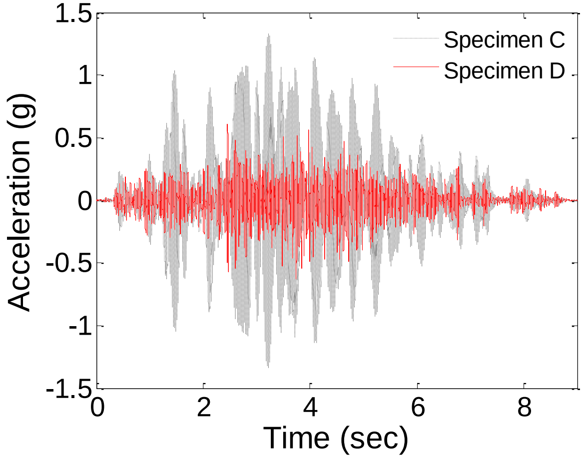
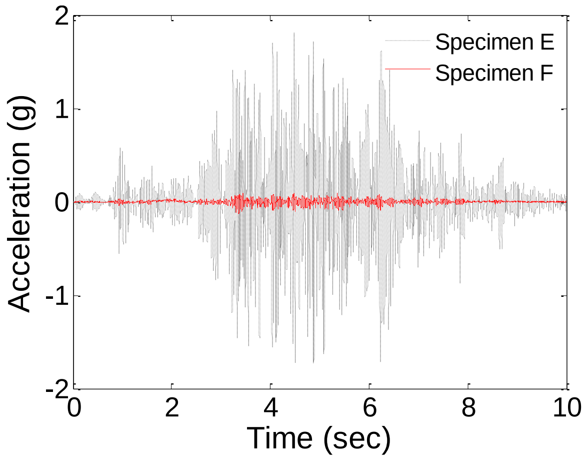
Experimental study on periodic foundation

1D Periodic foundation | **2D Periodic foundation** | **3D Periodic foundation**





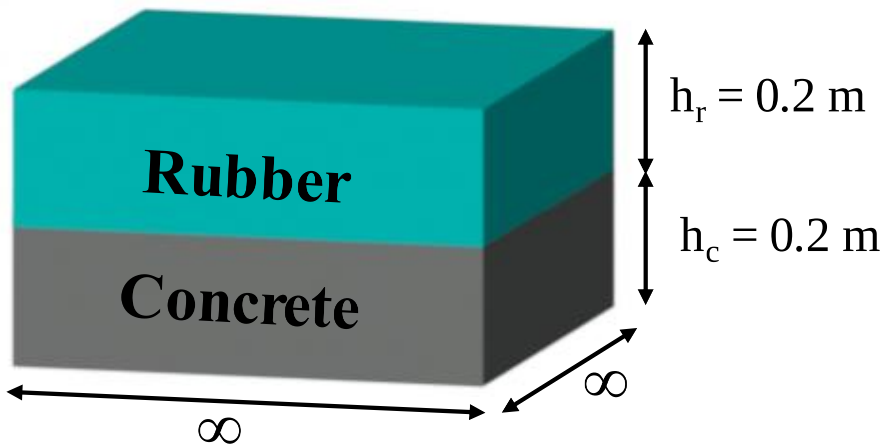




DOE Technical Report, Project No. 3219, 2014.

1D Periodic Foundations

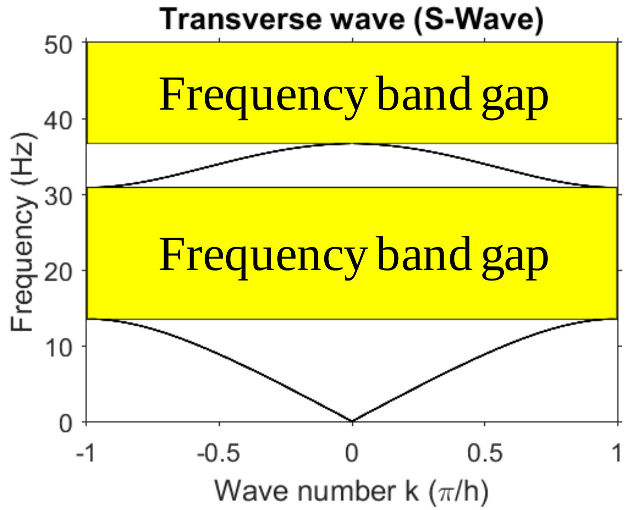
One unit cell of 1D periodic foundation

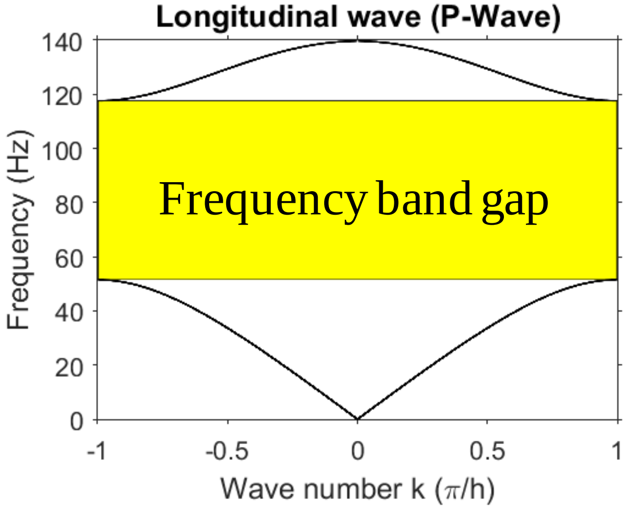


Fix material properties

Material	Young's Modulus (Pa)	Density (kg/m³)	Poisson's Ratio
Concrete	3.14×10^{10}	2300	0.2
Rubber	5.8×10^{5}	1300	0.463

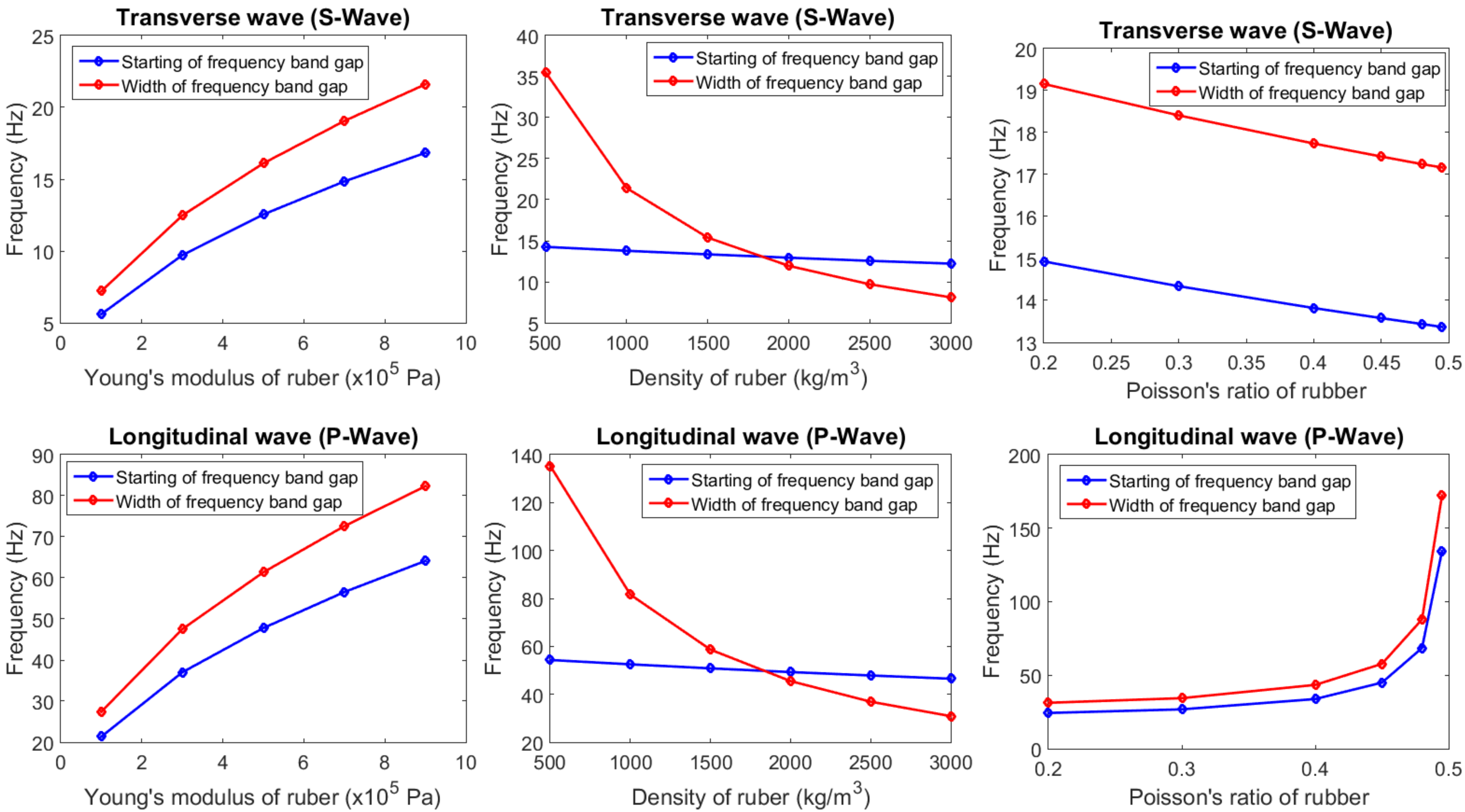
Dispersion curve for infinite number of unit cells





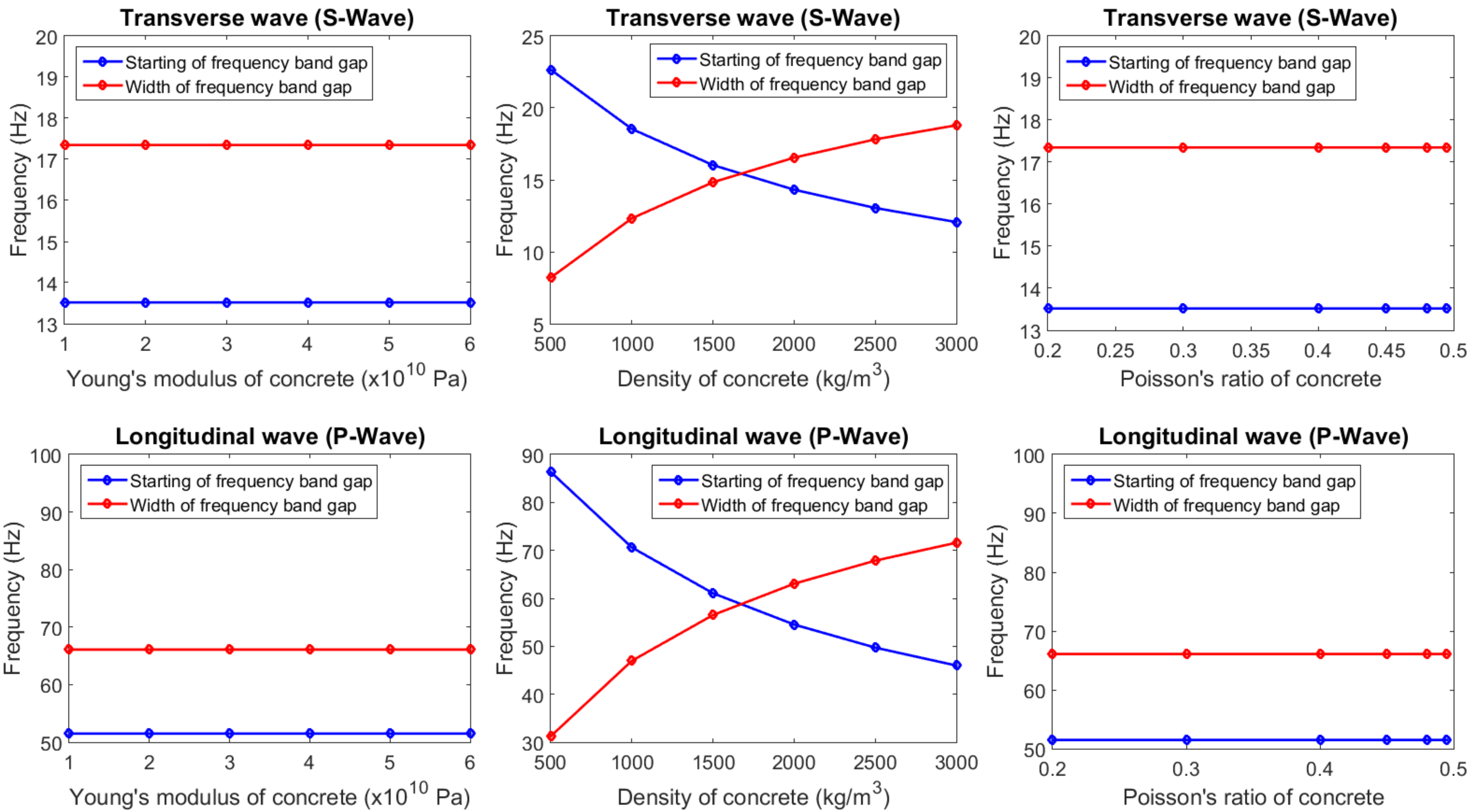
Parametric study of 1D periodic foundations

Effect of rubber material properties on the first frequency band gap



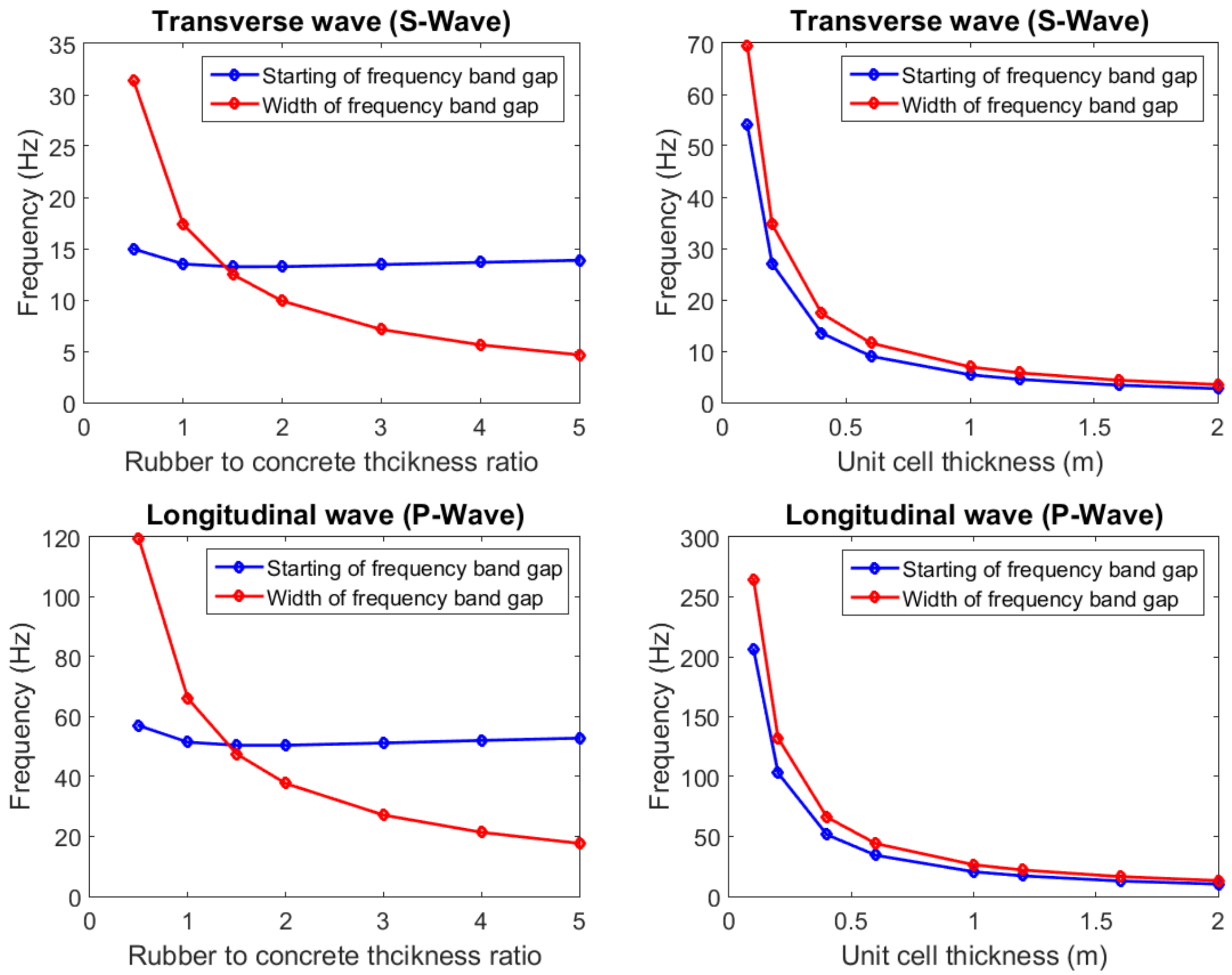
Parametric study of 1D periodic foundations

Effect of concrete material properties on the first frequency band gap



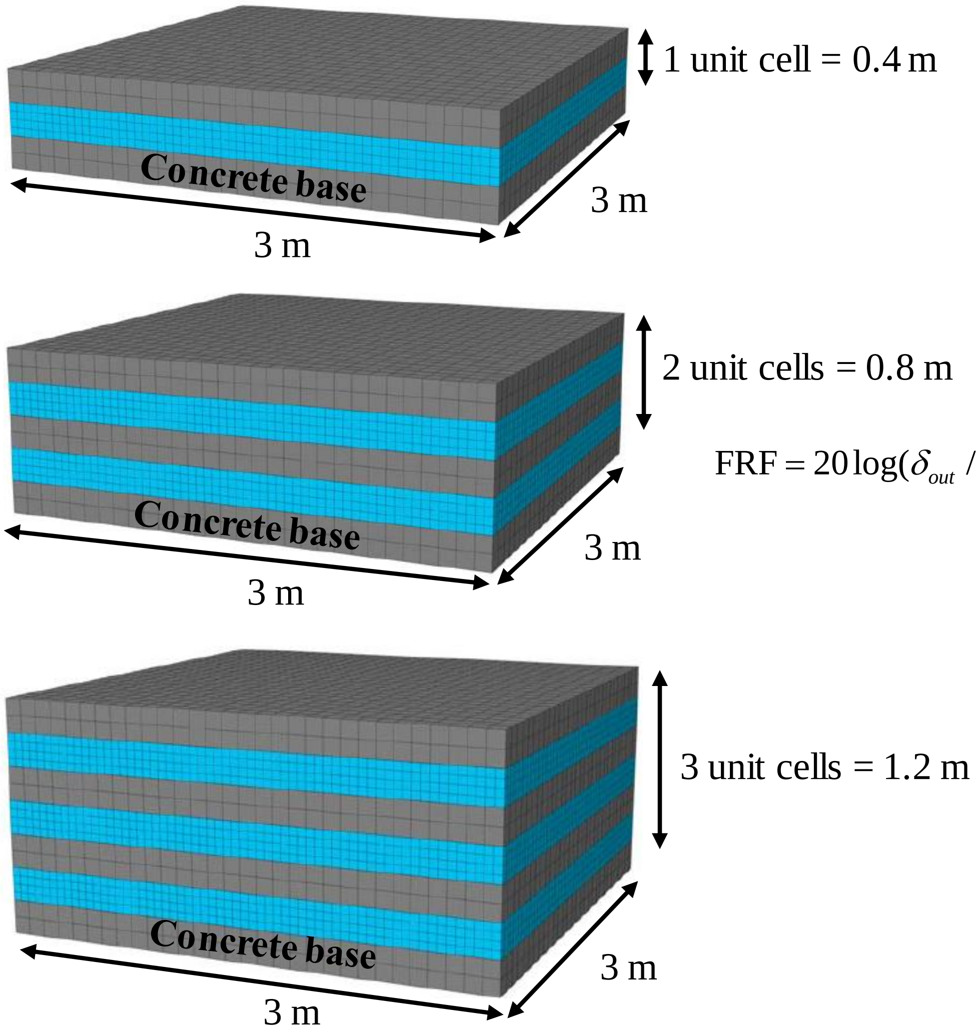
Parametric study of 1D periodic foundations

Effect of geometric properties on the first frequency band gap

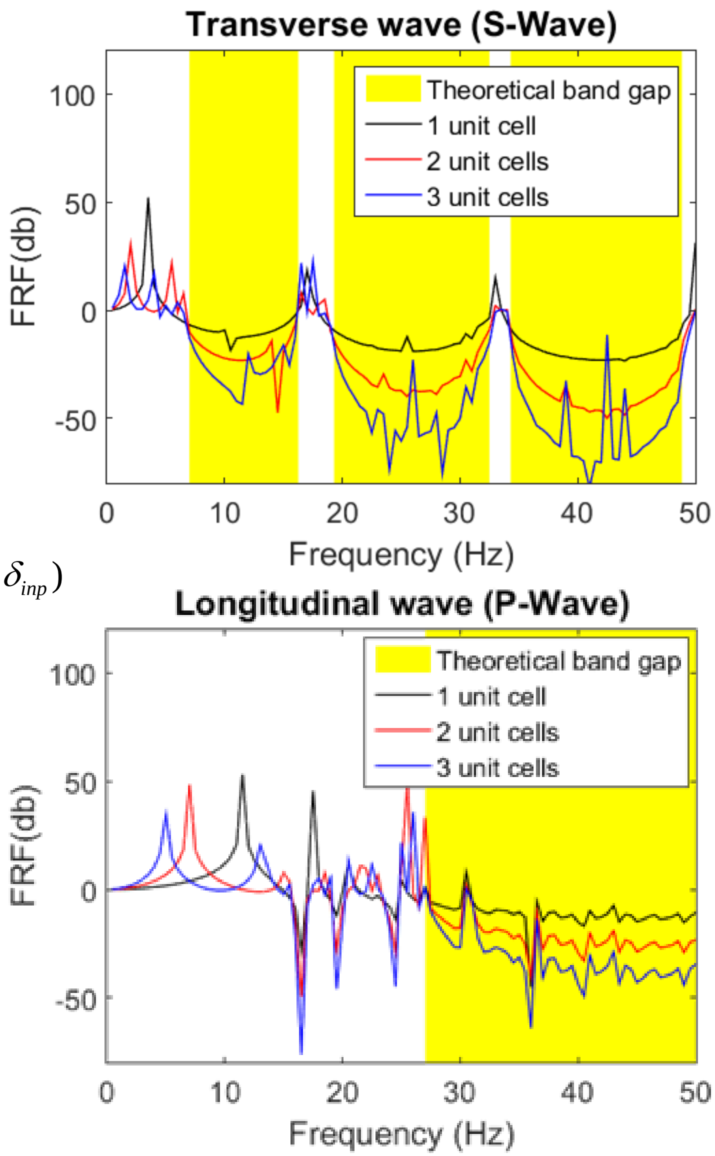


Parametric study of 1D periodic foundations

Effect of number of unit cells



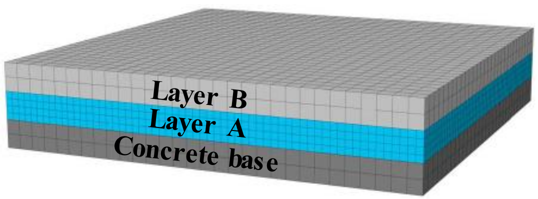
$$FRF = 20\log(\delta_{out} / \delta_{inp})$$



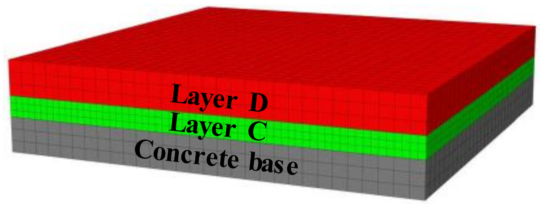
Parametric study of 1D periodic foundations

Effect of combined unit cells

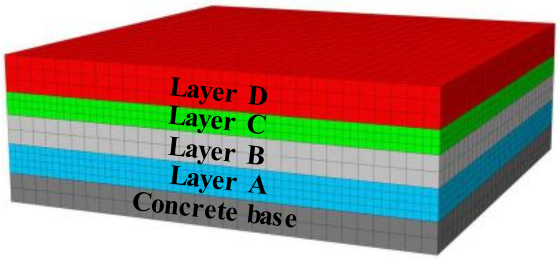
Unit cell-1

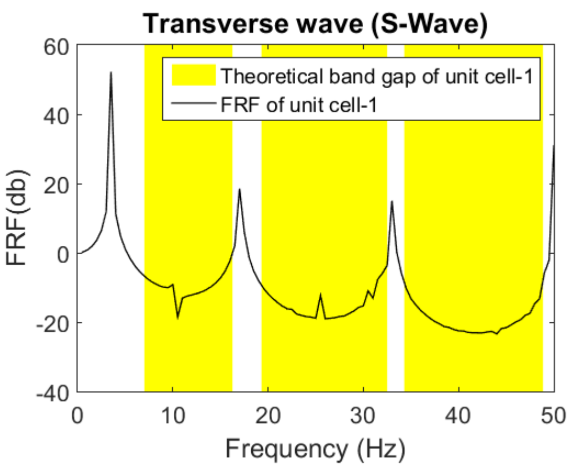


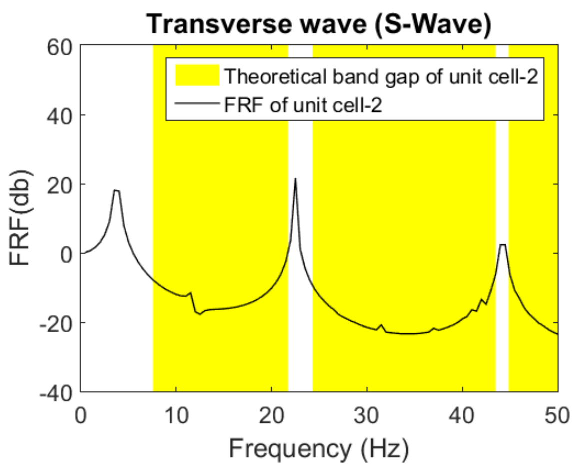
Unit cell-2

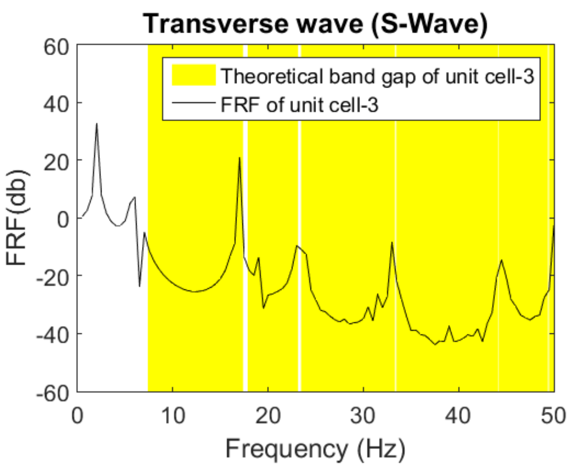


Unit cell-3





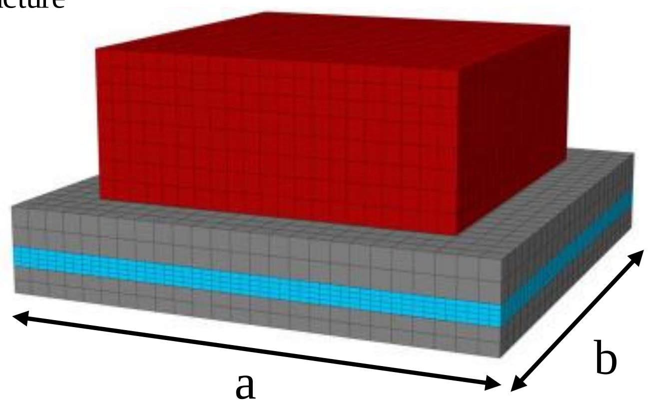


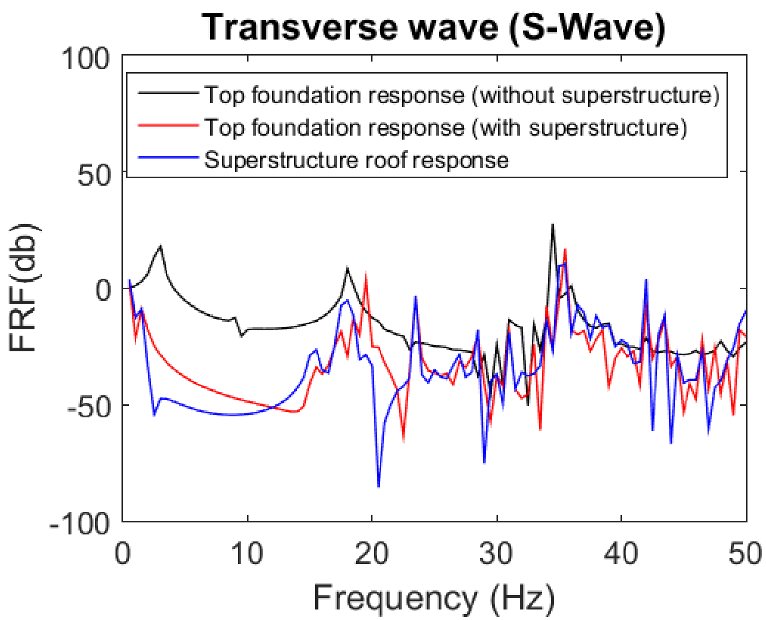


Parametric study of 1D periodic foundations

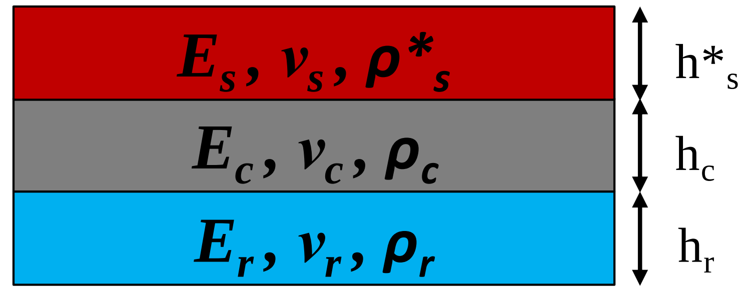
Effect of superstructure

$f_{superstructure}$ =10 Hz

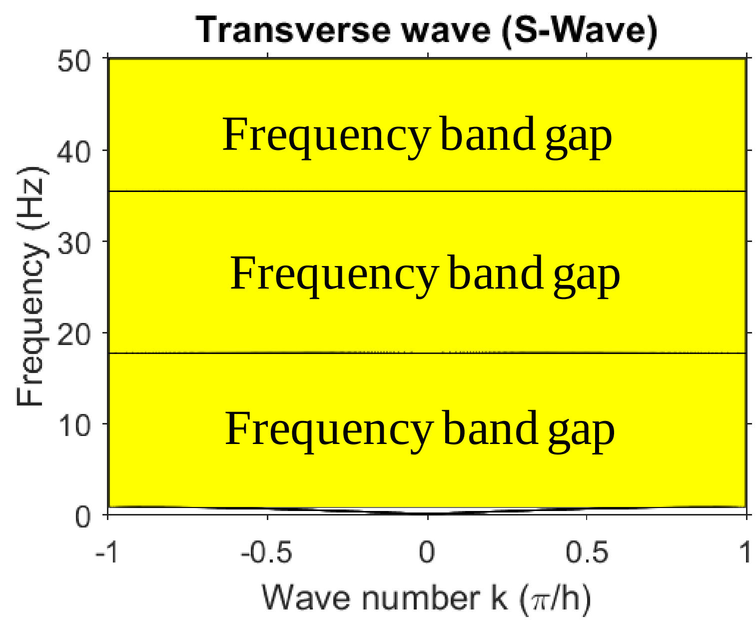




Equivalent model



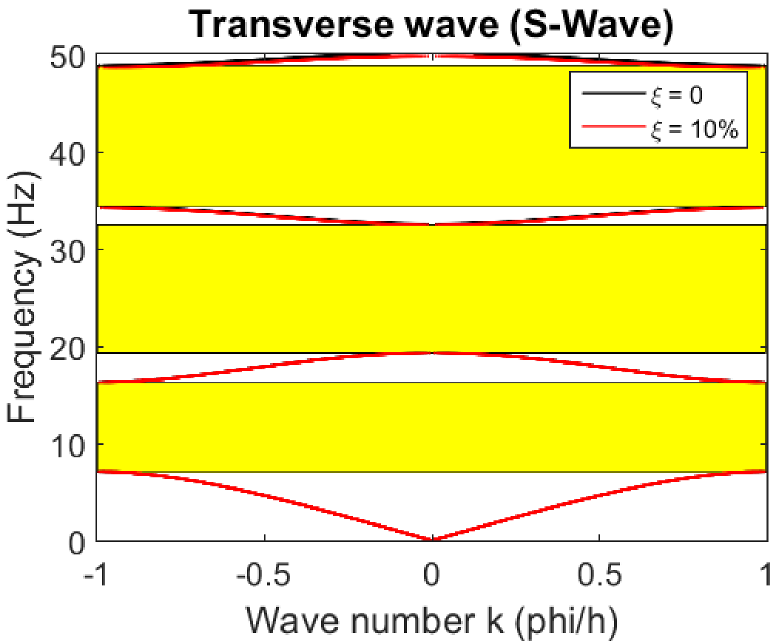
Where: $\rho^*_s = \frac{W_{superstructure}}{a \times b \times h^*_s}$

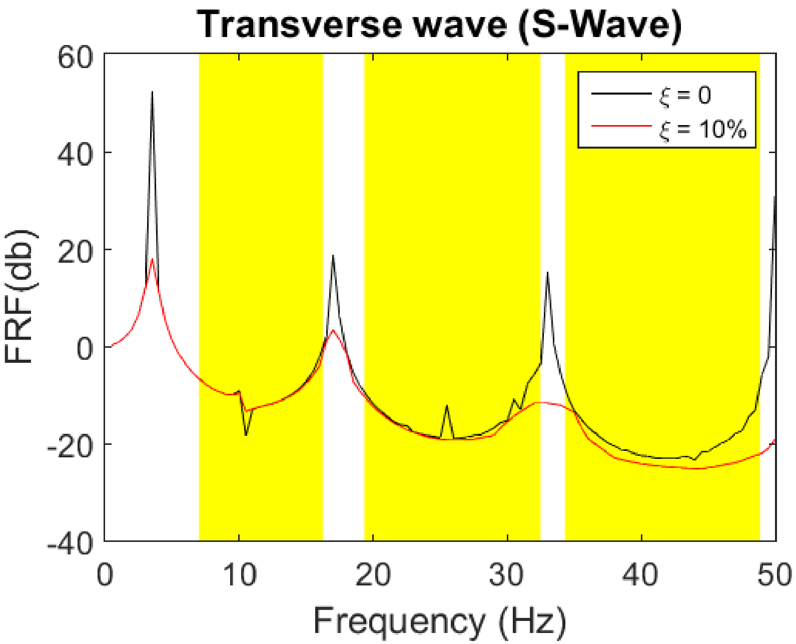


Parametric study of 1D periodic foundations

Effect of damping

$$\omega_d(\mathbf{K}) = \omega(\mathbf{K})\sqrt{1-\zeta(\mathbf{K})^2}$$ **[1]**



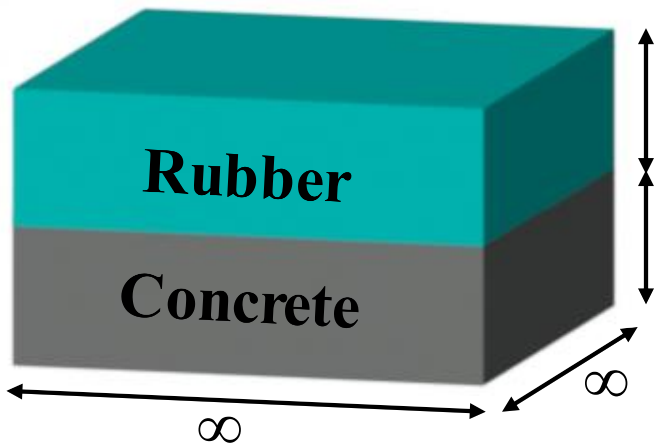


[1] Hussein, M. I. (2009). Theory of damped Bloch waves in elastic media. *Physical Review B, 80*(21), 212301.

Design guidelines of 1D periodic foundations

One unit cell of 1D periodic foundations

Fix geometric properties

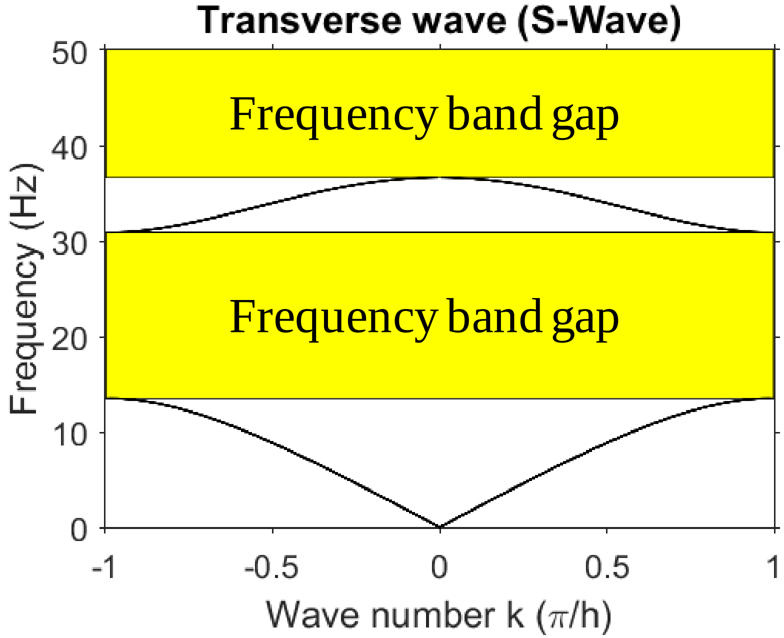


Unit cell size = 1
Rubber to concrete thickness ratio = 1

Fix material properties

Material	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Concrete	3.14×10^{10}	2300	0.2
Rubber	5.8×10^{5}	1300	0.463

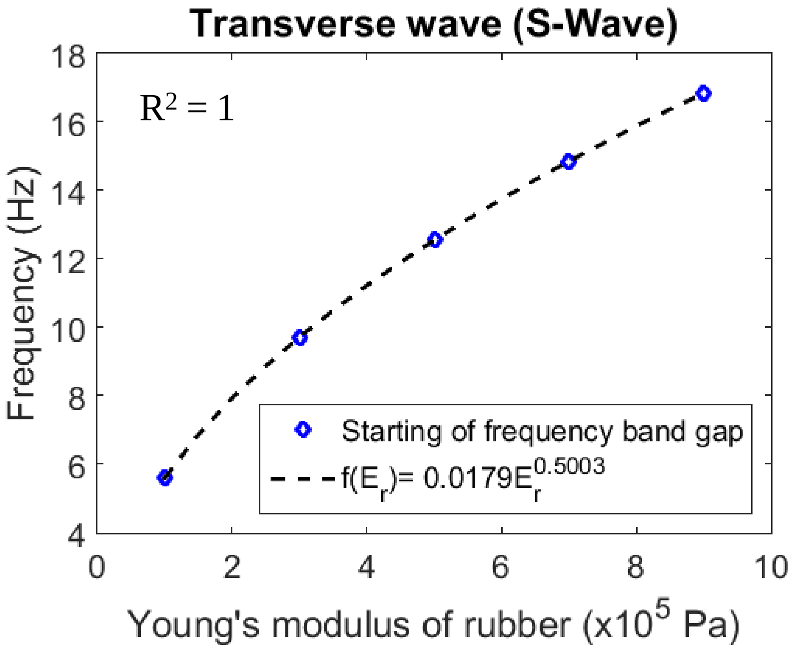
Dispersion curve for infinite number of unit cells

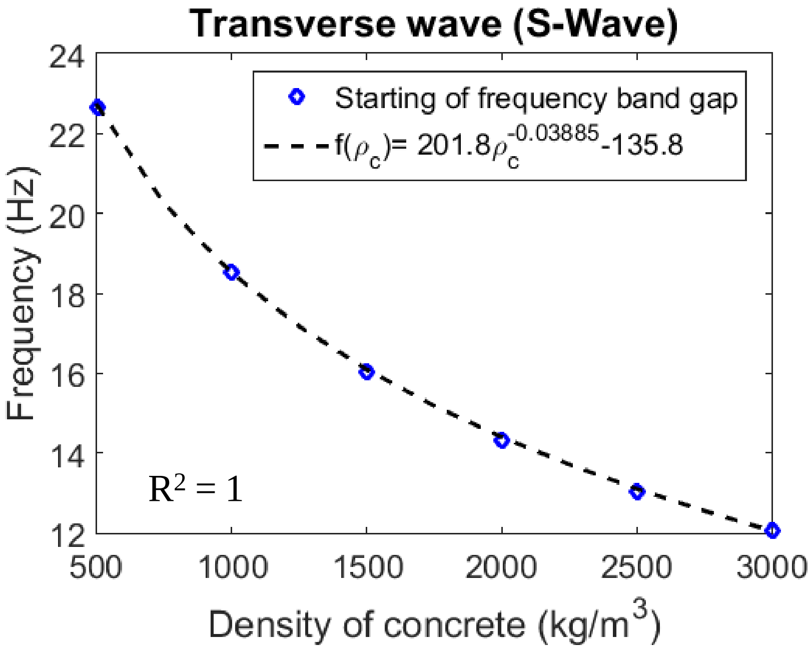


Starting of 1st frequency band gap = 13.51 Hz
Width of 1st frequency band gap = 17.36 Hz

Design guidelines of 1D periodic foundations

Perform regression on each contributing factor





Normalized by the starting of frequency band gap from fixed property

Function of Young's modulus of rubber $F_1(\mathrm{E}_r) = \dfrac{0.01769\,\mathrm{E}_r^{\;0.5003}}{13.51} = 1.3094\times10^{-3}\,\mathrm{E}_r^{\;0.5003}$

Function of density of concrete $F_4(\rho_c) = \dfrac{201.8\rho_c^{\;-0.03885} - 135.8}{13.51} = 14.937\rho_c^{\;-0.03885} - 10.0518$

Design guidelines of 1D periodic foundations

S-Wave design parameter

Parameter	**Function**
Young's modulus of rubber (E_r)	$F_1(E_r) = 1.3094\times10^{-3}\, E_r^{\;0.5003}$
Density of rubber (ρ_r)	$F_2(\rho_r) = \left(2.814\rho_r + 1.627\times10^5\right)/\left(13.51\rho_r + 13.6451\times10^4\right)$
Poisson's ratio of rubber (ν_r)	$F_3(\nu_r) = -0.4139\nu_r^{\;0.6263} + 1.2561$
Density of concrete (ρ_c)	$F_4(\rho_c) = 14.937\rho_c^{\;-0.03885} - 10.0518$
Unit cell size (S)	$F_5(S) = 0.4/S$
Rubber to concrete thickness ratio (r)	$F_6(r) = 0.6403e^{-2.878r} + 0.9489e^{0.01594r}$

Starting of frequency band gap = $13.51F_1(E_r)F_2(\rho_r)F_3(\nu_r)F_4(\rho_c)F_5(S)F_6(r)$

Design guidelines of 1D periodic foundations

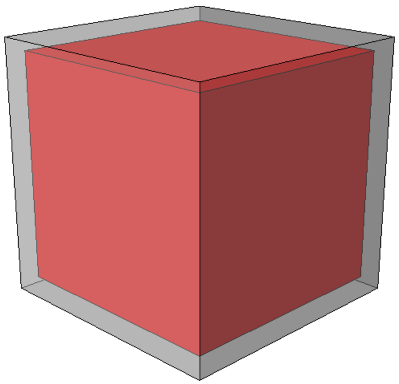
S-Wave design parameters

Parameter	Function
Young's modulus of rubber (E_r)	$G_1(E_r) = 1.3185\times10^{-3}\, E_r^{\ 0.4996}$
Density of rubber (ρ_r)	$G_2(\rho_r) = 98.0991\rho_r^{\ -0.5964} - 0.3632$
Poisson's ratio of rubber (ν_r)	$G_3(\nu_r) = -0.4112\nu_r^{\ 0.6325} + 1.2523$
Density of concrete (ρ_c)	$G_4(\rho_c) = -11.6244\rho_c^{\ -0.03885} + 9.6025$
Unit cell size (S)	$G_5(S) = 0.4 / S$
Rubber to concrete thickness ratio (r)	$G_6(r) = r^{-0.8319}$

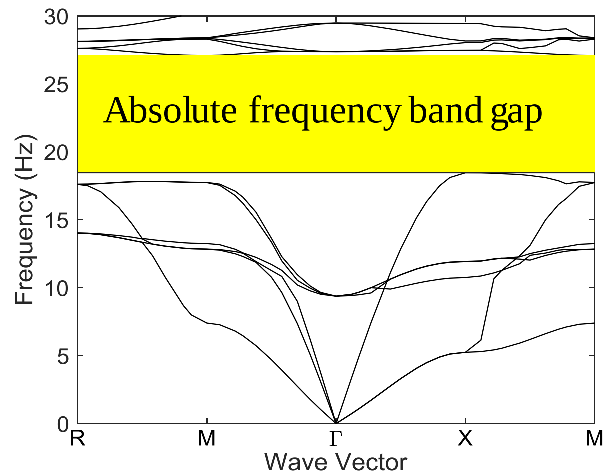
Width of frequency band gap = $17.36G_1(E_r)G_2(\rho_r)G_3(\nu_r)G_4(\rho_c)G_5(S)G_6(r)$

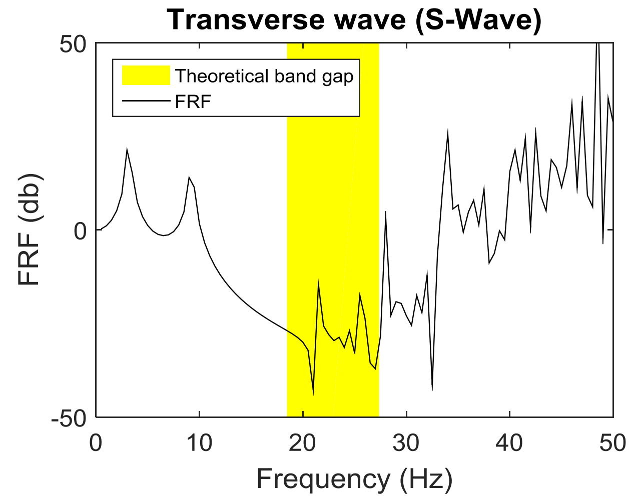
3D Periodic Foundations

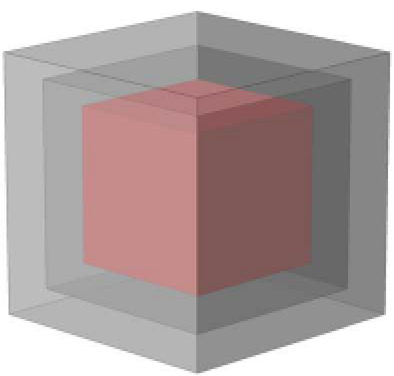
Types of unit cell in 3D periodic foundation



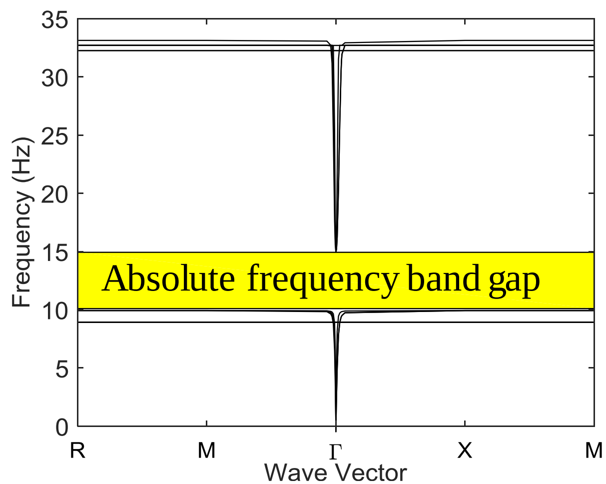
Two components

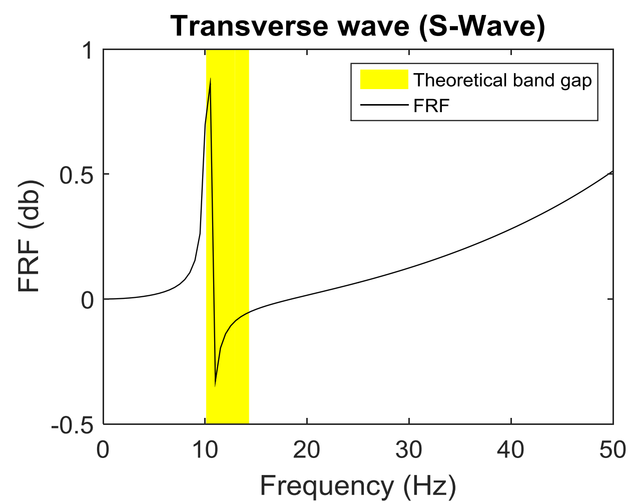






Three components

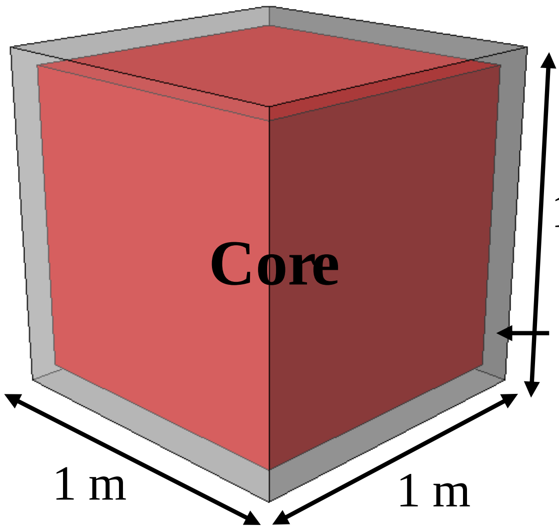




3D Periodic Foundations

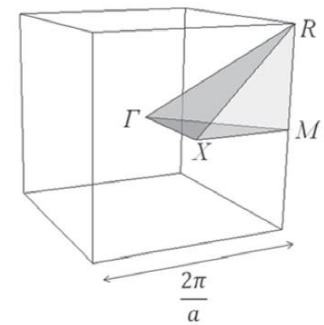
One unit cell of two-component 3D periodic foundation

Fix geometric properties

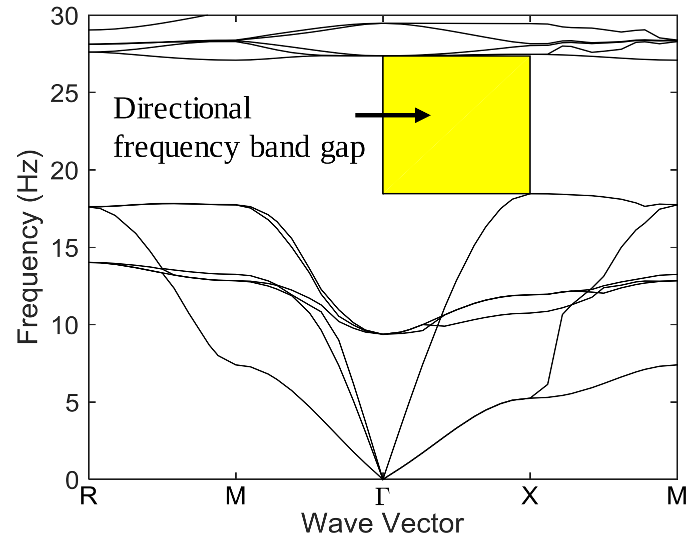


Unit cell size = 1 m
Core size = 0.9 m
Filling ratio = 0.729

First irreducible Brillouin zone



Dispersion curve for infinite number of unit cells

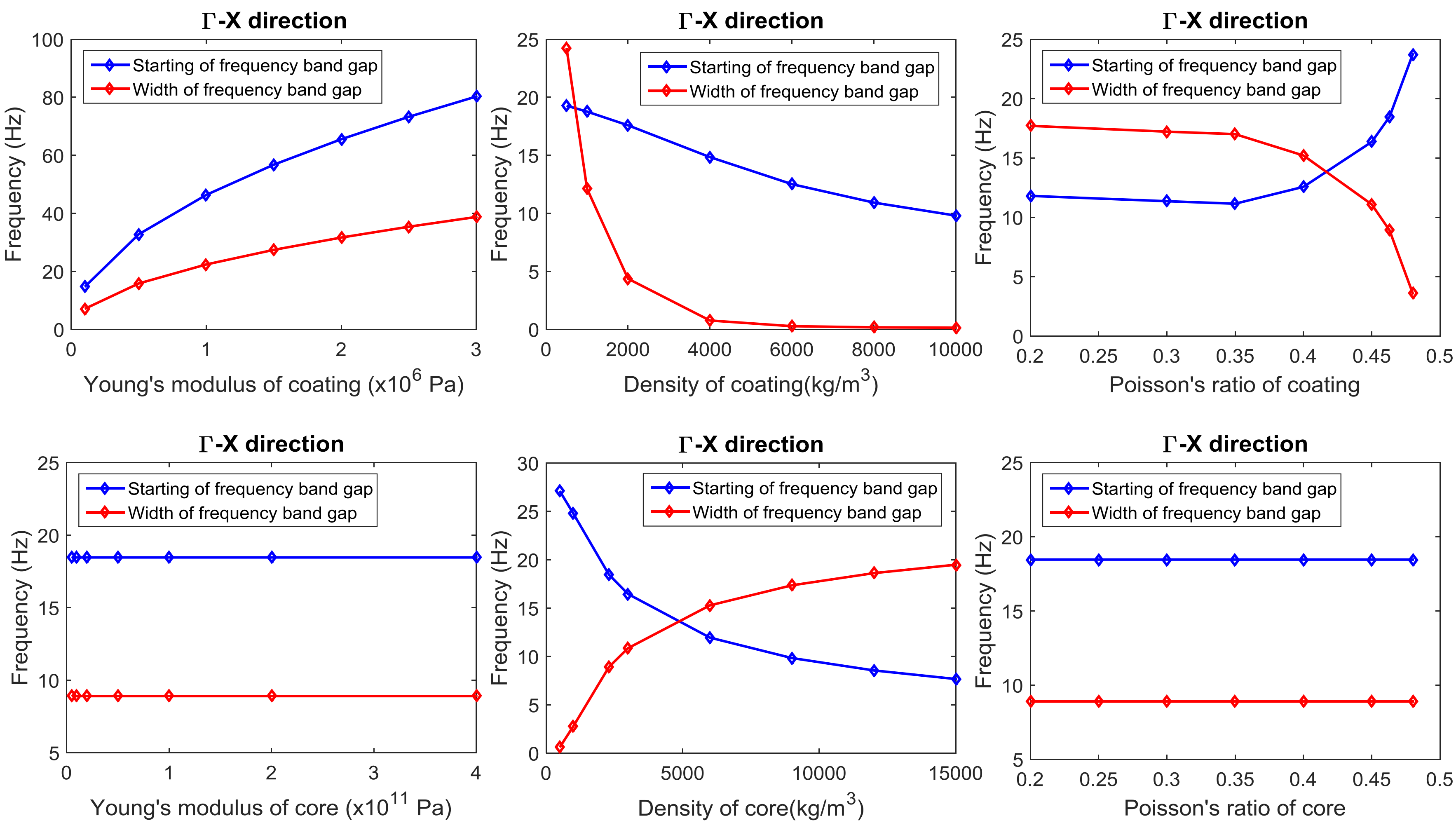


Fix material properties

Component	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Core	4×10^{10}	2300	0.2
Coating	1.586×10^{5}	1277	0.463

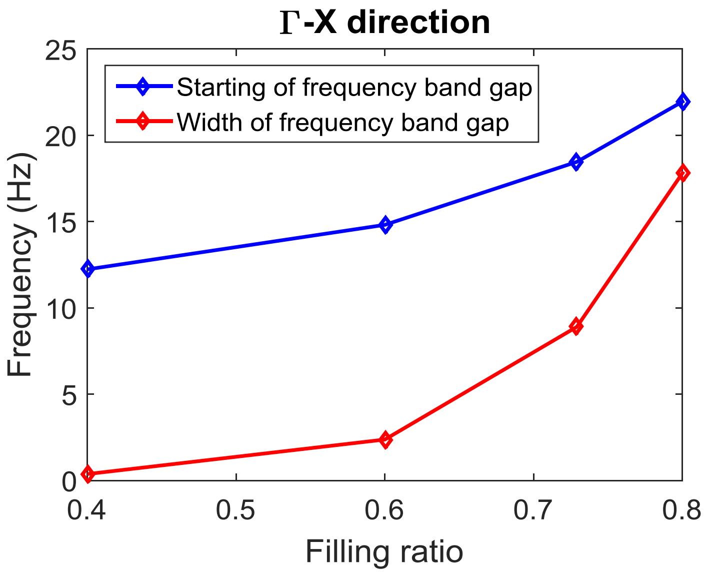
Parametric study of 3D periodic foundations

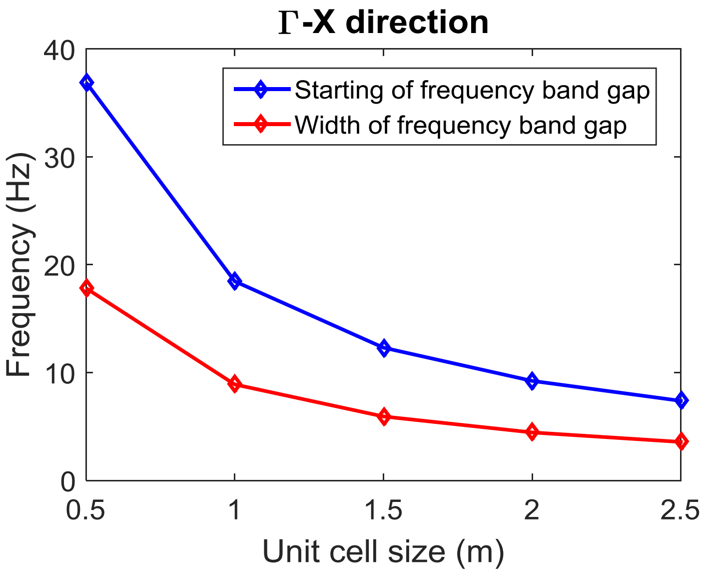
Effect of material properties on the first directional frequency band gap



Parametric study of 3D periodic foundations

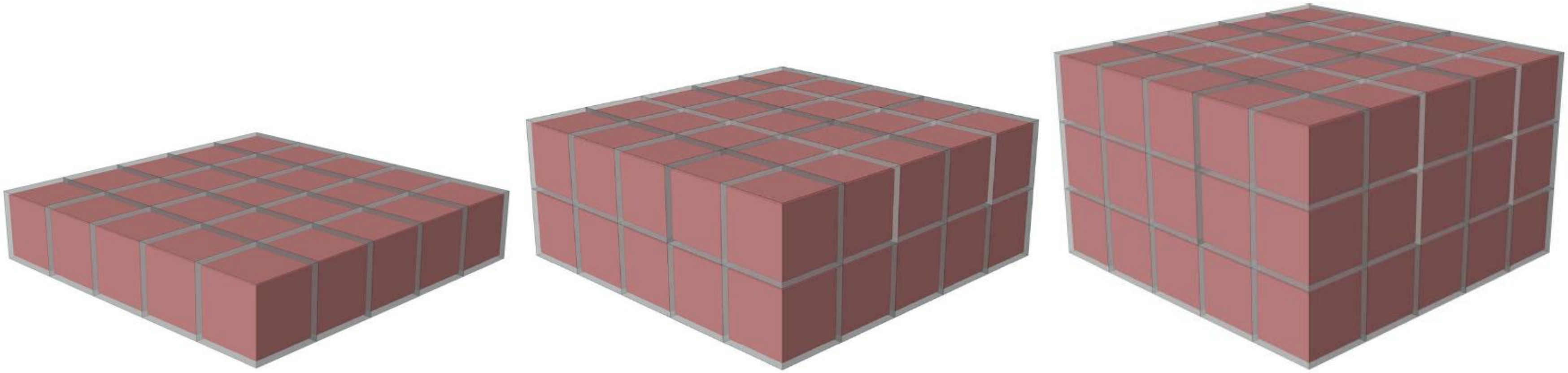
Effect of geometric properties on the first directional frequency band gap



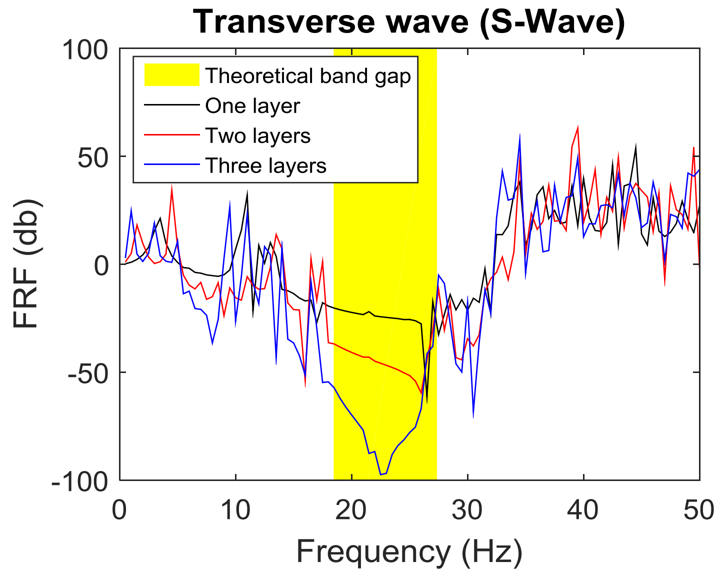


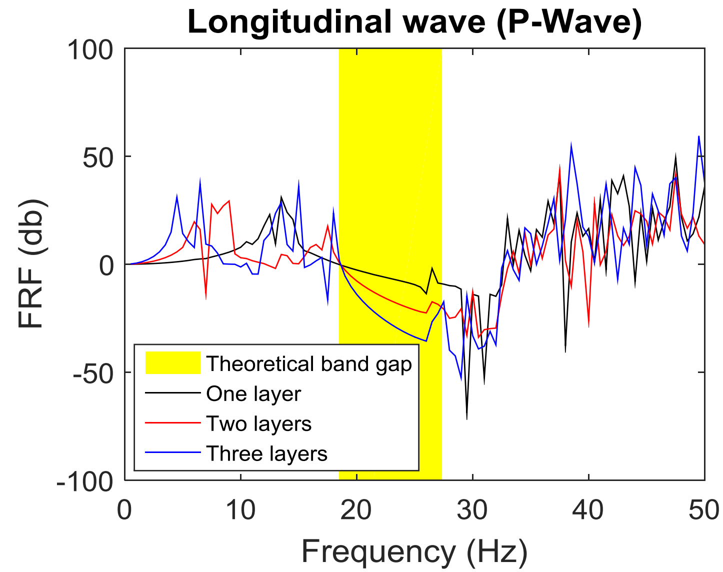
Parametric study of 3D periodic foundation

Effect of number of layer in vertical direction



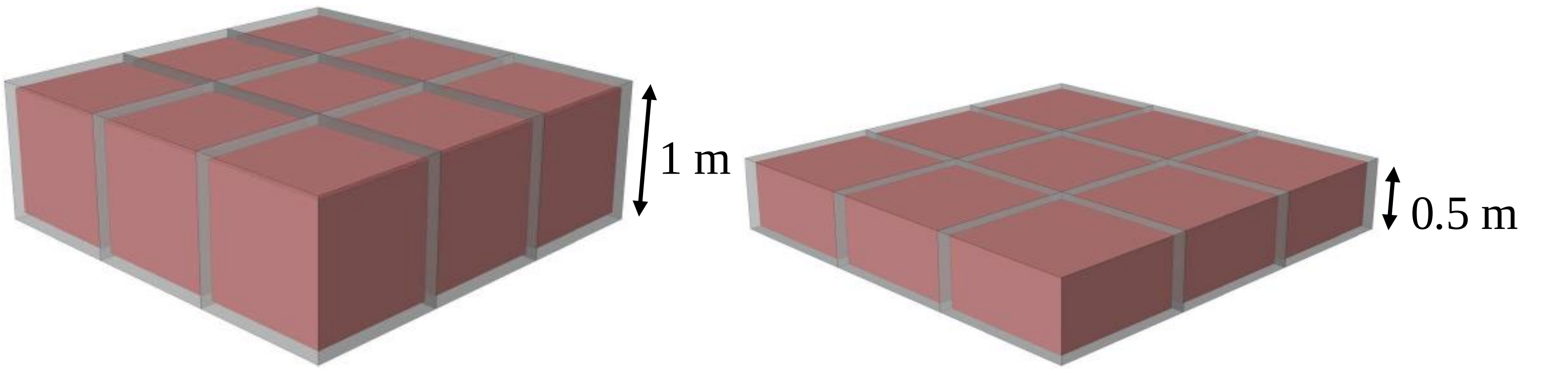
(a) One layer (b) Two layers (b) Three layers



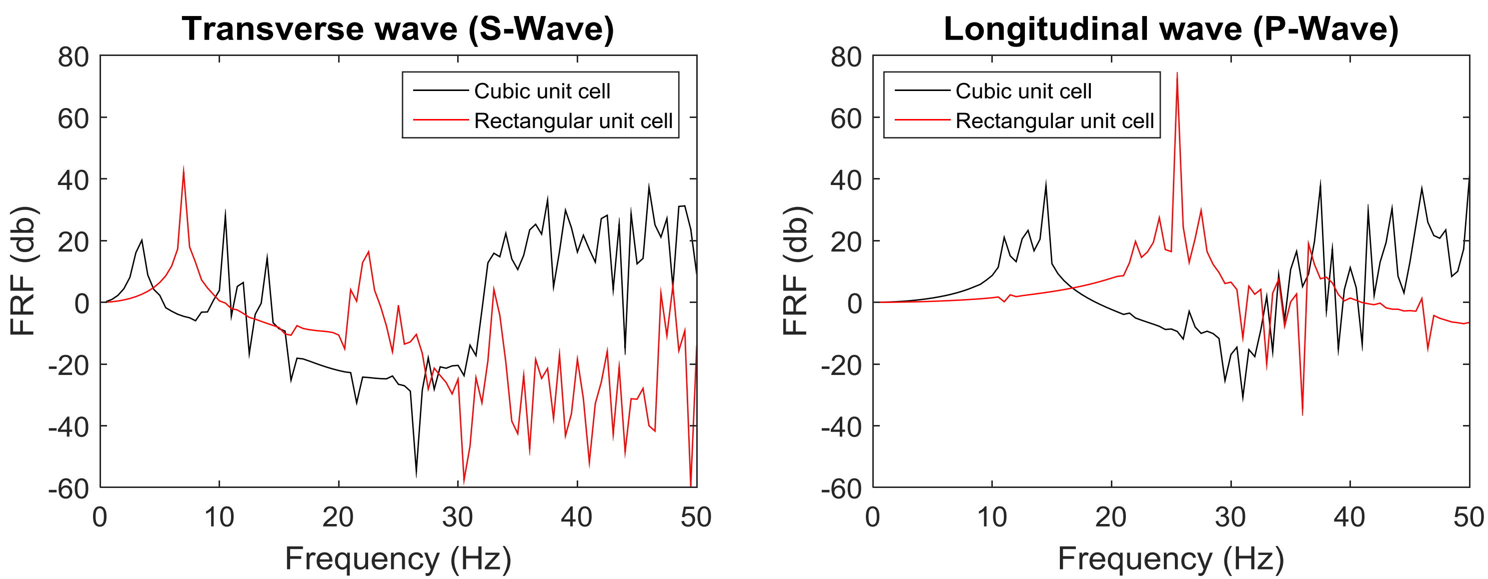


Parametric study of 3D periodic foundations

Effect of suppressed unit cell



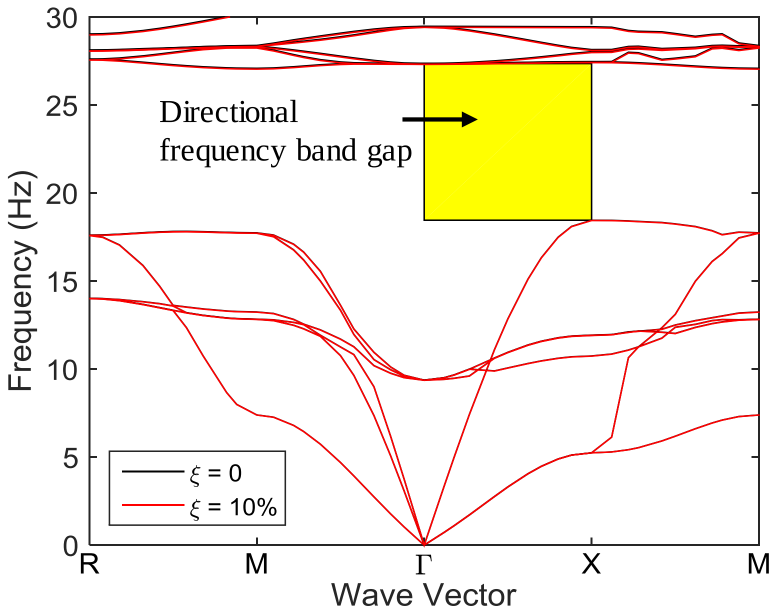
(a) Cubic unit cell (b) Rectangular unit cell

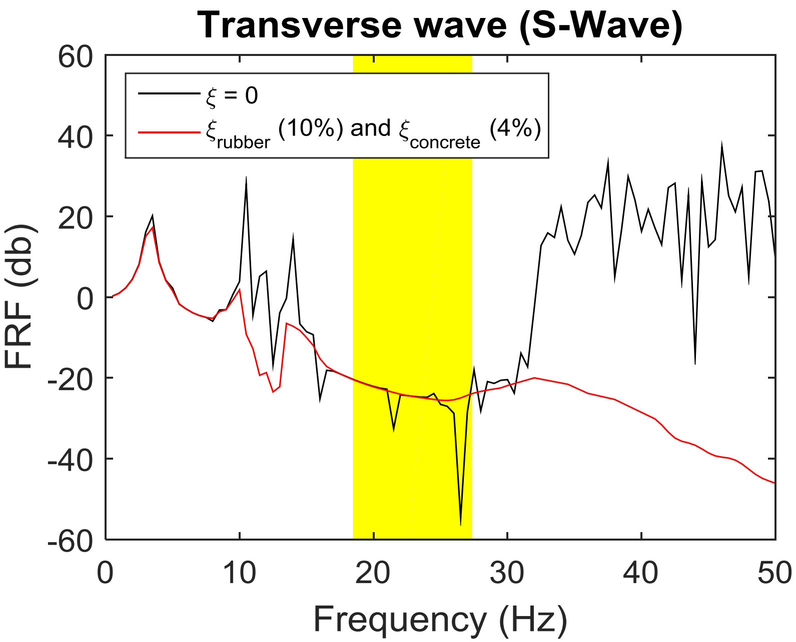


Parametric study of 3D periodic foundations

Effect of damping

$$\omega_d(\mathbf{K}) = \omega(\mathbf{K})\sqrt{1-\zeta(\mathbf{K})^2}$$ [1]



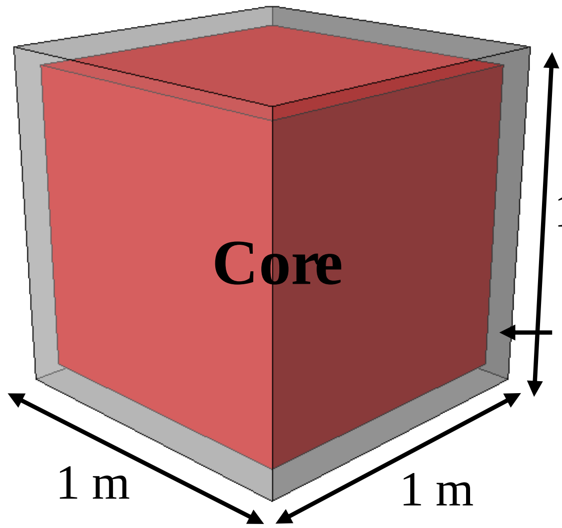


[1] Hussein, M. I. (2009). Theory of damped Bloch waves in elastic media. *Physical Review B, 80*(21), 212301.

Design guidelines of 3D periodic foundations

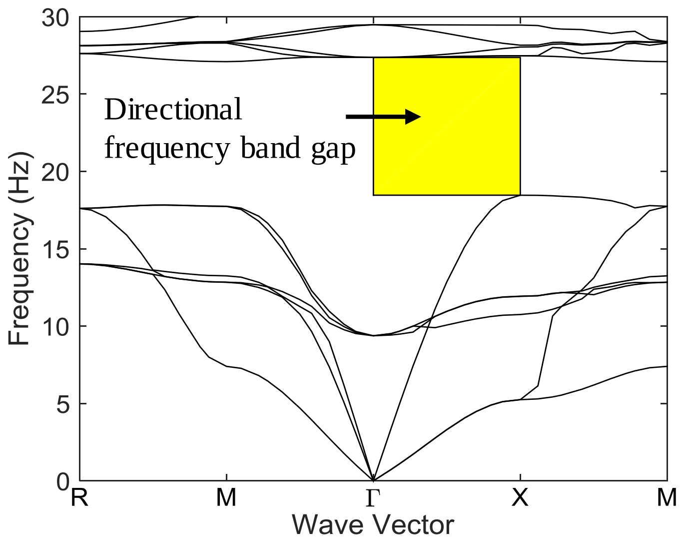
One unit cell of two components 3D periodic foundation

Fix geometric properties



Unit cell size = 1 m
Core size = 0.9 m
Filling ratio = 0.729

Dispersion curve for infinite number of unit cells



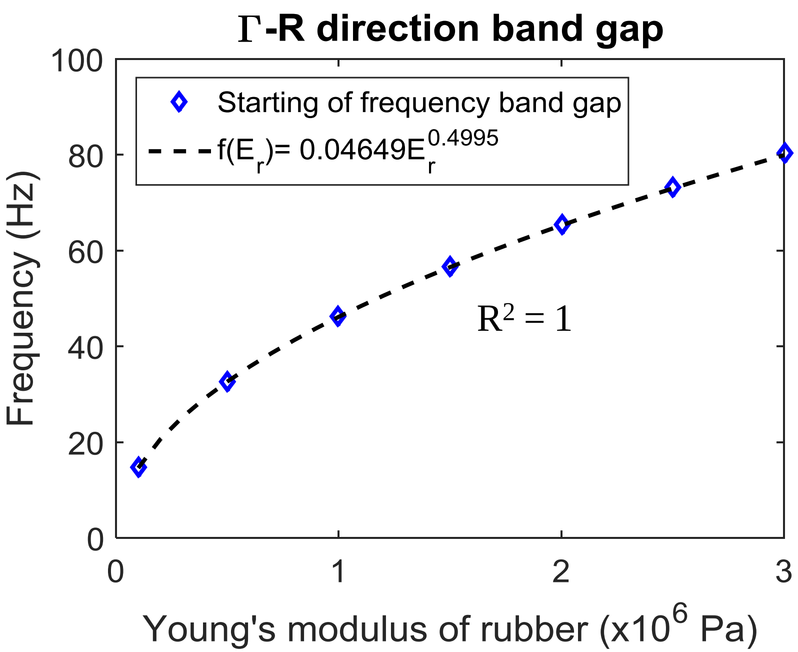
Fix material properties

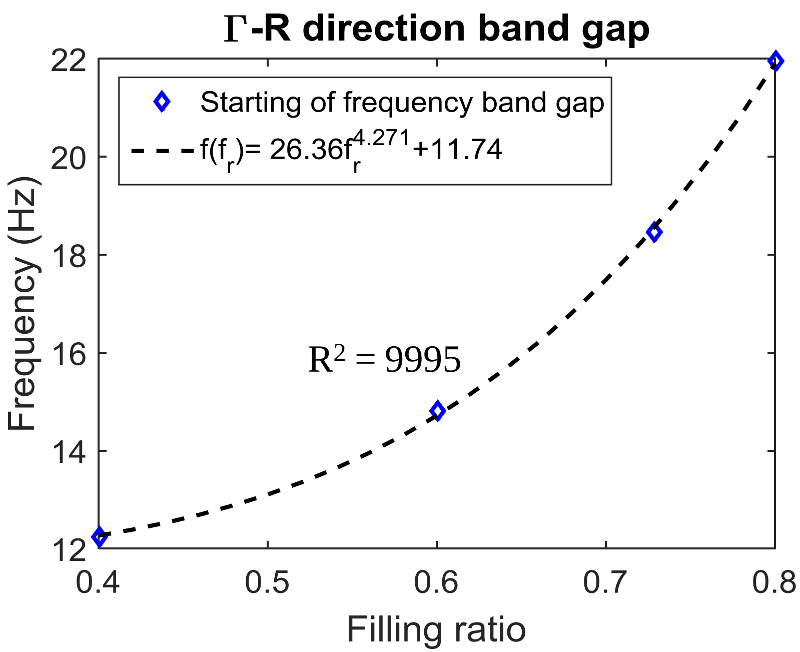
Component	Young's Modulus (Pa)	Density (kg/m^3)	Poisson's Ratio
Core	4×10^{10}	2300	0.2
Coating	1.586×10^{5}	1277	0.463

Starting of 1st frequency band gap = 18.46 Hz
Width of 1st frequency band gap = 8.9 Hz

Design guidelines of 3D periodic foundations

Perform regression on each contributing factor





Normalized by the starting of frequency band gap from fixed property

Function of Young's modulus of rubber $J_1(\mathrm{E}_r)=\dfrac{0.04649\,\mathrm{E}_r^{\ 0.4995}}{18.46}=2.5184\times10^{-3}\ \mathrm{E}_r^{\ 0.4995}$

Function of filling ratio $J_6(\mathrm{f_r})=\dfrac{26.36\mathrm{f_r}^{4.271}+11.74}{18.46}=1.428\mathrm{f_r}^{4.271}+0.636$

Design guidelines of 3D periodic foundations

Design parameter

Parameter	**Function**
Young's modulus of rubber (E_r)	$J_1(E_r) = 2.5184\times10^{-3} E_r^{0.4995}$
Density of rubber (ρ_r)	$J_2(\rho_r) = 0.9 + 0.1793\cos(0.000187\rho_r) - 0.3282\sin(0.000187\rho_r)$
Poisson's ratio of rubber (ν_r)	$J_3(\nu_r) = 0.688e^{-0.3911\nu_r} + 9.6479\times10^{-7} e^{28.14\nu_r}$
Density of concrete (ρ_c)	$J_4(\rho_c) = 0.9832e^{-0.0004377\rho_c} + 0.7053e^{-3.557\times10^{-5}\rho_c}$
Unit cell size (S)	$J_5(S) = 1/S$
Filling ratio (f_r)	$J_6(f_r) = 1.428 f_r^{4.271} + 0.636$

Starting of directional frequency band gap = $18.46J_1(E_r)J_2(\rho_r)J_3(\nu_r)J_4(\rho_c)J_5(S)J_6(f_r)$

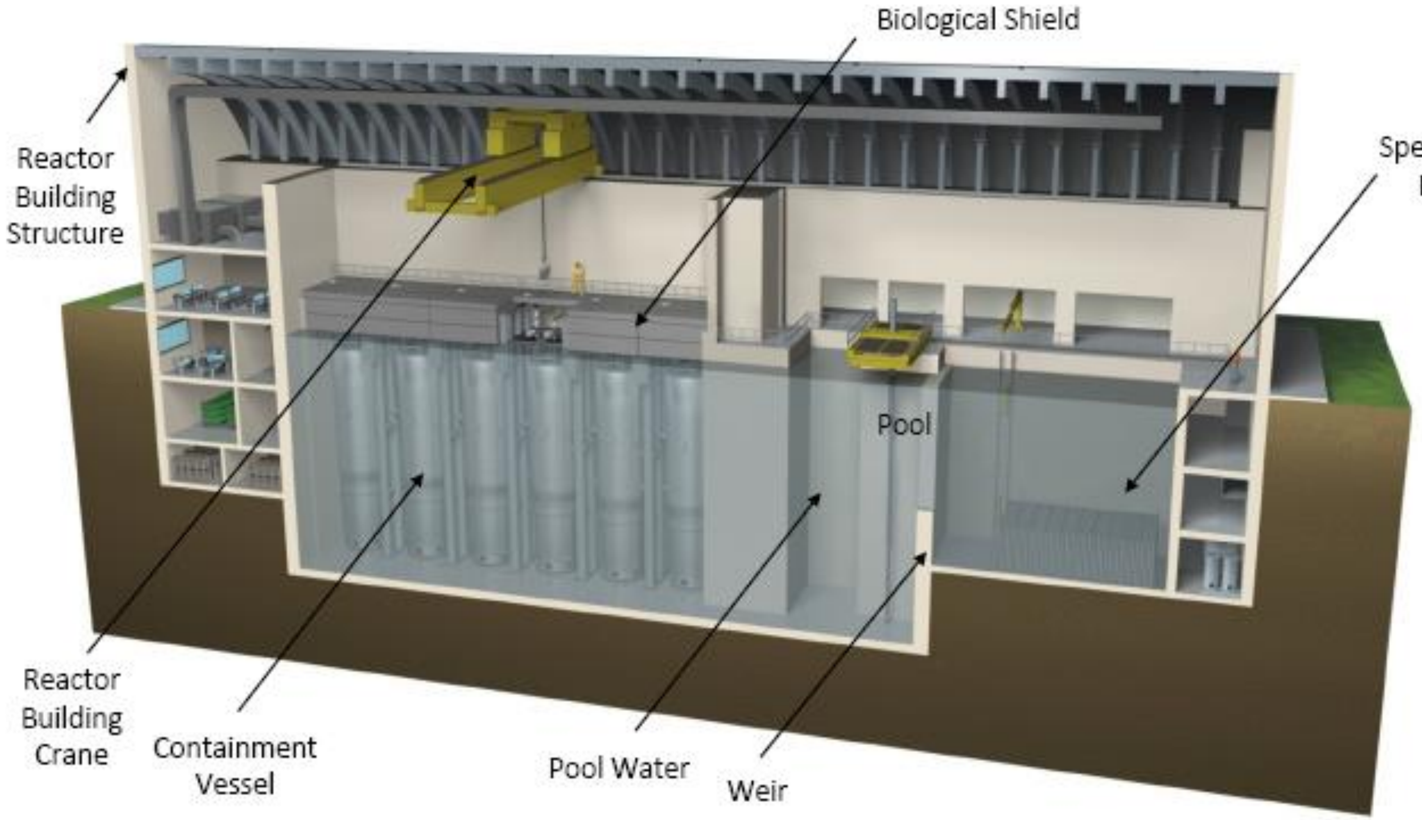
Design guidelines of 3D periodic foundations

Design parameter

Parameter	**Function**
Young's modulus of rubber (E_r)	$K_1(E_r) = 2.51\times10^{-3}\, E_r^{\ 0.5001}$
Density of rubber (ρ_r)	$K_2(\rho_r) = \left(0.0003842\rho_r^{\ 2} - 5.454\rho_r + 19290\right)/\left(8.9\rho_r + 1661.63\right)$
Poisson's ratio of rubber (ν_r)	$K_3(\nu_r) = -8488.764\nu_r^{\ 11.76} + 1.9472$
Density of concrete (ρ_c)	$K_4(\rho_c) = 1.7506e^{1.512\times10^{-5}\rho_c} - 2.1157e^{-0.0004053\rho_c}$
Unit cell size (S)	$K_5(S) = 1/S$
Filling ratio (f_r)	$K_6(f_r) = 10.064 f_r^{\ 7.252}$

Width of directional frequency band gap = $8.9K_1(E_r)K_2(\rho_r)K_3(\nu_r)K_4(\rho_c)K_5(S)K_6(f_r)$

NuScale Reactor Building



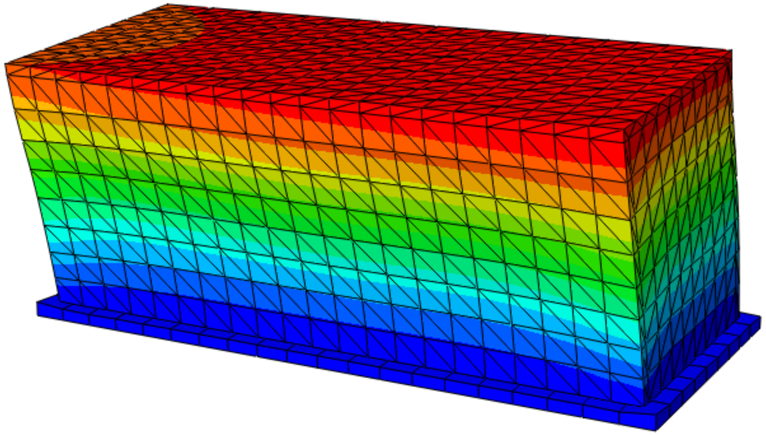
Finite element model of reactor building

Nuclear reactor building is made of reinforced concrete.

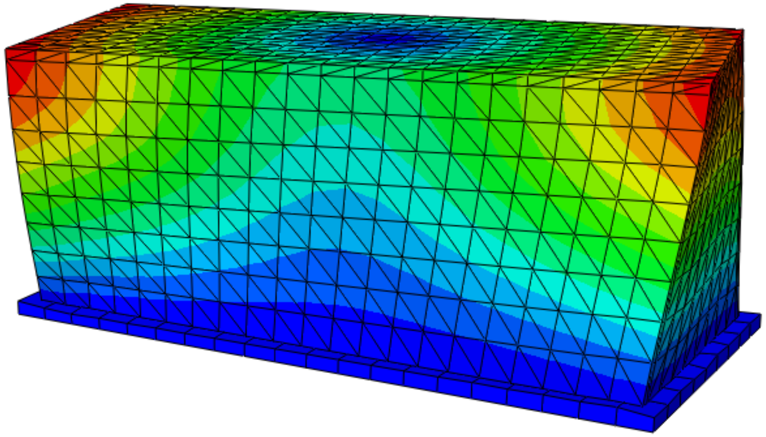
Superimposed dead load:

- Water in the reactor pool = 7 million gallon
- Crane + utilities = 800 ton
- Small modular reactors = 12@800 ton

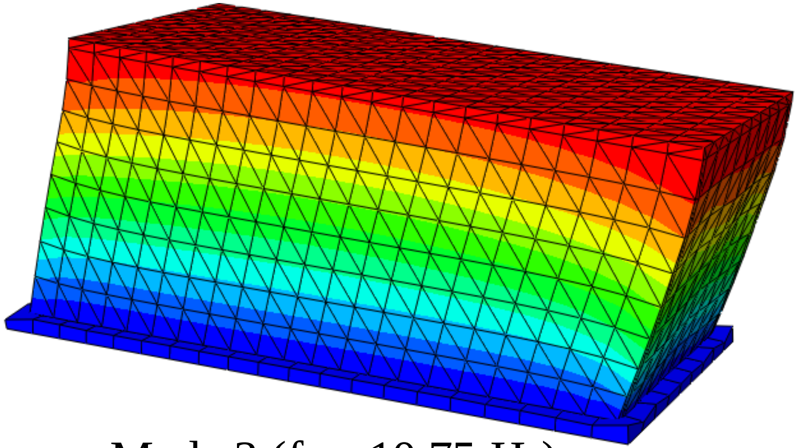
Finite element model of reactor building



Mode 1 (f_n = 6.13 Hz)



Mode 2 (f_n = 10 Hz)

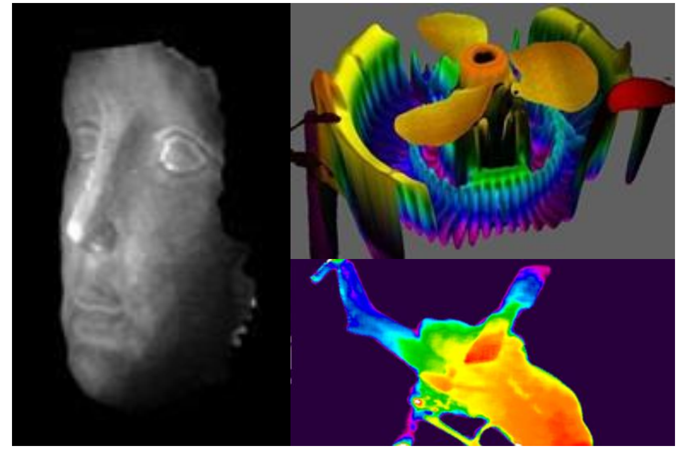


Mode 3 (f_n = 10.75 Hz)

Conclusions

- Basic theory of periodic foundations have been understood.
- Behavior of 1D and 3D periodic foundations have been critically examined.
- Simplified design guidelines for 1D and 3D periodic foundations have been proposed.
- Simplified drawing of reactor building has been obtained from NuScale Power.
- Project will proceed on schedule.

Thank you.



High speed 3D capture for Configuration Management

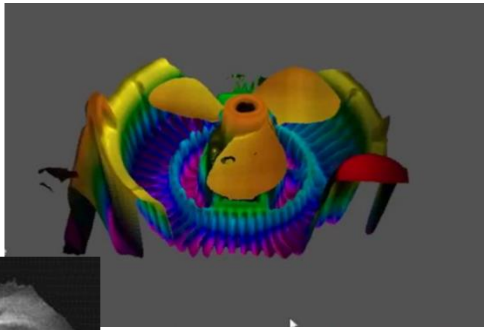
DOE SBIR Phase II

Paul Banks
Paul.banks@tetravue.com

Advanced Methods for Manufacturing Workshop
September 29, 2015

TetraVue does high resolution 3D imagery

- **Founded in 2008 to make high resolution 3D camcorders a reality**
  - Simple instant capture of location of surroundings
  - Patented system technology
  - High resolution, long range, low power



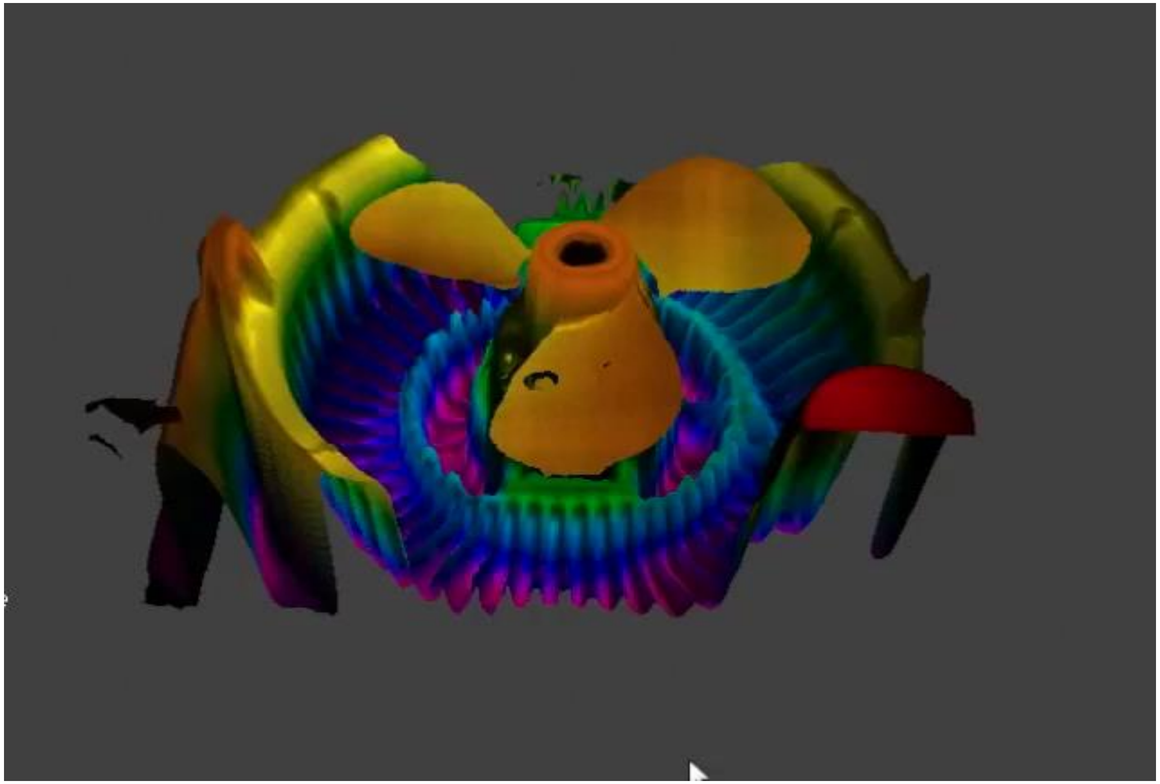
- **Technology team has demonstrated core technology**
  - Exceptional core team with world-class engineering partners
  - Technology projects to show utility for Mars landers, autonomous helicopters, biometrics, and industrial construction

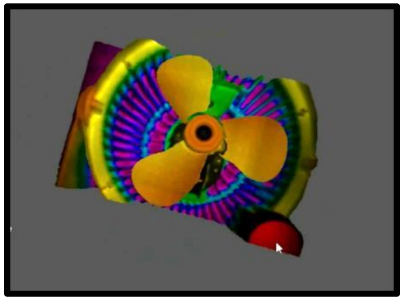
- **Beginning productization to create small, high resolution 3D camera product**

TetraVue

True high resolution 3D video is revolutionary

High resolution 3D video changes how machines & humans interact with the world





Acquisition point of view

6 m range, 12 fps, ~3 mm range resolution, 2 Mpx sensor

TetraVue has unique 3D capability in resolution, range, power & speed

Nuclear power plant configuration management requires a new solution

- **Modern configuration management requires as-built information**
  - Accurate, up-to-date
  - Cost-effective

Nuclear facilities have high density of components & tight tolerances

<u>Existing solutions are too costly & slow.</u>

- **Existing approaches (3D laser scanners) require extensive setups and post-processing**
  - 1000s of scans per facility
  - Manual registration to plant coordinate system
  - Separate imagery for component ID
- **New tablet scanners are limited**
  - Short range operation
  - Slow acquisition
  - Poor resolution
  - But less expensive ($5 – 10K + software)

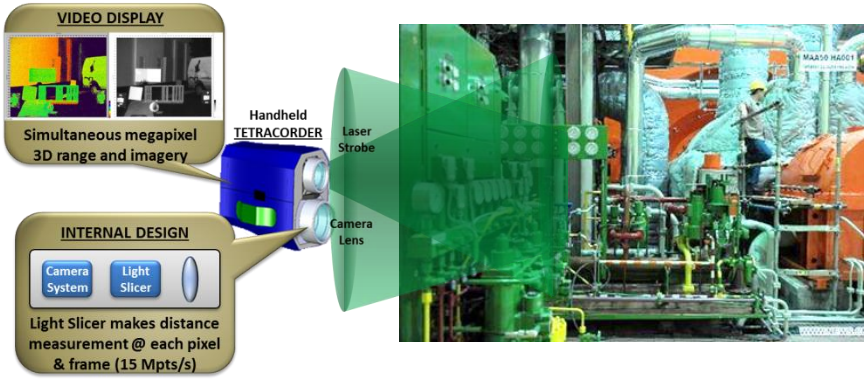
TetraVue's 3D camera technology promises automate registration without setups
- Imagery & coordinate information from a single sensor

Megapixels, 30 m range, low power

TetraVue

Phase II will demonstrate the value & utility of acquiring 3D data from a moving platform

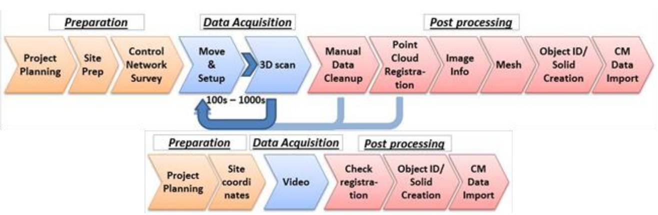
- **3D coordinate and image capture from a moving platform.**
  - <Improve 2X with 2X FOV in handheld>
- **3D frame registration into a project-based reference frame**
  - <Improve accuracy & speed>
- **Determine control network density required.**
  - <Confirm 100 m between control points>
- **Demonstrate integration of data in CAD software for comparison with design**
  - <Near real-time integration>
- **Demonstrate in test environment relevant to nuclear power plant construction.**
  - <End-to-end live demo>
- **ID fieldable design requirements.**
  - <Update from input from stakeholders>



Phase II handheld 3D camera

Traditional Workflow for 3D scanning

Potential TetraCorder Workflow



TetraVue

Phase II objectives will demonstrate practicality of high resolution 3D video for cost-effective configuration management

- 1" accuracy to plant system [ultimate goal is 2-4X better for critical dimensions]
- Eye-safe (class 1M)
- Max Range 20 – 30 m
- Near real-time 3D models of complex structures
- 10 - 45°C operation
- Demonstrate 1 person operation/handling

- **Improve camera performance by 3X over Phase I**
- **Build handheld, single person operation 3D camera prototype**
- **Show near-real-time, accurate model generation**

End-to-end demonstration: incorporate 3D model into common CM software in < 4X the capture time

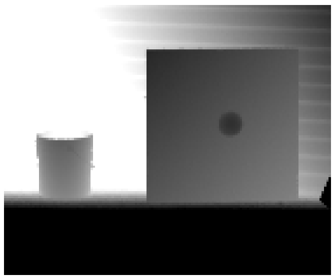
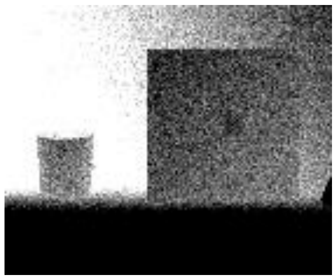
TetraVue

Pixels matter

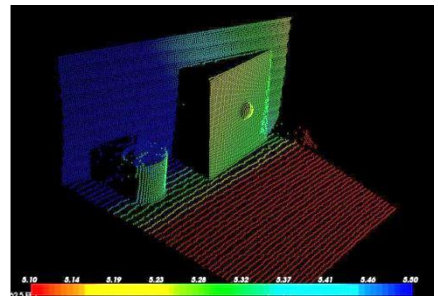
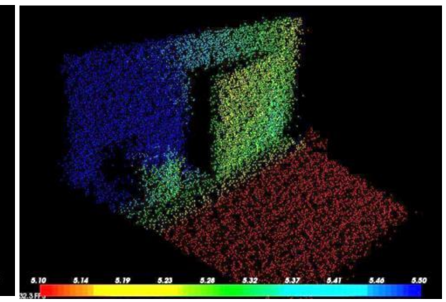
Impact of image & range noise (and therefore distance) is much less with higher pixel counts

Simulated depth images

3D rendering of same data

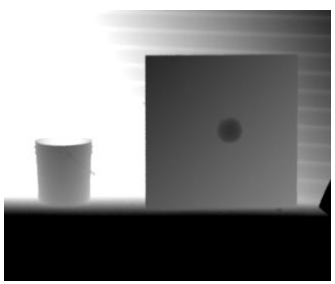
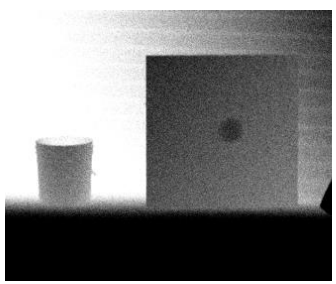



140 px x 116 px

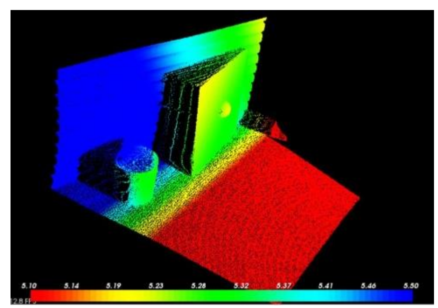
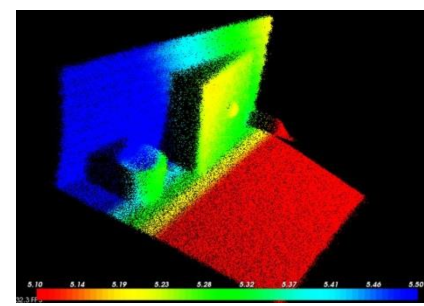



No depth noise | 4 cm depth noise

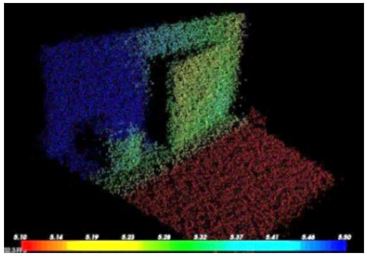
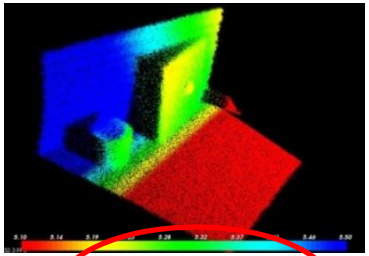
No noise | With BLF filter | 4 cm noise

700 px x 580 px

4 keys for 3D: pixels, range, power, & cost

	State-of-the-Art	TetraVue
		
More Pixels (Megapixel)	10,000 – 40,000	2,000,000
More Range (10 – 100+ m)	< 5 m	100+ m
Less Light Power Electric power 4-100X	2,260 W*	0.4 W* (Quantum limited)
Low cost	?	< $200 (high vol)

*For 1Mpx @ 50 m, 10% reflectivity

An optical approach to TOF 3D imaging promises makes high resolution 3D imagery possible

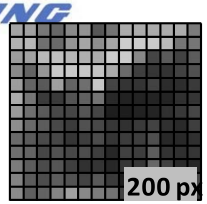
TRADITIONAL

MIT Lincoln Laboratory

BOEING

SAMSUNG

Google



< 40,000 pixels

and many others…

High bandwidth (GHz) time-sensitive

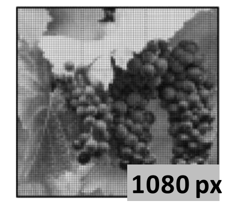
Pixel count

Think different

Medium Bandwidth (<15 MHz) optical

REVOLUTIONARY

Optical TOF



Stock CMOS imaging sensor

--Leverages CMOS sensor improvements

2,000,000 pixels

20 – 100+ m range

TetraVue

$100Ms for ~10 – 40 kpx

Development cost to date:

$3M for 2Mpx

Scaling has been VERY challenging

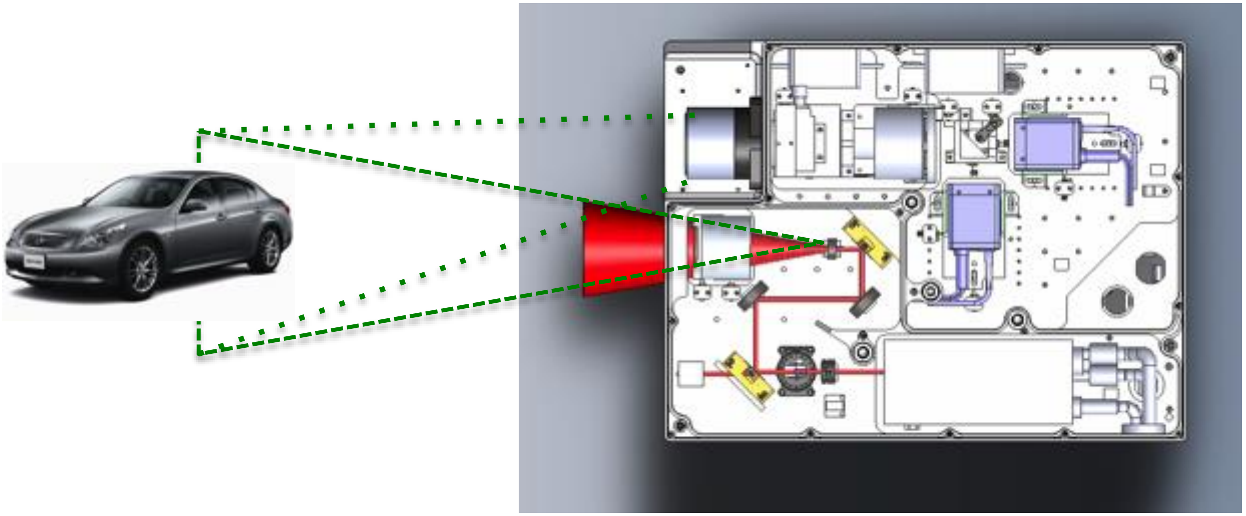
Known productization steps

Path to monolithic 3D sensor:

TetraVue

TetraVue's 3D Camera Technology uses optics to measured time and distance

Instantaneous 3D image capture with a single aperture



IMPACT

- 10 – 100X more pixels
- 10 – 100X longer ranges
- 25 – 100X less power
- 100X lower development cost
- Scene captured instantly
- Path to low cost 3D sensor

- Patented "light slicer" technology
- Extended laser strobe (no blurring/no scanning)
- Simultaneously capture information for all pixels
- Camera-like HD imaging: coordinates & image
- Low latency—"instant" decisions

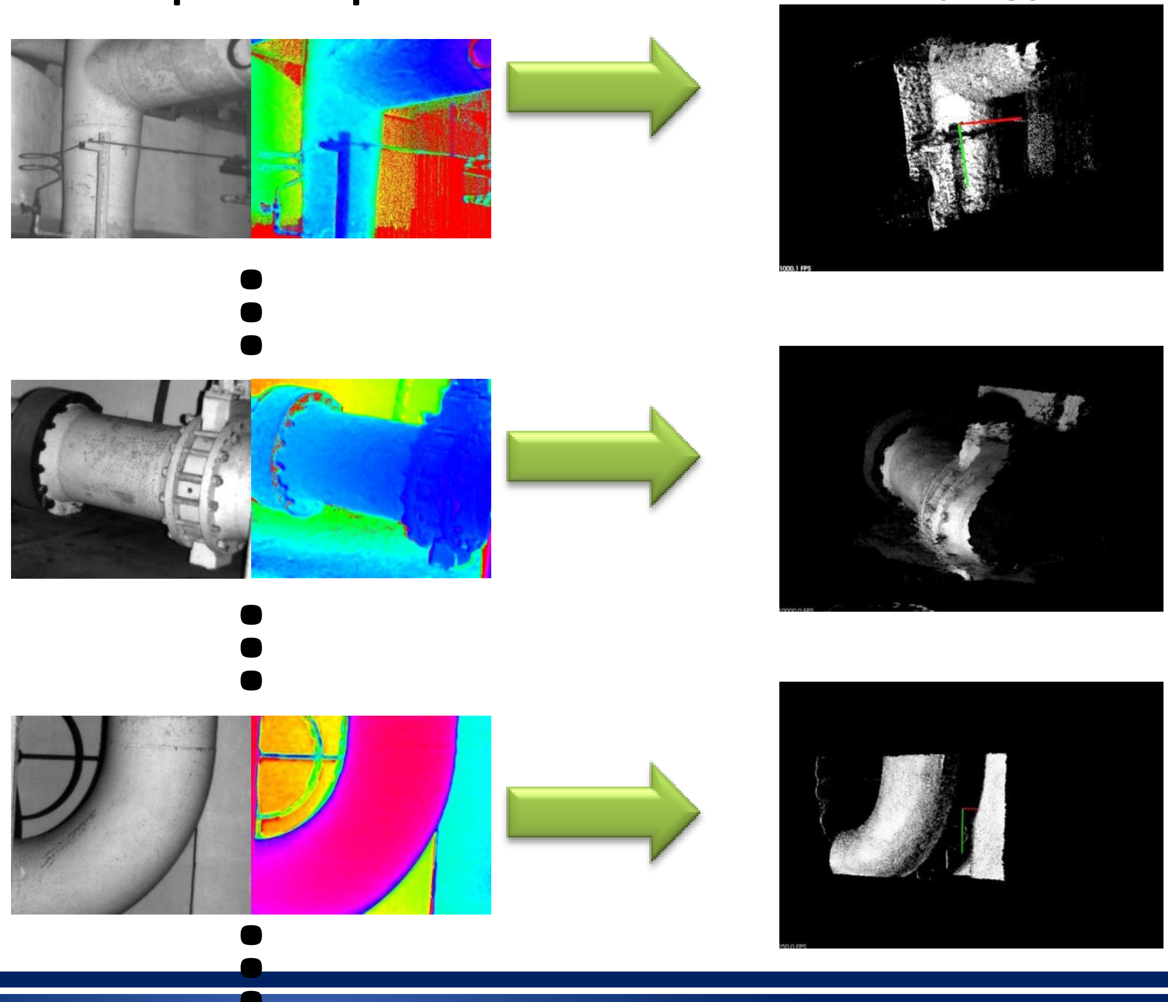
TetraVue

3D video imagery from nuclear plant

TetraVue Prototype 3D camera at site

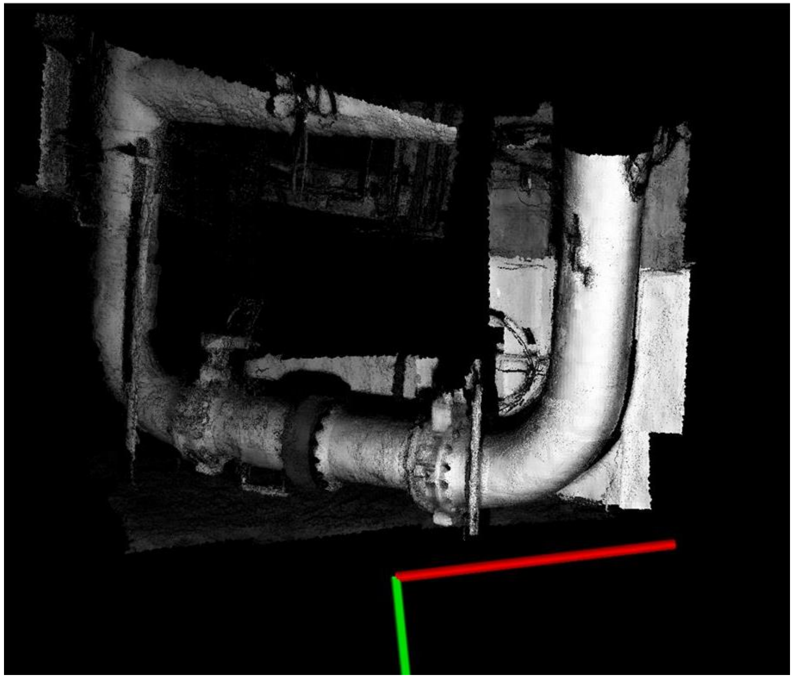
Simultaneous Intensity & range maps at 10 fps

Generation of 3D object frames

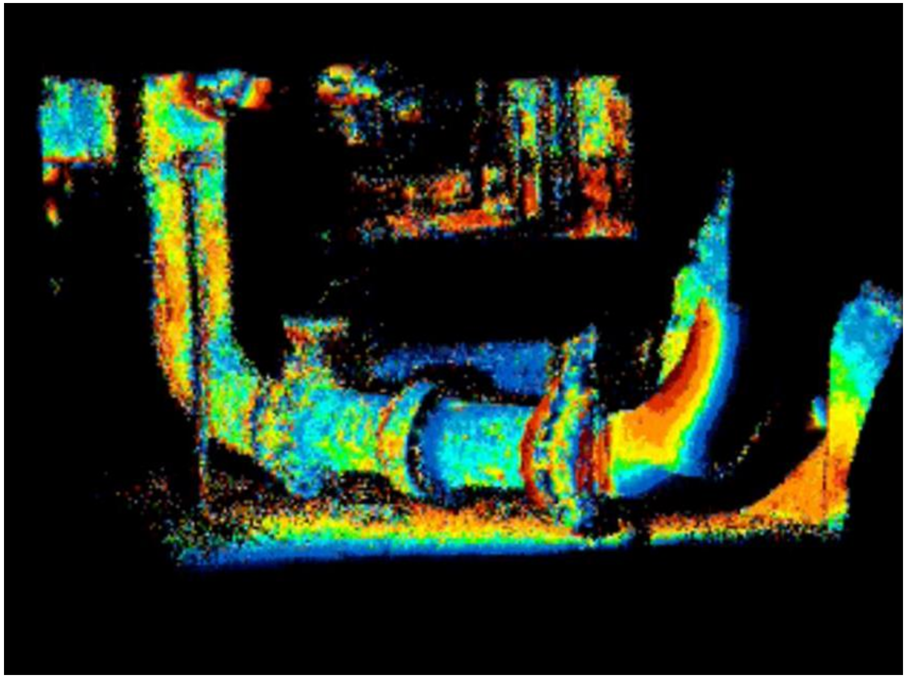


Automated model creation from 100 frames compares well with prior as-built 3D data

Registered 3D model from video



Comparison (color indicates error)



Registered model within 2” of prior as-built measurements

- **DOE Phase II will demonstrate engineering grade performance**
  - < 1” accuracy to plant coordinate system over extended area

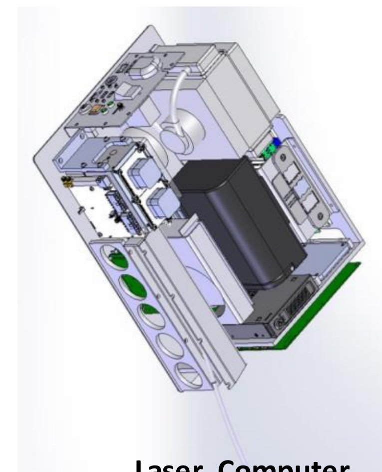
TetraVue

Phase II 3D camera is designed to allow 1-person operatio in congested environments

- Handheld camera + backpack
- > 45 min operation on battery
  - 5 min can cover 6000 m^2 (90% overlap)
- Sub-cm resolution and accuracy out to 10 m
  - Operational to > 30 m
- Operation like a camcorder


Camera & display
6" x 6" x 6"
7 lb

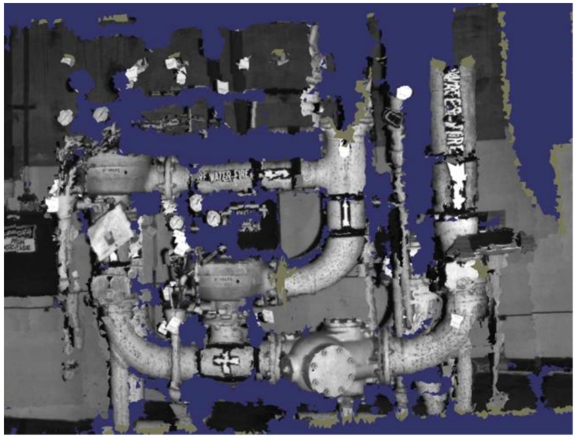
- Optics optimized & miniaturized
- Minimal electronics miniaturization



Laser, Computer, timing & battery
6" x 10" x 16"
25 lb

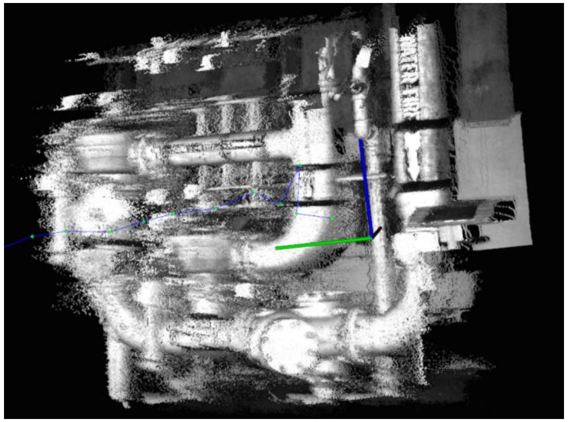
TetraVue

3D Registration is pursuing 2 parallel paths to achieve project goals



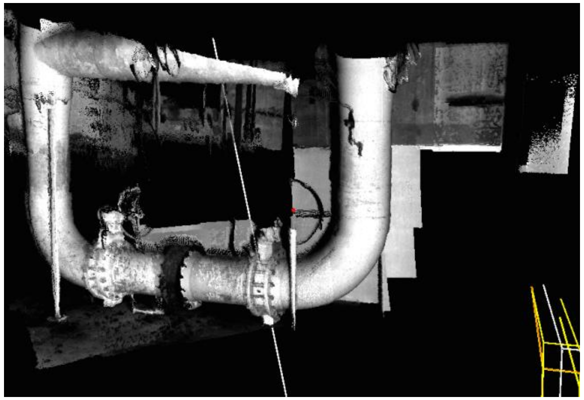
PRELIMINARY RESULTS FROM Phase I
Texture applied to mesh but created registered surface relatively inaccurate

Modified open source



Approach I

Modified commercial product

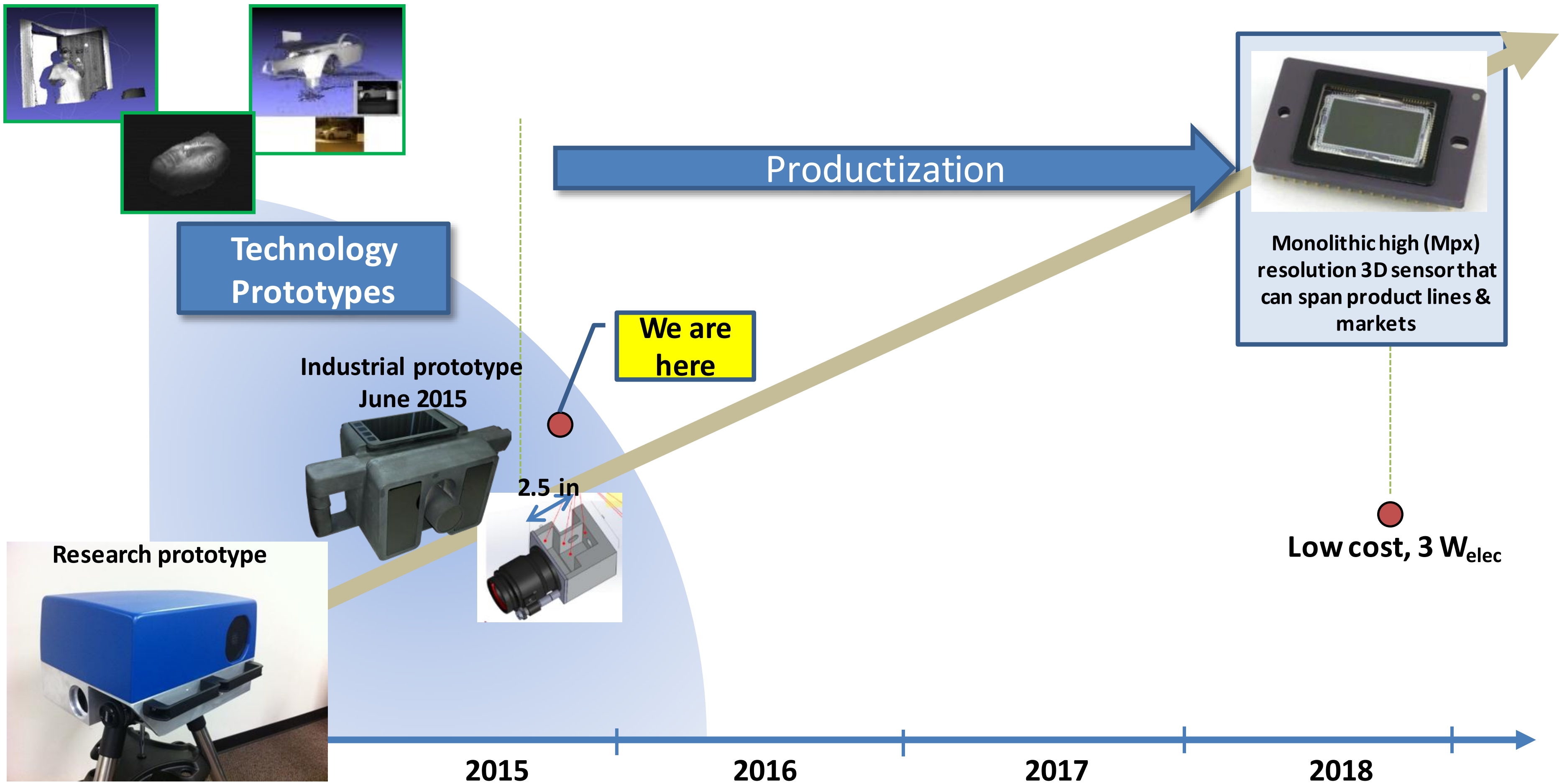


Approach II (Dot Product)

Live registration demo

Product will be ubiquitous low-cost, long range, megapixel 3D sensor and cameras

High resolution monolithic sensors can now be realized with TetraVue's optical TOF technology



TetraVue

What is missing in the Information Age?

Design/Virtual

- Autonomy
- CAD
- Machine Vision
- CG
- Visual f/x
- Augmented Reality
- Virtual Worlds
- Avatars

Reality/Live

- Objects
- Scenes
- Live Action
- Equipment
- As built
- People

REALITY MEETS DESIGN

Friction Stir Additive Manufacturing as a potential route to achieve high performing structures

James Withers
MER Corporation

Rajiv S. Mishra
Center for Friction Stir Processing, Department of Materials Science and Engineering, University of North Texas, Denton, TX 76203, USA

Acknowledgement – DOE STTR Contract No. DE-SC0013783; Dr. Alison Hahn, Program Manager

US DOE workshop on Advanced Methods for Manufacturing (AMM)
September 29, 2015

Presentation outline

- Grand challenges confronting metal based additive manufacturing
- An overview of FSAM & where it fits best
- Seed results: Fabrication of high performance light-weight (Mg & Al based) alloys by FSAM
- Potential Application I: Integrated stringer assemblies on a skin panel fabricated by FSAM for aircraft fuselage
- Potential Application II: FSAM for fossil & nuclear energy applications
- Potential Application III: Functional & gradient materials by FSAM and listing of other potential applications for aerospace & energy industries
- Laser-FSAM hybrid & mini-sample testing capabilites

Center for Friction Stir Processing

Chronological evolution of metal based additive technologies and key challenges

Current limitations and challenges (Fourfold)

Scale of production: 1) Build volume 2) Layer thickness → *Limits part size (few mm³ and microrons)*

Economic consideration: 1) High production cost 2) Low production rate → *Cost of product, delivery time*

Mechanical property: Solidification microstructures leading to property knockdown → *Part lifetime and efficiency*

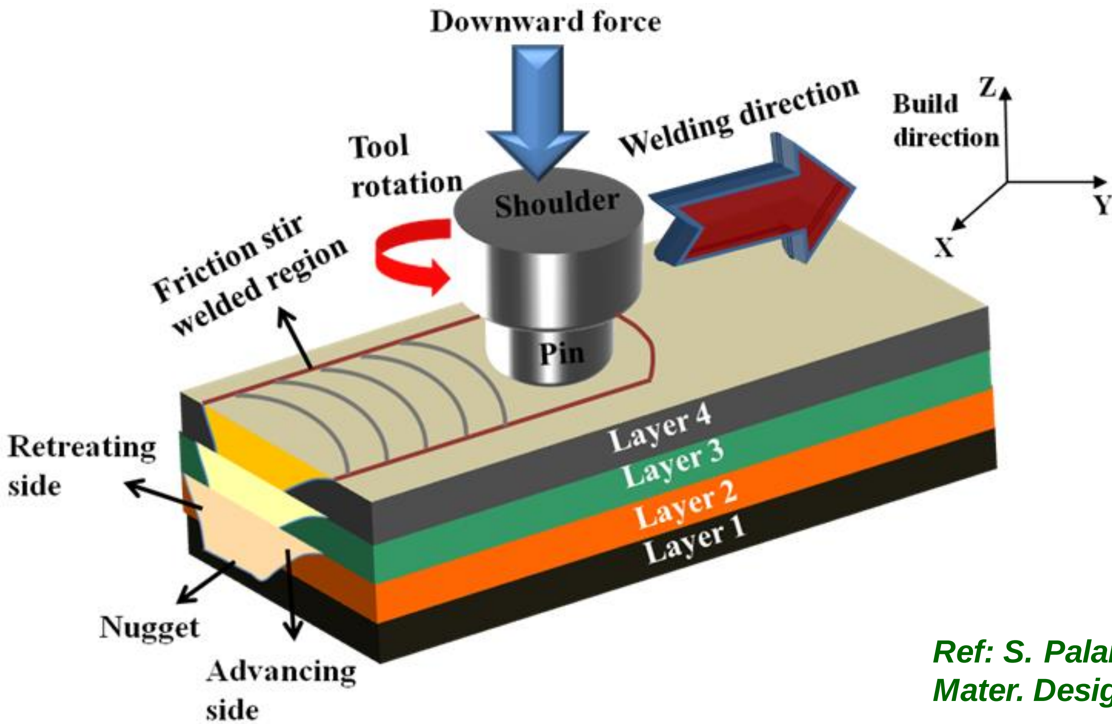
Environment & Energy 1) Usage of shielding gas by fusion process 2) High power requirement

Key issues	➢ Severe overhangs ➢ Solidification microstructure ➢ Mechanical properties	➢ Post processing ➢ Time consuming ➢ Mechanical properties	➢ Post processing ➢ High production cost ➢ Properties	➢ Post processing ➢ Low build rate	➢ Foil preparation ➢ Low build volume ➢ Mechanical properties	➢ Post processing ➢ High operating cost	➢ Mechanical property ➢ Low build rate	➢ Surface quality
Build volume (mm³) Build rate (mm³/s)	- 300x300x300 - 60	- 750x400x400 - 2000	- 250x250x250 - 4-16	- 1500x800x800 - 85	- Small - Slow	- 250x250x325 - 2-8	250x250x 280 - 0.5-5.5	200x200x 350 - 45-66
Layer thickness	120 µm	280-500 µm	20-100 µm	140 µm	Less	20-80 µm	20 – 80 µm	50 µm
Materials studied	Steels, Nickel based super alloy, Inconel, Titanium, Cobalt	Steel, Bronze	Steels, Inconel, Titanium, Cobalt, Aluminum(Al)	Steels, Wasp alloy, Titanium(Ti)	Aluminum alloys	Steels, Titanium, Cobalt, Aluminum	Precious metals, Steel, Titanium, Aluminum	Copper, Beryllium, Steels, Ti, Al, Ni
Advantages	➢ Can use composite powder mixture ➢ High cooling rate	➢ Complex geometry is achievable	➢ Complex geometry is achievable	➢ Neutral gas ➢ Better property in comparison to castings	➢ Solid state ➢ Multi material structure ➢ Environment friendly	➢ Multi material structure	➢ High quality finishing ➢ Reduction in stress	Faster builds in comparison to DMLS and SLM
Temporal evolution of metal based additive technology	Laser engineered net shaping (LENS); Laser additive manufacturing (LAM)	Digital part metallization (Prometal)	Selective laser melting (SLM)	Easy clad; Direct metal deposition (DMD), Similar to LENS with higher build capacity	Ultrasonic consolidation (UAM)	Direct metal laser sintering (DMLS)	Laser cusing	Electron beam melting (EBM)
Year	1997,98	1999	1999	2000	2001	2003	2004	2006

Selective laser sintering; Laminated object manufacturing (LOM) — 1991,92

Ref: S. Palanivel, N. Phalgun, B. Glass, R.S. Mishra, Mater. Design, 65 (2015), 934-952

Friction stir additive manufacturing (FSAM): Process description

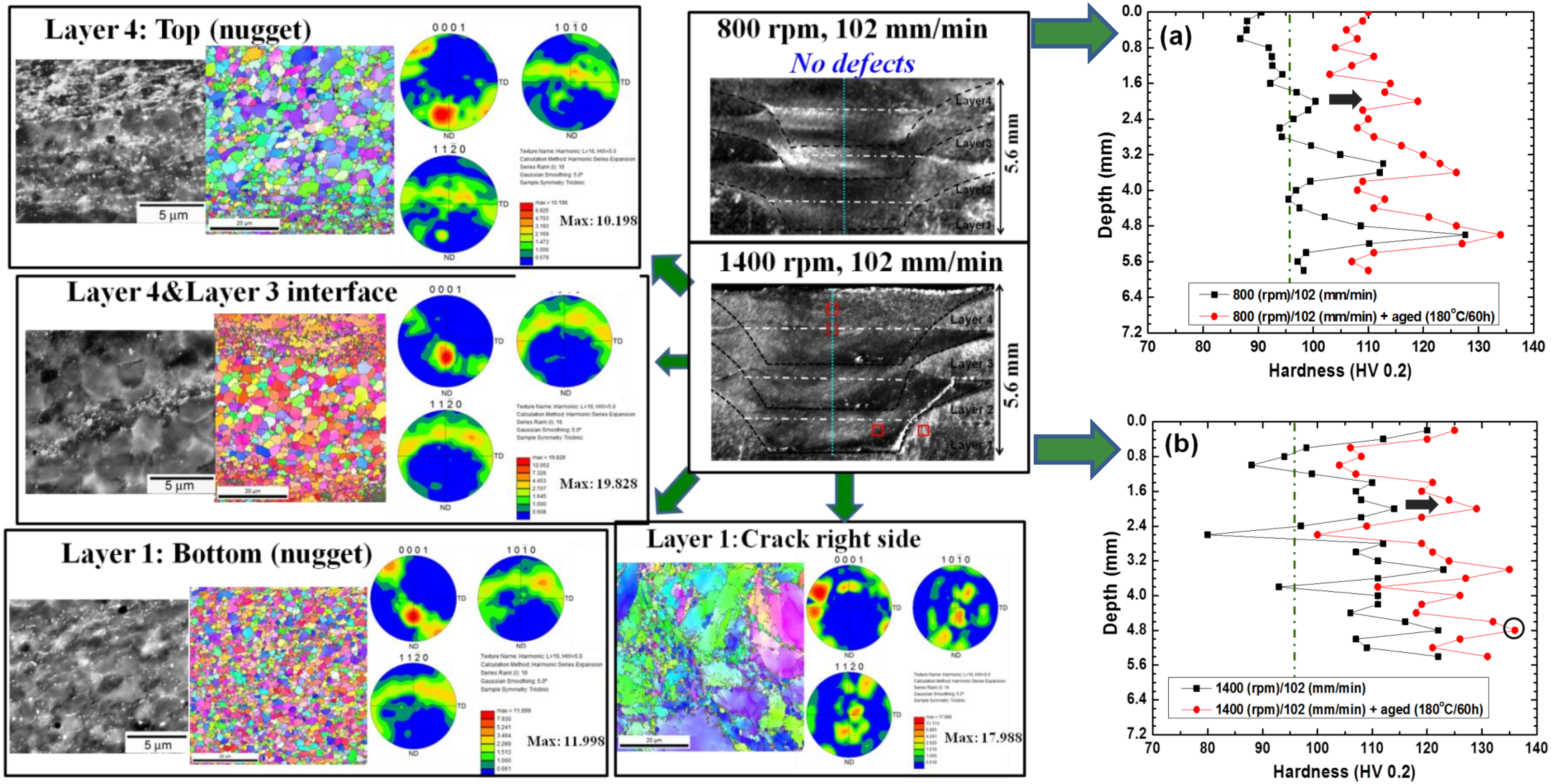


Friction Stir- Laser Hybrid Machine at CFSP

Ref: S. Palanivel, N. Phalgun, B. Glass, R.S. Mishra, Mater. Design, 65 (2015), 934-952

- Non-consumable rotating tool with a custom designed pin and shoulder is inserted into the surfaces of sheets or plates to be joined and traversed along the joint line
- Joints are produced in solid state and involve no melting.
- Final thickness of the joint depends on the: (i) thickness of the sheets/plate, and (ii) number of assembly stages/layers
- In contrast to the cast approach in fusion based techniques, ***FSAM leads to wrought microstructures***

Seed results: High performance Mg-Y-Nd alloy built by FSAM

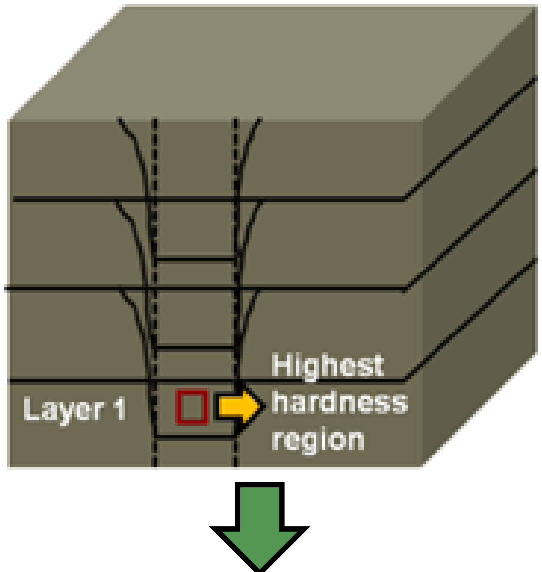


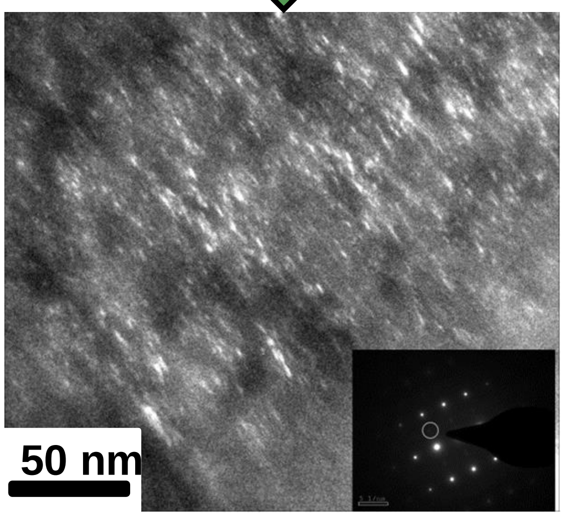
Ref: S. Palanivel, N. Phalgun, B. Glass, R.S. Mishra, Mater. Design, 65 (2015), 934-952

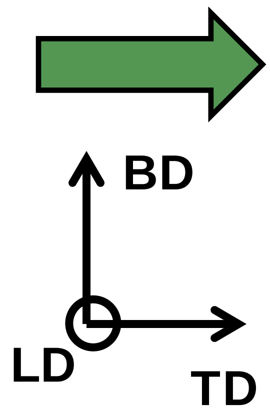
- ***Hardness- 135 HV (Built+aged). These values are similar to Al 2XXX alloys!***
- Maximum hardness achieved by conventional techniques/heat treatment routes is 110-120 HV

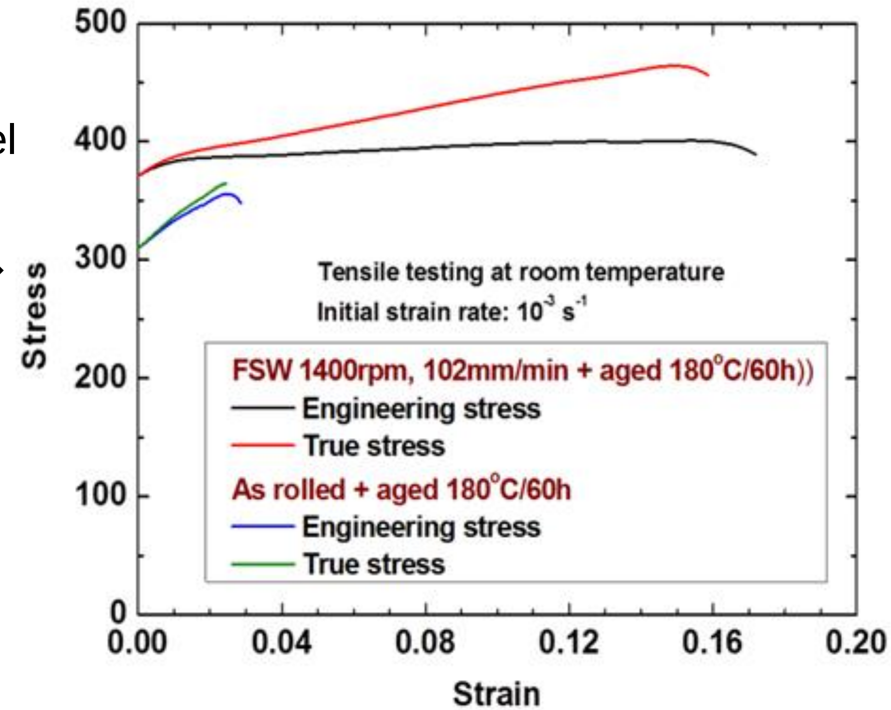
Center for Friction Stir Processing

Seed results: High performance Mg-Y-Nd alloy built by FSAM







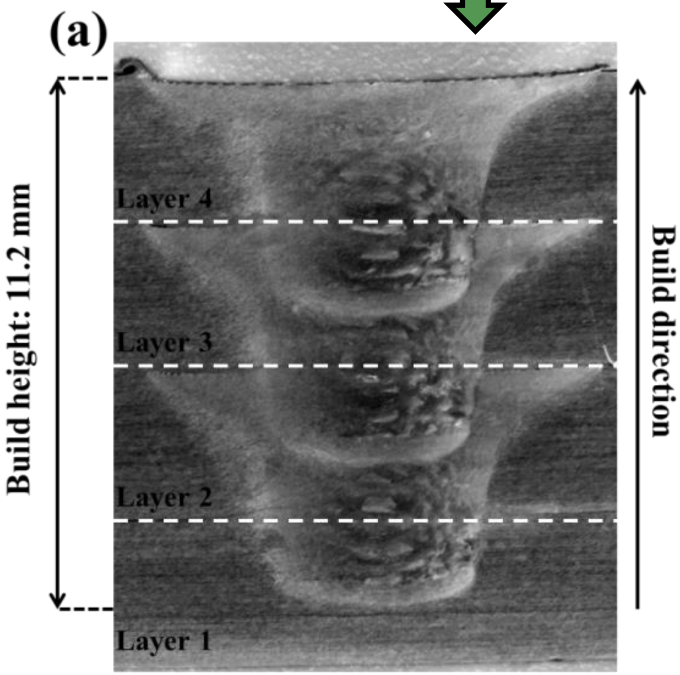


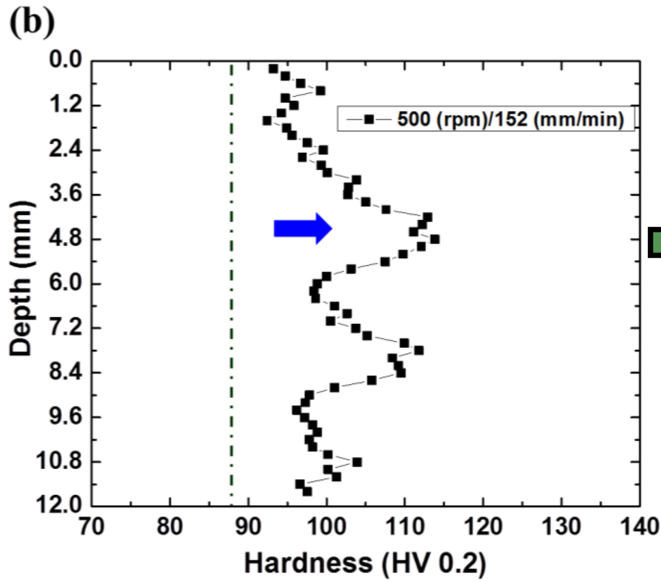
- Higher strength and ductility
- Fine (2-7 nm) and uniform distribution of strengthening precipitates lead to high strength in FSAM + aged specimen
- ***Properties achieved are much higher than the starting material (T5)***

Center for Friction Stir Processing

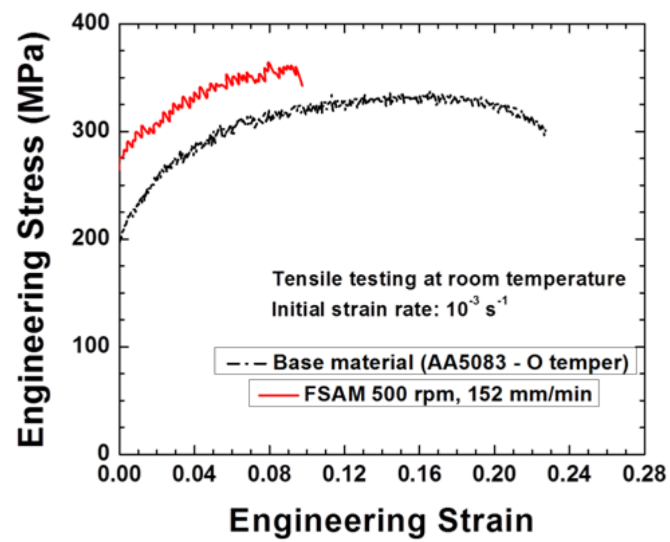
Seed results: High performance AA 5083 alloy built by FSAM

Fully consolidated build fabricated at rotation and tool speed of 500 rpm and 152mm/min





In comparison to base material, hardness in build is higher by 18%



Tested parallel to build direction

Condition	Yield Strength (MPa)	Tensile strength (MPa)	% E
Base Material	190	336	22.5
FSAM build	267	362	10

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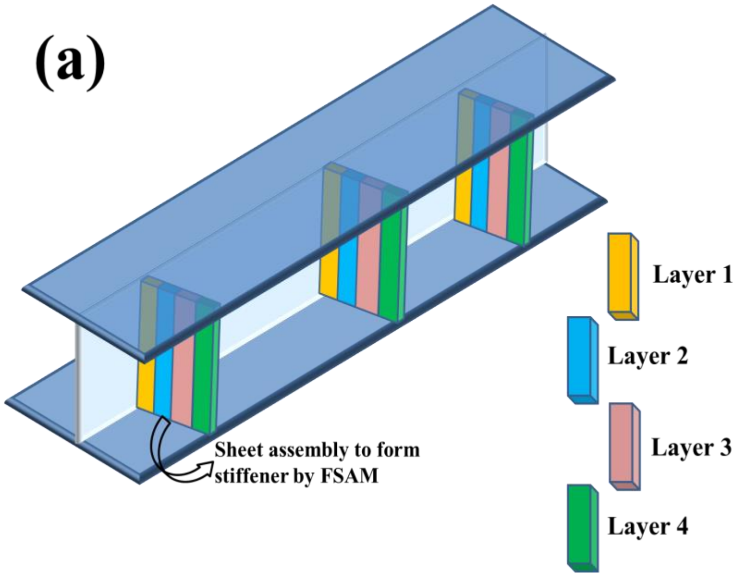
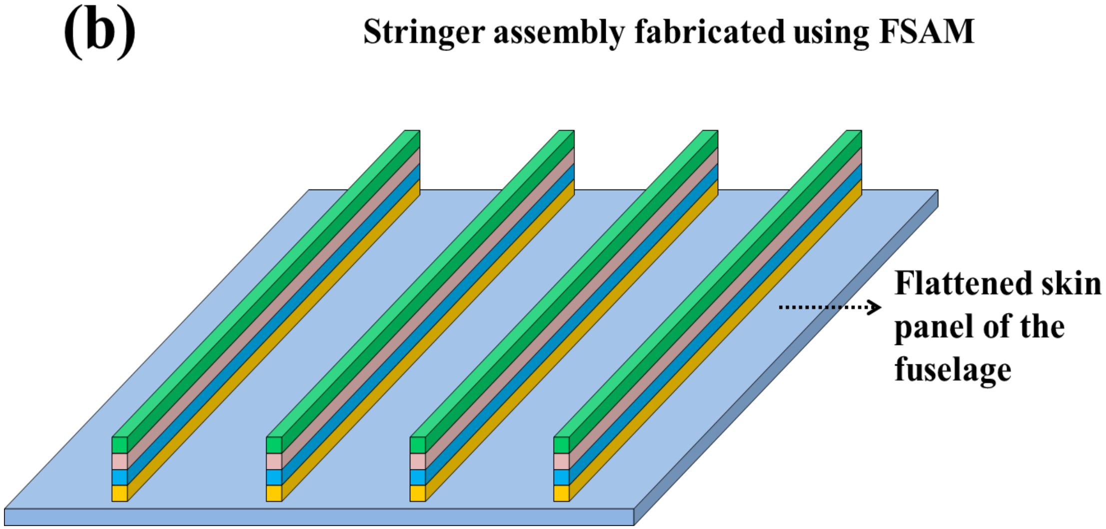
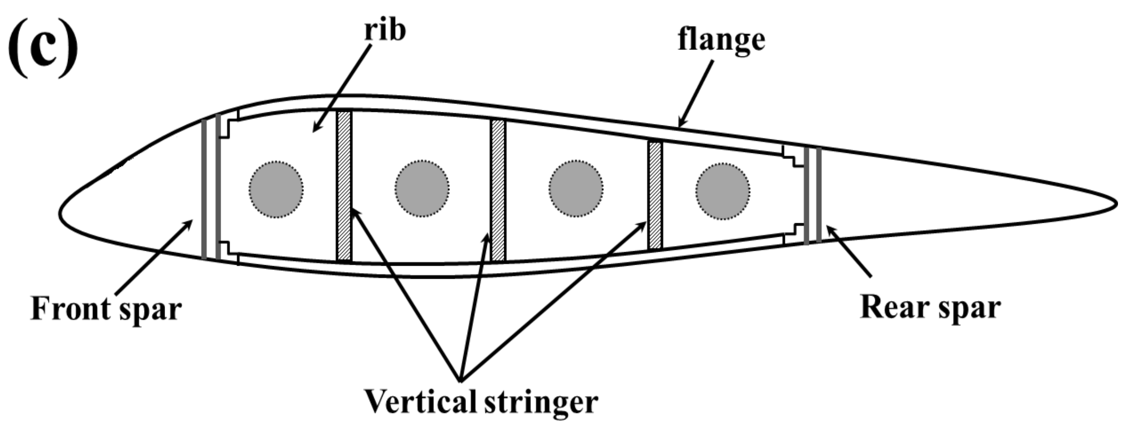
S. Palanivel, H. Sidhar, R. S. Mishra, JOM 67 (3) (2015), 616-621.

Potential application I: strong stiffener/stringer configurations for aerospace by FSAM







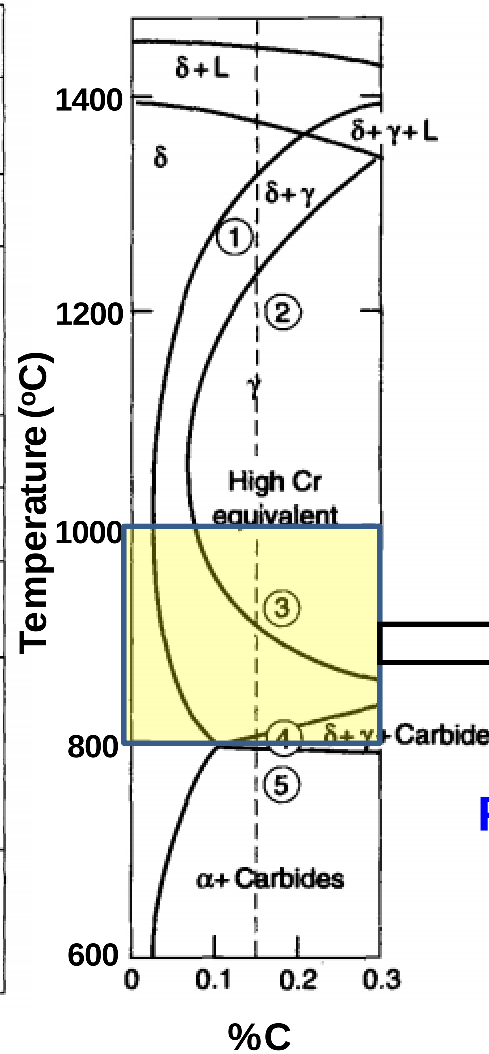
- FSAM can also be extended for designing and manufacturing longerons in skin panels

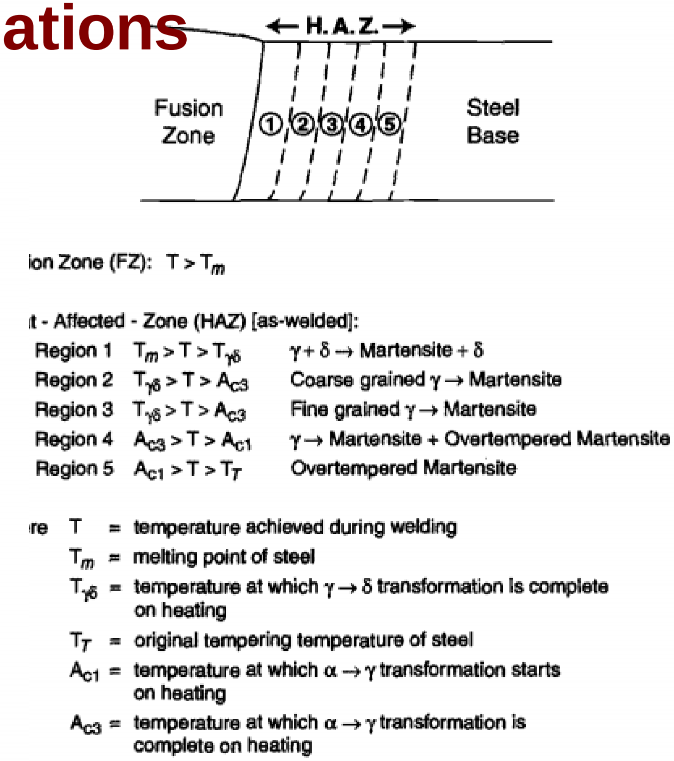
S. Palanivel, H. Sidhar, R. S. Mishra, JOM 67 (3) (2015), 616-621.

Drive behind FSAM for energy — physical metallurgy of ferritic-martensitic steels used in fossil & nuclear applications

Precipitate phases and their distribution in ferritic-martensitic steels

Precipitate Phase	Crystal Structure and Lattice Parameter	Typical Composition	Distribution of Precipitates
$M_{23}C_6$	fcc a = 1.066 nm	$(Cr_{16}Fe_6Mo)C_6$ $(Cr_4Fe_{12}Mo_4Si_2WV)C_6$	Coarse particles at prior austenite grain and martensite lath boundaries and fine intra-lath particles
MX	f.c.c. a = 0.444-0.447 nm	NbC, NbN, VN, (CrV)N, Nb(CN) and (NbV)C	Undissolved particles and fine precipitates at martensite lath boundaries
M_2X	Hexagonal a = 0.478 nm c = 0.444 nm	Cr_2N, Mo_2C and W_2C	Martensite lath boundaries (Cr_2N and Mo_2C); prior austenite grain boundaries (Mo_2C); intra-lath (Mo_2C and W_2C); δ-ferrite in duplex steels [$Cr_2(CN)$ and $(CrMo)_2(CN)$]
Z-phase	Tetragonal a = 0.286 nm c = 0.739 nm	(CrVNb)N	Large plate-like particles in the matrix after creep straining at 600°C
η-carbide	Diamond cubic a = 1.07-1.22 nm	M_6C $(Fe_{39}Cr_6Mo_4Si_{10})C$	Prior austenite grain and martensite lath boundaries and intra-lath
Vanadium carbide	f.c.c. a = 0.420 nm	V_4C_3	Low number density in matrix
Laves	Hexagonal a = 0.4744 nm c = 0.7725 nm	Fe_2Mo Fe_2W and $Fe_2(MoW)$	Prior austenite grain and martensite lath boundaries and intra-lath; δ-ferrite in duplex steels
Chi (χ)	b.c.c. a = 0.892 nm.	$M_{18}C$ or $Fe_{35}Cr_{12}Mo_{10}C$	Intra-martensite lath; δ-ferrite in duplex steels





FSAM range

↓

No δ phase, Finer prior austenite grain size

↓

Better mechanical properties??

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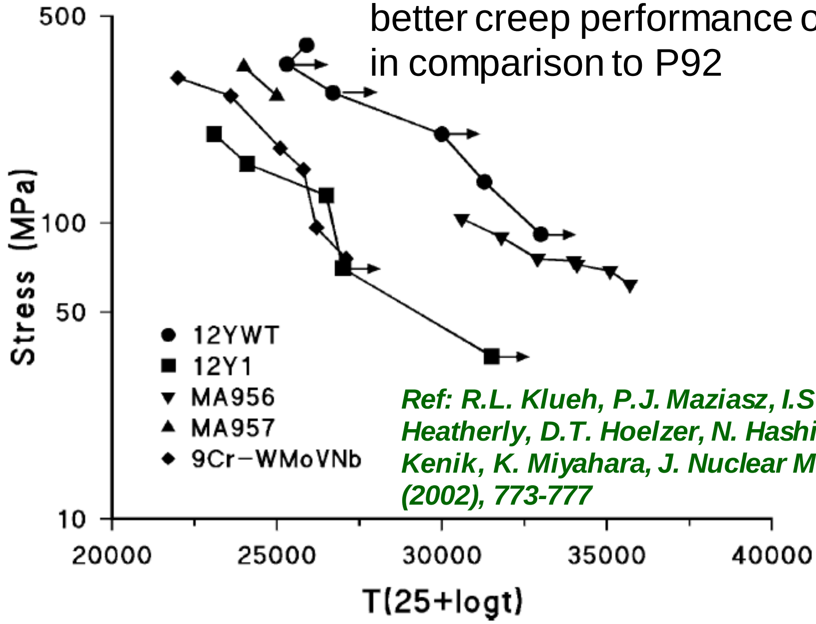
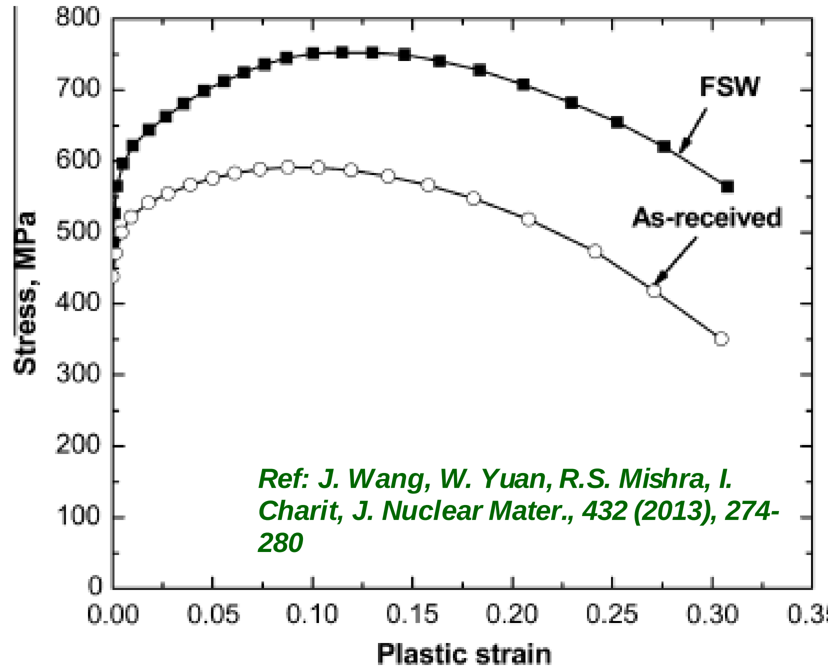
Drive behind FSAM for energy

Larson–Miller diagram showing better creep performance of MA956 in comparison to P92



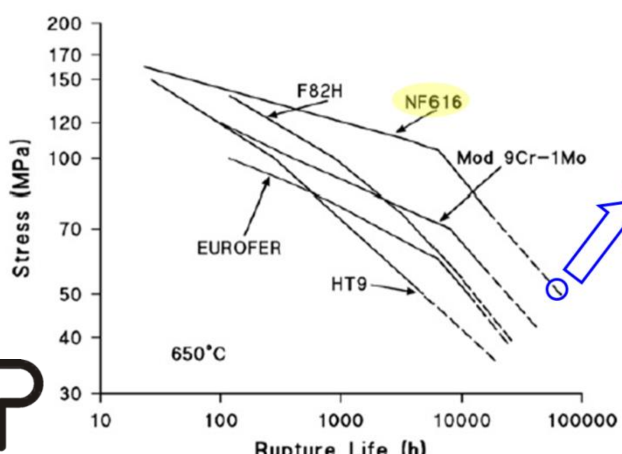
Ref: R.L. Klueh, P.J. Maziasz, I.S. Kim, L. Heatherly, D.T. Hoelzer, N. Hashimoto, E.A. Kenik, K. Miyahara, J. Nuclear Mater., 307 (2002), 773-777



Ref: J. Wang, W. Yuan, R.S. Mishra, I. Charit, J. Nuclear Mater., 432 (2013), 274-280

- ***Grain refinement & higher dislocation density after friction stir welding resulted in higher RT strength***

Condition	As-received	FSW
YS (MPa)	493 ± 17	574 ± 17
UTS (MPa)	591 ± 4	736 ± 14
UE (%)	8.1 ± 1.2	11.2 ± 1.1
E (%)	28.5 ± 1.9	30.7 ± 1.3



Increase creep strength (?) and rupture life by adding MA956 stringers to P92 steels using FSAM

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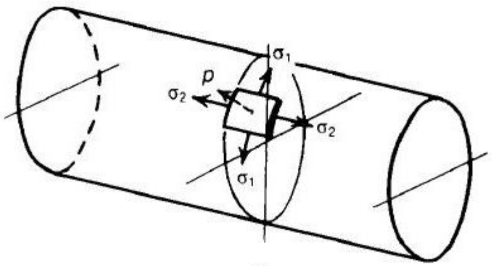
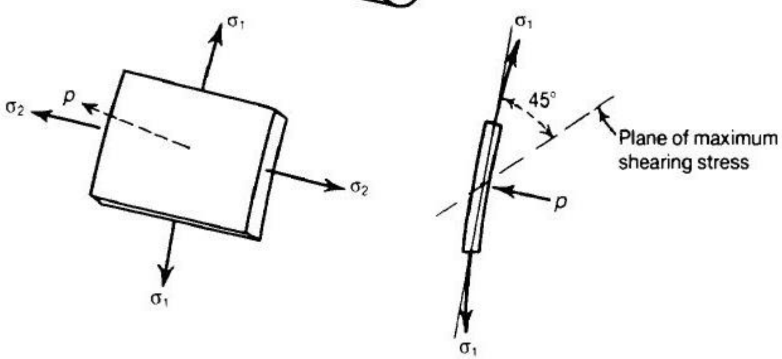
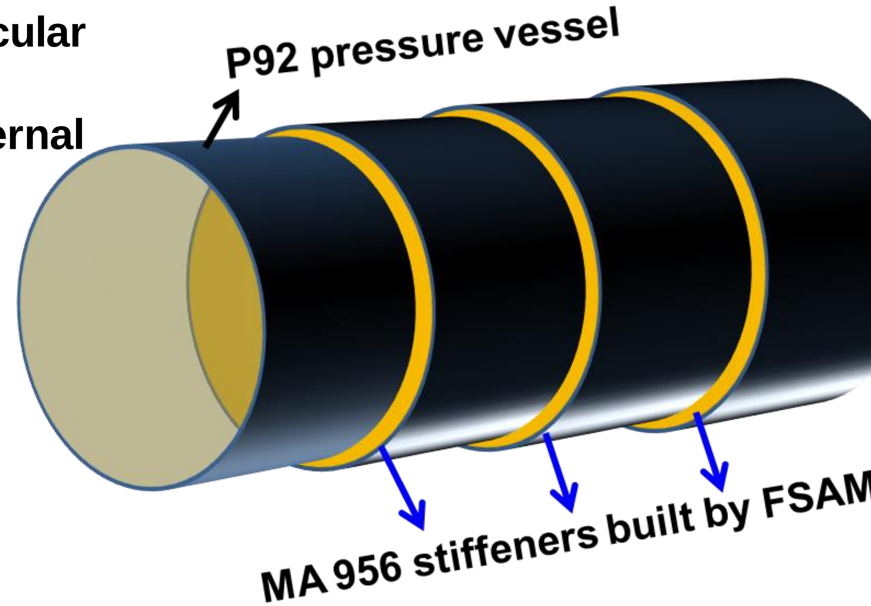
Potential application II: Architecting creep resistant structures by FSAM for fossil & nuclear sectors



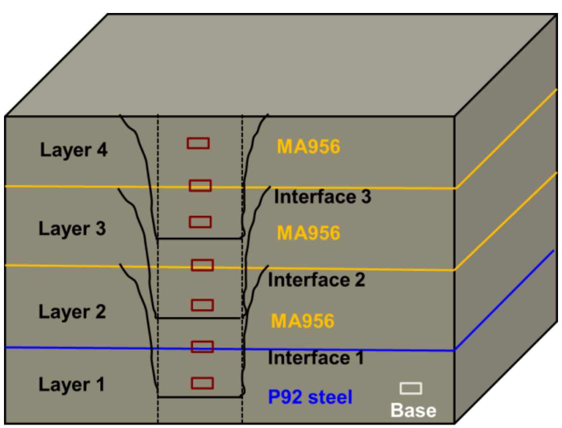


Stresses acting on circular cylindrical shell with closed ends under internal pressure



Schematic of MA956 stiffener rings on P92 steel for enhanced creep resistance

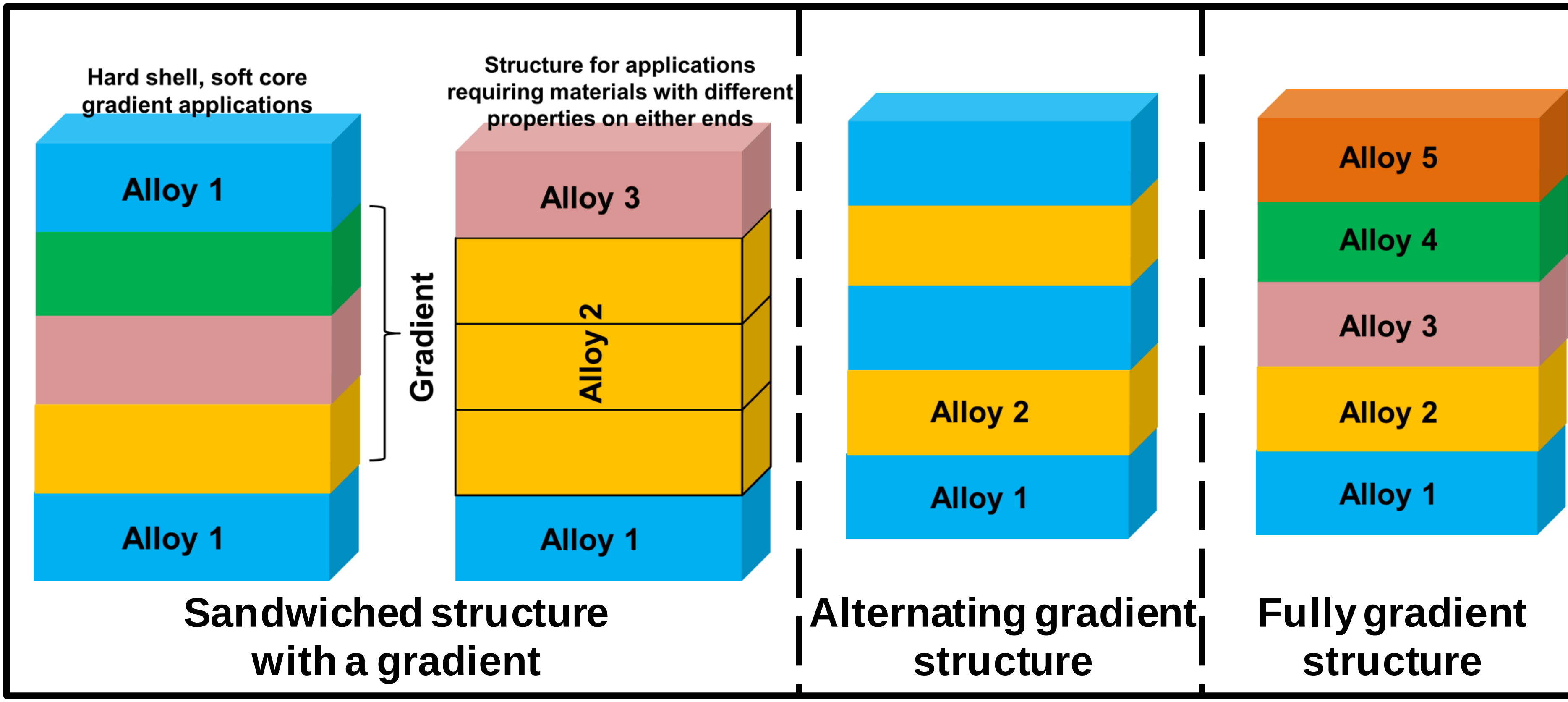
Schematic cross-sectional view of stiffened MA956 assembly over P92



- Addition of partial or full ring stiffeners for pressure vessels to increase their lifetime
- Selection & design of the stiffening material needs to be in such a way that creep and internal stresses are accommodated by the built stiffener

Potential application III: Functional & gradient materials by FSAM for other applications

Conceptual schematic showing few possible configurations

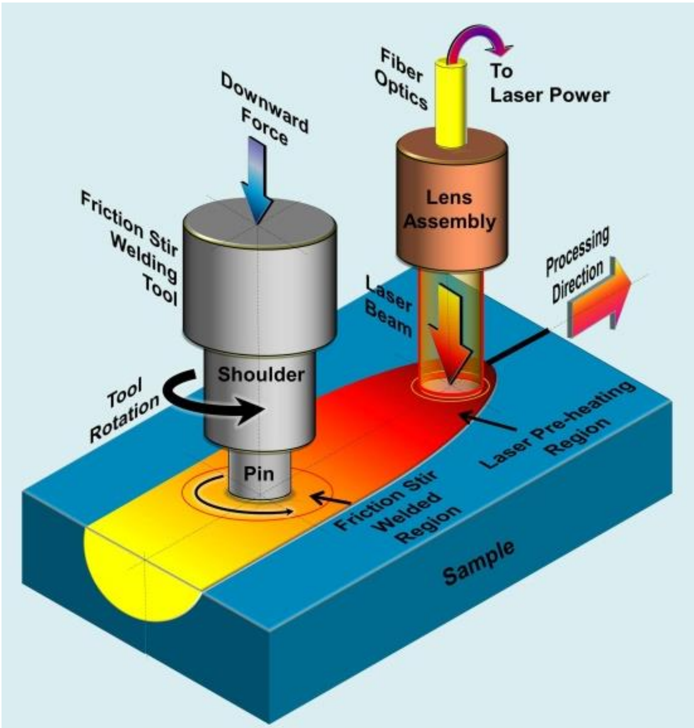


- FSAM of composite materials

FSAM is a potential route to customize build performance by controlling microstructure

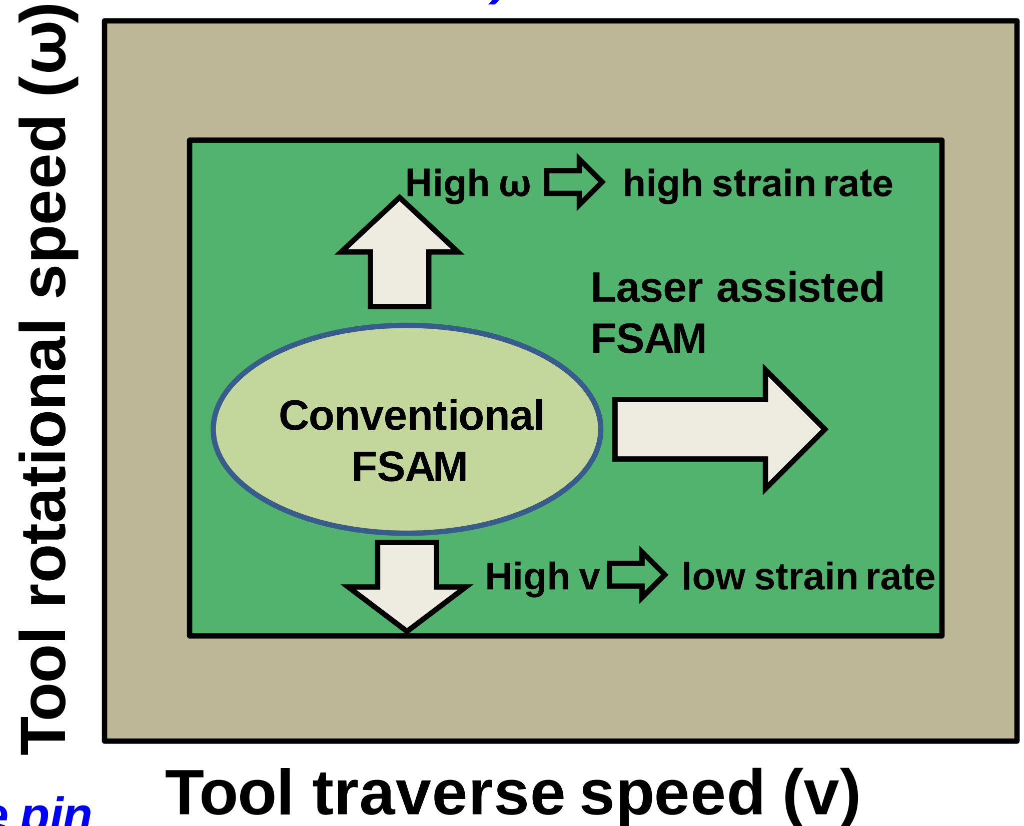
Laser assisted FSAM for reduction of forces and greater processing window

Pre-FSAM thermal treatment

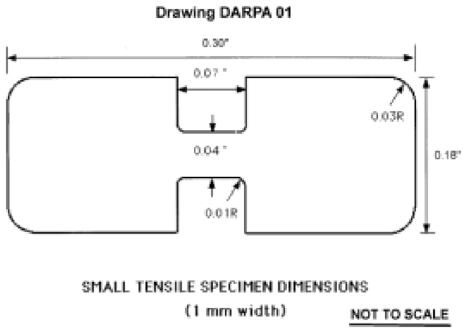


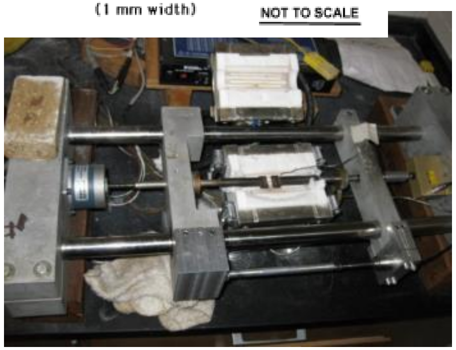
Preheating by laser source leads to softening of the material ahead of the pin and reduction of tool forces

Expansion of processing window by decoupling heat (greater control on microstructure)

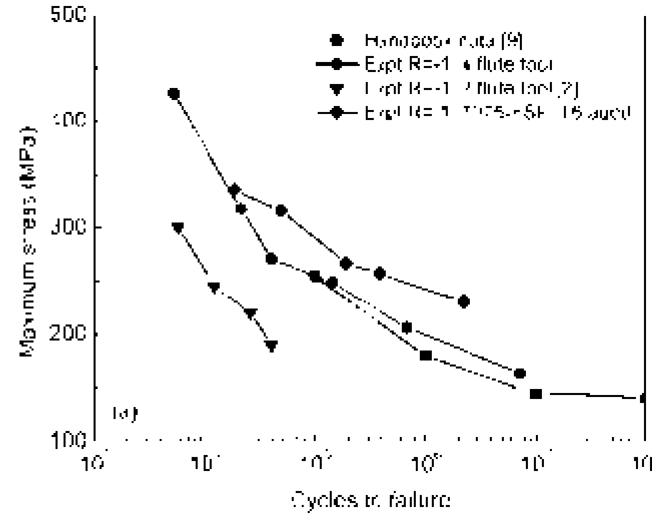


Mini testing capabilities to support FASM

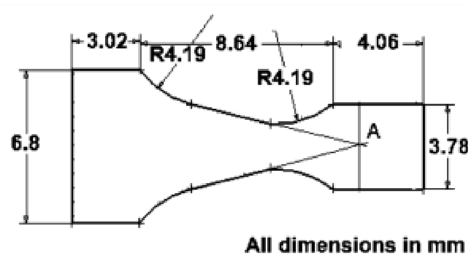


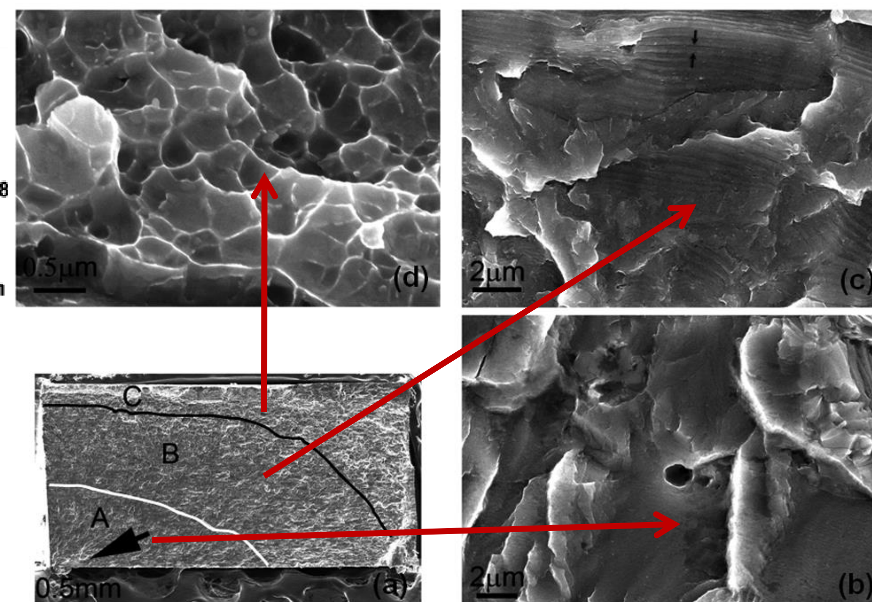


Mini-fatigue of 7075-T6



Mini-Fatigue





- ***Can FSAM be an effective technique for production of high performance components?***
  - ***It certainly appears promising for simpler geometries***
  - ***Looking for collaborative opportunities to explore more material/design combinations***

Thank you

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