AMM Newsletter

Advanced Methods for Manufacturing

Issue 1 • March 2015

Welcome to the Advanced Methods for Manufacturing Newsletter

Alison Hahn
U.S. Department
of Energy

Welcome to the first edition of the Nuclear Energy Enabling Technologies Crosscutting Technologies Development (NEET CTD) Advanced Methods for Manufacturing (AMM) newsletter. Contained within are the details of five selected projects pertaining to additive manufacturing, concrete technologies, and welding innovations. This newsletter will be issued semi-annually to provide information on various AMM projects currently funded by the Department of Energy's (DOE) Office of Nuclear Energy (NE) for industry to keep abreast of the manufacturing innovations being developed.

Created in FY 2012, the vision of the AMM program is to improve the manufacturing, fabrication, and assembly methods for nuclear equipment, components, and plants by utilizing practices found in industries such as oil, aircraft, and shipbuilding. The technologies and techniques researched are independent of reactor type and broadly applicable to industry. The specific goals of the program are to:

- Reduce cost and schedule for new nuclear construction by making fabrication and manufacture of nuclear plant structures and components faster and cheaper, with equal or better reliability and;
- Restore the U.S. position as a manufacturer and constructor of nuclear power plant designs, both domestically and worldwide.

The program seeks to develop manufacturing and fabrication innovation, assembly processes, and materials innovation that support the "factory fabrication" and expeditious deployment of new reactor builds through the annual Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA). These multi-year, competitively awarded projects are open to industry, universities, and national laboratories. For more information on this solicitation, please visit www.NEUP.gov. In addition, the Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) programs target the small business community for manufacturing RD&D. For more information on the SBIR/STTR opportunities, please visit www.science.energy.gov/sbir.

Each year, AMM holds a program review meeting with all of the DOE-NE AMM awarded projects and manufacturing representatives to receive feedback. The location of the meeting rotates annually to provide the opportunity for the PI to give a tour of their facility and/or their current AMM and NE relevant research. The FY 2014 AMM program review meeting was held on October 21, 2014 at the Electric Power Research Institute facilities in Charlotte, NC. This year's meeting has been tentatively scheduled for September at the Lockheed Martin facilities in Crystal City, Va. More information on the meeting will be sent out once the meeting details have been finalized.

Any feedback you have on the newsletter or the AMM program itself is appreciated and can be directed to me via e-mail at Alison.Hahn@nuclear.energy.gov.

In This Issue

For more program information, including recent publications, please visit www.nuclear.gov

Innovative Manufacturing Process for Nuclear Power Plant Components via Powder Metallurgy–HIP

David Gandy
Electric Power Research Institute

For more than 60 years, the nuclear power industry has relied on structural and pressure-retaining materials produced via established manufacturing practices such as casting, plate rolling-and-welding, forging, drawing, and/or extrusion. Under Department of Energy (DOE) sponsorship, Electric Power Research Institute (EPRI), Carpenter Technology, GE-Hitachi, and Rolls Royce have been leading the development and introduction of another process, powder metallurgy and hot isostatic pressing (PM-HIP), for reactor pressure internal and external applications. The RD&D project has been focused on the manufacture and assessment of large, near-net shaped (NNS) components from three alloy families: low alloy steel, stainless steels, and nickel-based alloys. This research will have a tremendous impact as we move forward over the next few decades on the selection of new alloys and components for advanced light water reactors and small modular reactors. Furthermore, fabrication of high alloy materials/components may require the use of new manufacturing processes to achieve acceptable properties for higher temperature applications such as those in Generation IV applications.

Generation IV reactor applications

Powder metallurgy technology integrated with advanced alloy modeling/design capabilities, and state-of-the-art HIP technology, can have a significant impact on the energy industry's goals of lower manufacturing costs and energy consumption. HIP/PM can shorten production schedules by up to 6 months, lower installation and operating costs, increase energy efficiency, and reduce emissions. Specific benefits of manufacturing NNS components via PM/HIP include precise chemistry control for stainless steel or nickel/cobalt alloys, increased material utilization (resulting in reduced machining), material cost reduction, elimination of welding repairs, and a significant improvement in inspectability of components.

Current Status

PM-HIP is a forming and fabrication technique that consists of multiple stages: (1) component design, (2) manufacturing of a metallic powder normally by gas atomization, (3) loading of the powder into a can or container that mirrors the configuration of the final component, (4) degassing and sealing the can with the contained powder, and (5) consolidation by applying high temperature and pressure (>1040C and ~100MPa). HIP is a solid-state diffusion process that produces fully dense microstructures with no porosity.

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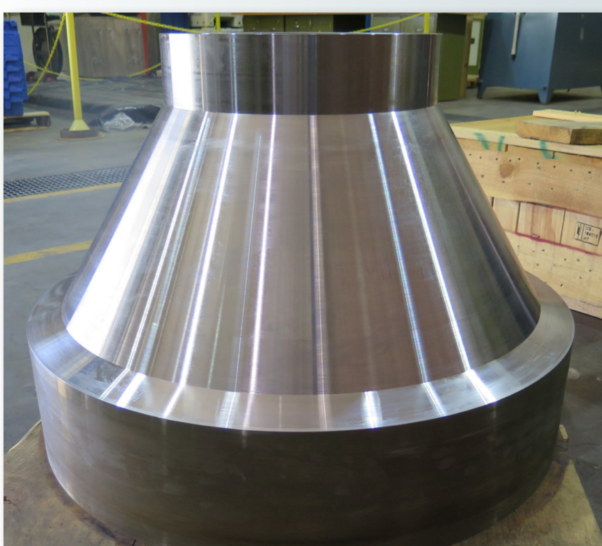

Figure 1: BWR Feedwater Nozzle

Figure 2: ALWR steam separator inlet swirler.

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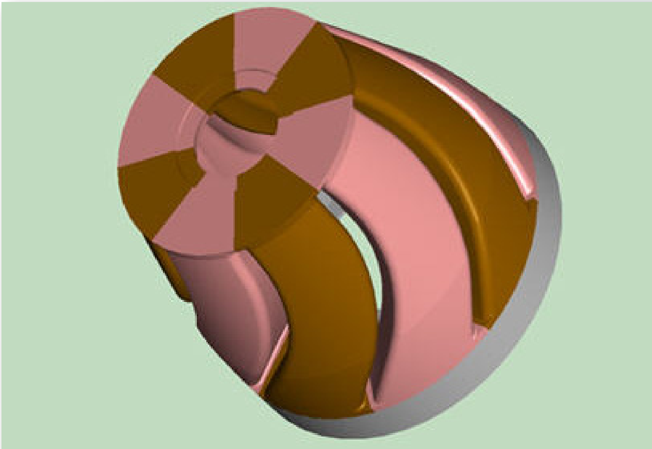

Figure 3. ALWR steam separator inlet swirler model.

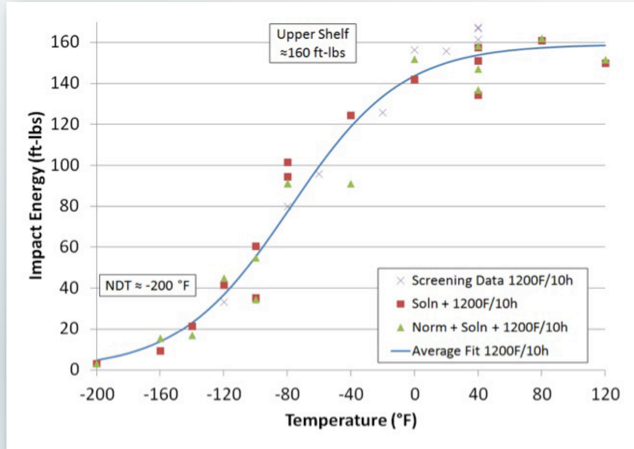

Figure 4. Charpy impact toughness results recorded for the SA508, Class 1, Grade 3 low hardenability test heat (Carbon equ.= 0.55).

During the first 2 years of this project, multiple test blocks and two full-sized NNS components have been manufactured.

Figure 1 shows a 16-inch (406 mm) diameter low alloy steel feedwater nozzle for a boiling water reactor (BWR). The 3700-lb (1678 kg) nozzle was produced to meet a chemistry consistent with SA508, Class 1, Grade 3 low alloy steel, while the inlet swirler was produced to a 316L stainless steel chemistry. Figure 2 shows an austenitic stainless steel advanced light water reactor (ALWR) steam separator inlet swirler that has been developed to produce the 316L stainless steel steam separator inlet swirler for an ALWR.

The process begins with a model of the swirler shown in Figure 3 and then manufacture of individual inserts that are used to produce the "can."

Excellent material properties have been achieved with both alloys consistent with those of wrought or forged products used today in nuclear applications, as can be seen in Figure 4 and Table 1.

Conclusion

In 2015, additional research, development, and demonstration is planned to produce an ALWR chimney head bolt from 600M (a corrosion resistant nickel-based alloy) and a partial ring section made from a low alloy steel, which is similar to what would be used in a reactor pressure vessel applications today. The results of this research will be used to support continuing American Society for Mechanical Engineers (ASME) Code efforts to introduce PM-HIP as another manufacturing process for nuclear components.

Coupon Number	Tensile Strength ksi (MPa)	Yield Strenght ksi (MPa)	Elongation in 4D (%)	Reducation of Area (%)
RTT1	88.2 (608)	49.9 (344)	50.5	73.5
RTT2	88.3 (609)	48.2 (332)	50.0	75.0
RTT2	88.2 (608)	51.3 (353)	50.5	71.5

Table 1. Room temperature tensile results for a 316L SS test block.

Laser Direct Manufacturing of Nuclear Power Components

Scott Anderson
Lockheed Martin Space Systems Company – Advanced Technology Center
Palo Alto, California

This three year project will extend expertise in Laser Direct Manufacturing (LDM) towards manufacturing nuclear reactor components. The LDM method will demonstrate accelerated schedule for deployment and reduction in manufacturing costs while incorporating improved resistance to nuclear radiation over standard, state of the art components. Lockheed Martin (LM) has been a leader since the 1990s in the development and implementation of LDM processes. Using an adaptation of Direct Manufacturing, the company is currently fielding pilot implementation articles on the well-known F-35 Fifth Generation Jet Fighter and the next generation human space vehicle, the Orion Multi-Purpose Crew Vehicle. Quad City Manufacturing Lab (QCML) is supporting LM with LDM fabrication of samples and demonstration components.

Current Status

The Direct Metal Laser Sintering (DMLS) used for fabricating parts on this project is a powder bed method using a stationary bed of powdered metal as the base for the layered build. The heat source and laser spot rapidly 'draws' the image of the layer section in the powder bed, fusing the material into a solid structure. The bed is indexed a small distance, and a blade scrapes a new layer of powder over the surface. The build continues with another melting and fusing of powder into a shaped structure (Figure 1). Powder bed methods have advantages in building shapes with trapped volumes but have disadvantages of size

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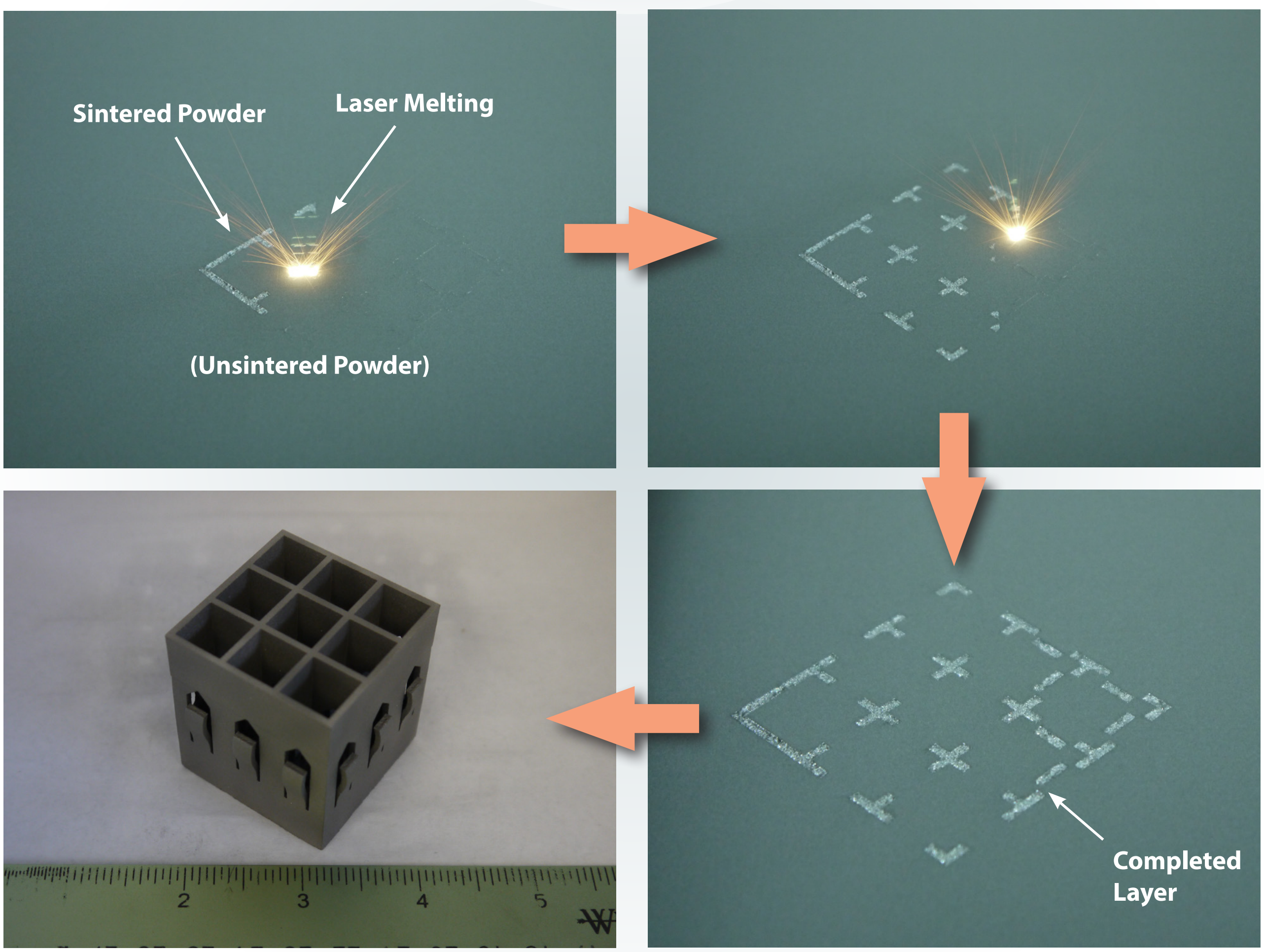

Figure 1. The sequence of steps in the layered build of a 316SSL demonstration article using DMLS

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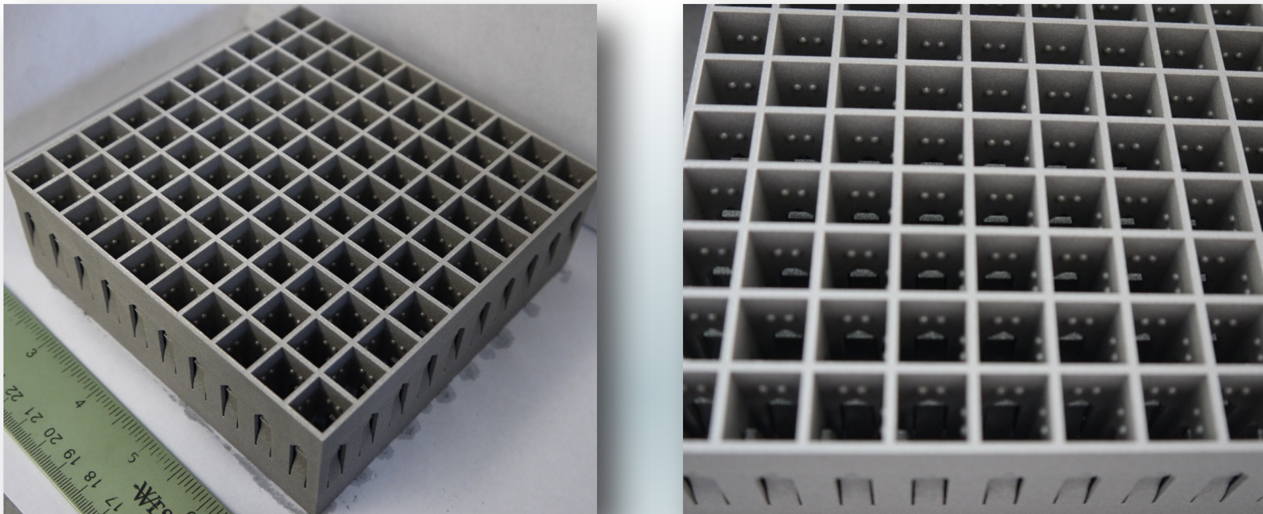

Figure 2. Inconel 600 10x10 fuel rod spacer grids fabricated using DMLS demonstrating the structural detail that can be achieved

limitations for the powder bed. Structures built with powder bed methods are typically Hot Isostatic Pressed (HIP) to reduce probability of void presence. QCML has two types of purpose built commercial LDM systems: nozzle powder delivered method and powder bed method. In the nozzle powder delivered method, a multi-axis position head delivers the metal powder and houses the laser. To reduce material costs during the development phase, oxide dispersion strenghened steel demonstration parts are to be fabricated with the nozzle powder delivered method as this needs less powder for process trails and fabrication. Based on a literature review of nuclear alloy materials, the capabilities of the powder bed direct manufacturing techniques and the availability of advanced alloy compositions as metal powders, two materials families - Stainless Steel and Inconel - were selected for further development with the DMLS technique. Most of these alloys are addressed for nuclear construction in the ASME Boiler and Pressure Vessel Code.

A series of experiments varying build process parameters (scan speed and laser power) was conducted at the outset to establish the optimal build conditions for each of the Inconel alloys. The density of all sample specimens was measured and compared to literature values. Optimal build process conditions giving fabricated part densities close to literature values were chosen for making mechanical test coupons. Test coupons whose principal axis is on the x-y plane (perpendicular to build direction) and on the z plane (parallel to build direction) are being built and tested as part of the experimental build matrix to understand the impact of the anisotropic nature of the DMLS process. Mechanical characterization samples have been fabricated and are in the process of being tested.

Build process conditions affect formation of the weld melt puddle and the subsequent rapid quenching. Figure 3 is a micrograph of the quenched melt puddle in an Inconel 600 additively manufactured sample. Here, the build direction is along the Z axis.

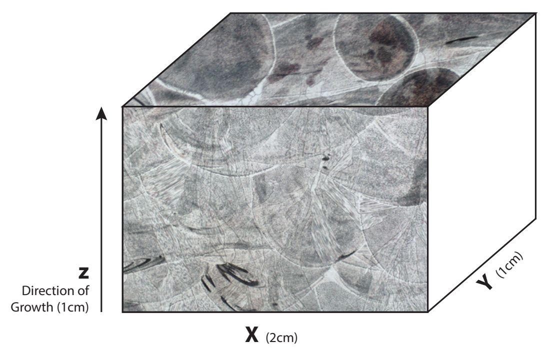

Figure 3: Micrographs in the x-z and x-y planes for the quench melt puddle in an Inconel 600 sample.

The rapid quenching of the weld melt puddle results in much smaller grain sizes for parts fabricated with additive manufacturing techniques. Figures 4a and 4b are scanning electron micrographs showing the difference in microstructure/grain size between Inconel 600 bar stock sample and an additively manufactured Inconel 600 specimen, respectively. The additively manufactured samples can be further heat treated for microstructural control.

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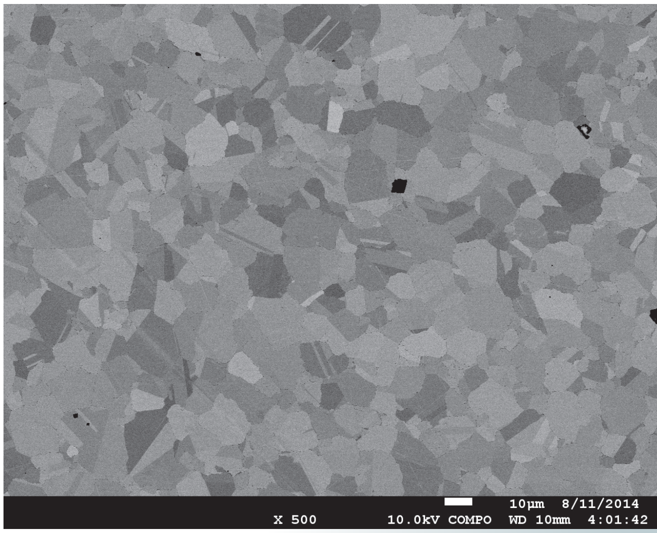

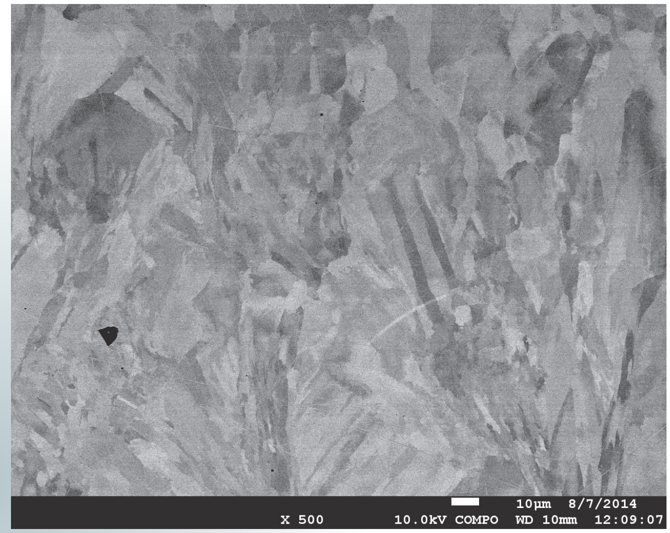

Figure 4: Micrographs showing microstructure/grain size between Inconel bar stock (left) and additively manufactured sample (right).

For most materials, the microstructure is dependent on alloy composition and thermal history. The microstructure in turn determines the mechanical properties. As discussed in the previous paragraph, additive manufacturing offers more flexibility in optimizing process conditions and alloy microstructure leading to better control of mechanical properties.

Improved performance through increased strength at high temperatures, increased hardness and improved tolerance to radiation has been demonstrated with advanced alloys that include nanometer scale phases of carbides, nitrides and oxides. Alloy development of specialized formulations that incorporate nanometer domains of oxides, carbides and nitrides is one of the attractive benefits of DM methods due to the rapid quenching effects as the point heat source moves from the melt puddle area. The quenching prevents migration and agglomeration of domains and traps them as discrete precipitates.

In Oxide-Dispersion Strengthened (ODS) steels, Y_2O_3 particles are mechanically milled with ferritic alloy giving a fine dispersion of Y_2O_3 nanoclusters that are stable to high operating temperatures. In this project, oxide dispersion strengthened (ODS) steel powders made by mixing of 316SS powders with Y_2O_3 particles shall be used to fabricate additively manufactured samples and the effect of direct manufacturing methods on nanoscale oxide domains shall be examined. This mixing process of the components gives particles sizes that are good for use with nozzle powder delivered method. Joining to ODS materials is considered to be difficult as the welding process could locally change the nanoscale oxide clusters. Direct manufacturing methods allow unitization of multiple pieces into larger components, saving assembly and inspection costs.

Conclusion

For the nuclear industry, laser direct manufacturing promises faster build schedules, reduced costs and a whole new process regime for the development of new alloys for use in the extreme environments seen within a nuclear reactor. Novel and challenging parts for improved performance can best be tested quickly and with high fidelity. Digital design optimization can be combined with simulation to dramatically improve new reactor designs, fluid flow performance and overall reactor safety. Additive manufacturing is changing the way all industries view manufacturing and the nuclear industry is poised to reap the benefits.

Development of Seismic Isolation Systems Using Periodic Materials

Y.L. Mo
University of Houston

This research seeks to develop seismic isolation systems for nuclear power plants using periodic material. The concept of periodic material or phononic crystal in solid-state physics has been known since the early 20th century. The distinct feature of this material is that it cannot pass elastic waves under certain frequency ranges. Inspired by the unique behavior of phononic crystal, the periodic material is proposed to be used as a foundation to protect the superstructure from incoming seismic waves. The focus is on the development of a concept that utilizes periodic material to completely obstruct or change the pattern of the earthquake event energy before it reaches the structural systems of nuclear power plants. The goals are to experimentally verify the principle of periodic material and to demonstrate the application of one dimensional (1D), two dimensional (2D), and three dimensional (3D) periodic foundations for seismic isolation of nuclear power plants. The experimental results show that the periodic foundation is a promising and effective way to mitigate structural damage caused by earthquake excitation.

Outcomes

The project has developed different types of 1D, 2D and 3D periodic foundations. These foundations have been experimentally proven to block or reflect the input seismic motion when the wave frequencies fall within the frequency band gaps.

Results and Highlights

Periodic foundations are classified as one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D), depending on the direction of the unit cell periodicity.

An experimental study was conducted to investigate the feasibility of a 1D periodic foundation. A small-scale model frame on a periodic foundation was designed, fabricated, and tested using a shake table facility. As shown in Figure 1, specimen A is a steel frame fixed on the shake table. Specimen B is a steel frame of the same design as specimen A but is fixed on a 1D periodic foundation.

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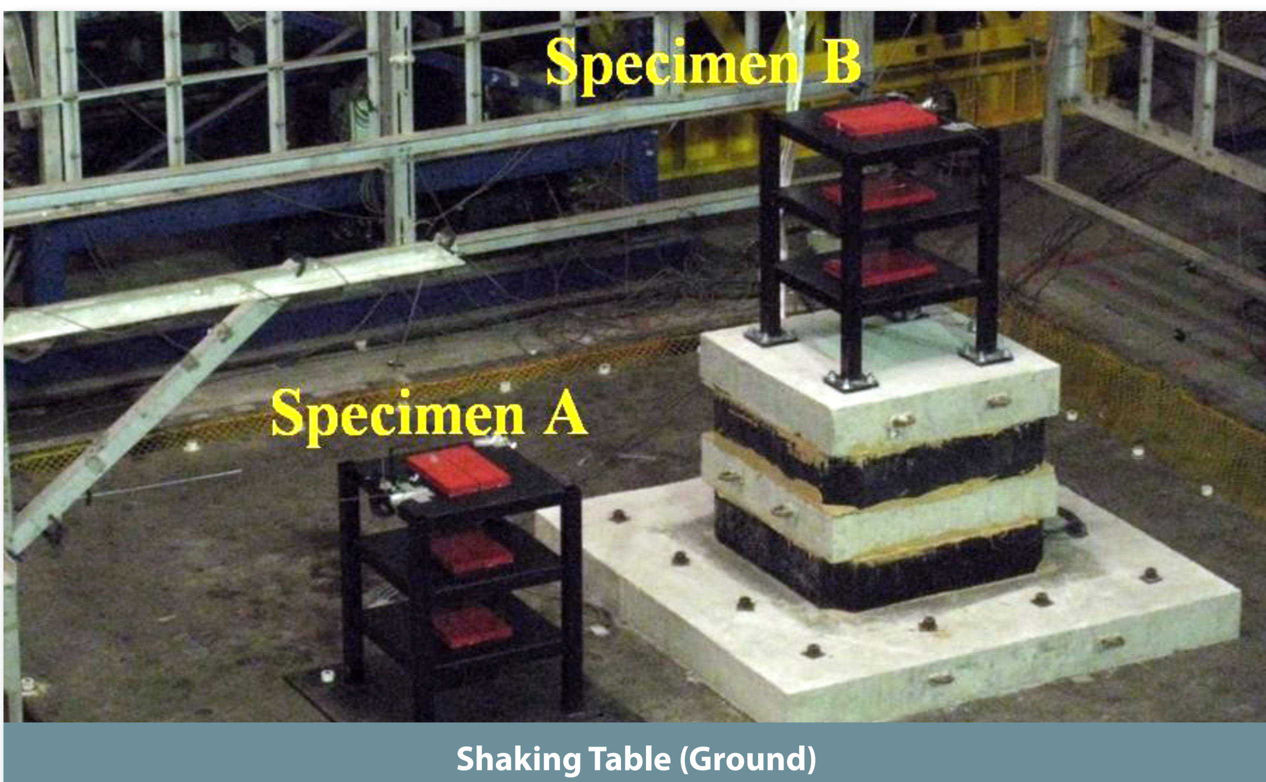

Figure 1: Test setup of 1D periodic foundation

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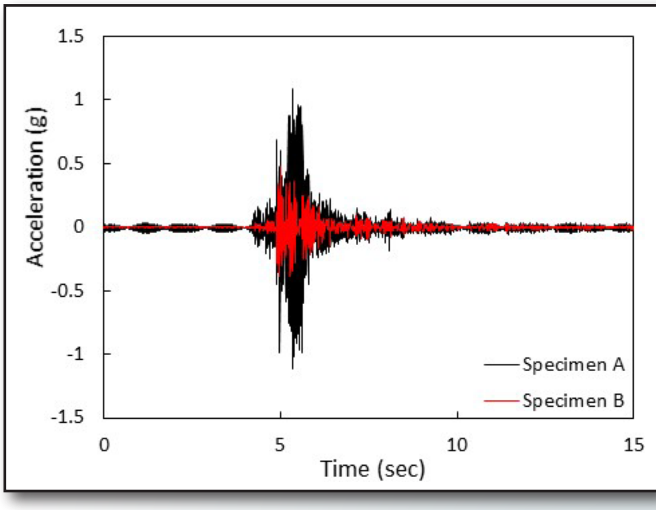

Figure 2: Test results of 1D periodic foundation

Figure 3: Test setup of 2D periodic foundation

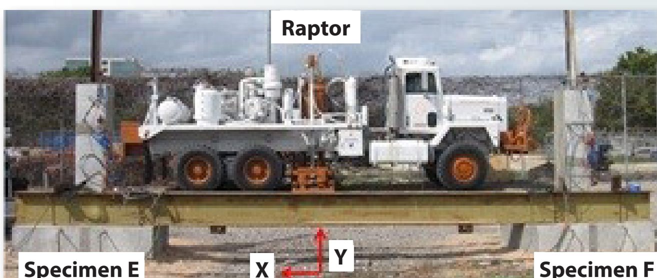

Figure 4: Test setup of 3D periodic foundation

Figure 2 shows that the peak acceleration at the top of specimen B (with 1D periodic foundation) was reduced by 56 % as compared to the peak acceleration at the top of specimen A (without periodic foundation).

Shaker trucks were utilized to generate seismic waves to both the 2D and 3D periodic foundation test specimens for the field tests, as shown in Figure 3 and Figure 4, respectively.

Figure 5 shows that under the same seismic input waves, the peak acceleration on the top of specimen D (with 2D periodic foundation) was reduced by 52 % as compared to the peak acceleration at the top of specimen C (without

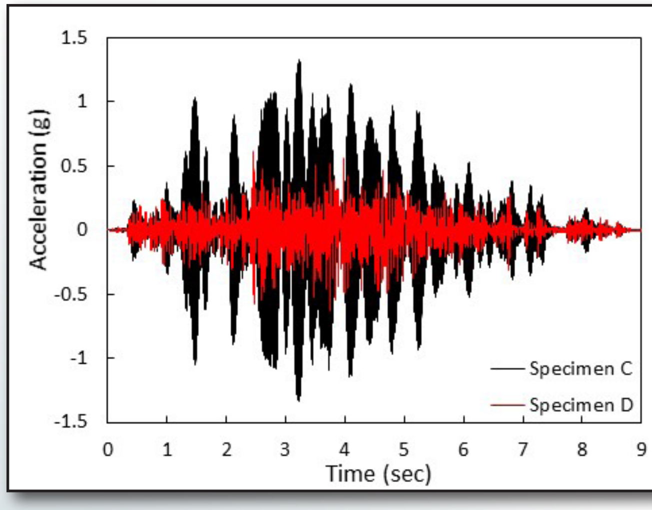

Figure 5: Test results of 2D periodic foundation

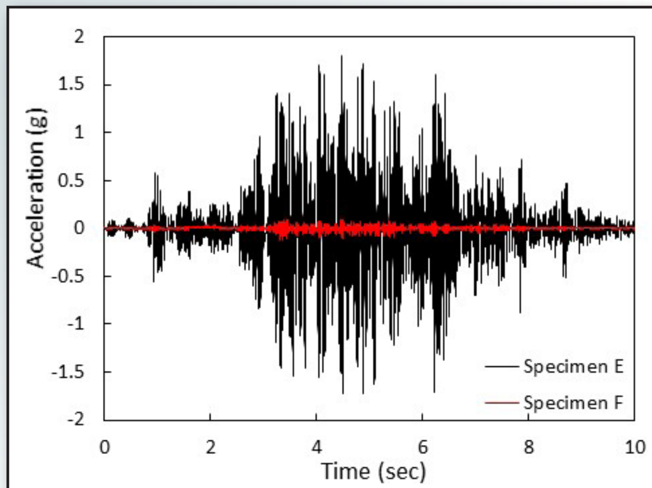

Figure 6: Test results of 3D periodic foundation

periodic foundation). While Figure 6 shows that the peak acceleration on the top of specimen F (with 3D periodic foundation) was reduced by 92 % as compared to the peak acceleration at the top of specimen E (without periodic foundation).

Impact and value to nuclear applications

The value of the developed periodic material for nuclear power plant applications is that it can potentially be made into seismic base isolators for nuclear power plants. With proper design, the periodic foundation will block seismic waves before the seismic waves can reach the superstructure. In addition, since the superstructure is firmly attached to the periodic foundation, horizontal displacement will be limited. The advantages are beneficial to not only the structural but also nonstructural components in nuclear power plants.

Modular Connection Technologies for SC Walls of SMRs

Dr. Amit Varma
Purdue University

Steel-plate composite (SC) structures (as illustrated in Figure 1) have been used to expedite construction of the third generation of nuclear power plants. SC walls are efficient for fabrication, erection, and construction of nuclear power plants, as evidenced by the construction progress of the AP1000® plants in the US and China. Therefore, they are being considered seriously as a candidate for optimizing and facilitating the next generation of Small Modular Reactors (SMRs).

The challenge for SC walls is that there is no governing or applicable design code or standard in the US that can be used for their design, inspection, and review. The current ACI 349 code applies only to conventional reinforced concrete (RC) walls and cannot be easily extended to SC walls. This has been a significant challenge for the NRC reviewers and extended the licensing schedule for power plants using SC walls.

Connections between SC-to-SC walls and SC-to-RC walls or slabs have been particular challenging because: (i) there are no clear performance requirements, and (ii) there are no pre-qualified and tested connections. The author at Purdue University was awarded a cooperative agreement to address these challenges by conducting both experimental and analytical studies.

Research Objectives and Tasks

The overall goal of the project is to develop and disseminate new knowledge in terms of design details, benchmarked numerical models, and experimental results concerning SC wall connections to other SC walls, RC slabs, and the concrete basemat. Detailed tasks are (i) developing modular SC wall connection strategies, and evaluating their structural behavior, fabrication efficiency, and construction economy for use in SMRs, (ii) developing and benchmarking numerical modeling and analysis techniques for SC wall connections, (iii) conducting experimental investigations to verify SC wall connection performance, and (iv) developing standardized connection details and design guidelines for SC wall connections.

Current Status

As of January 2015, the majority of the experimental and analytical tasks have been completed. The final design guidelines and standardizations will be completed in December 2015.

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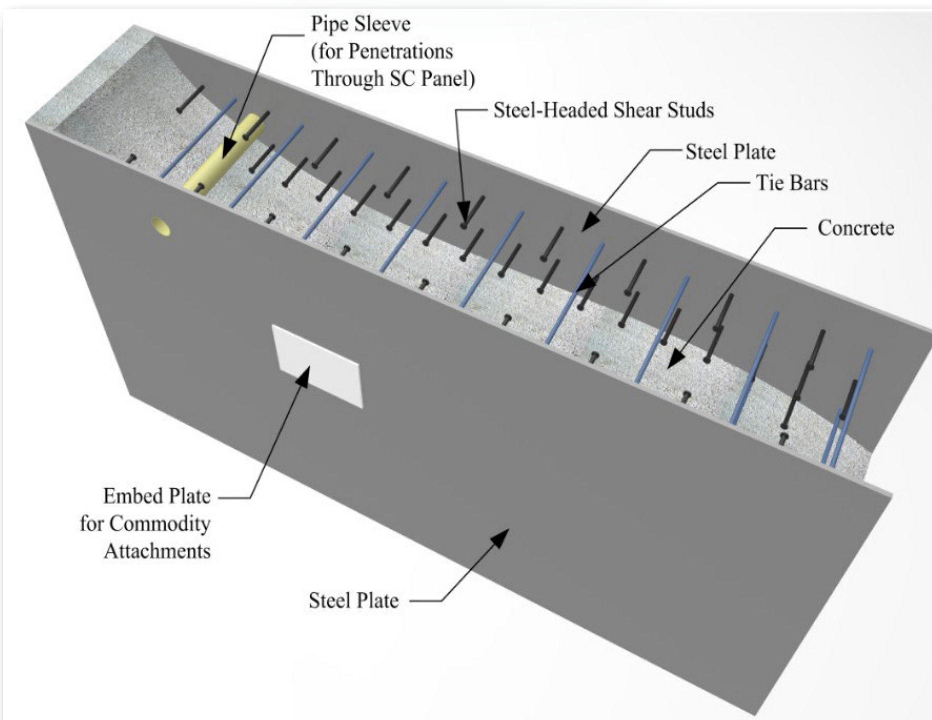

Figure 1: Typical SC wall and its components

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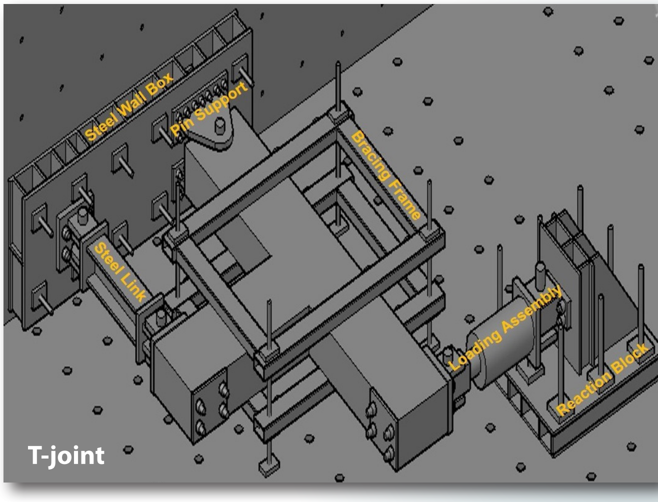

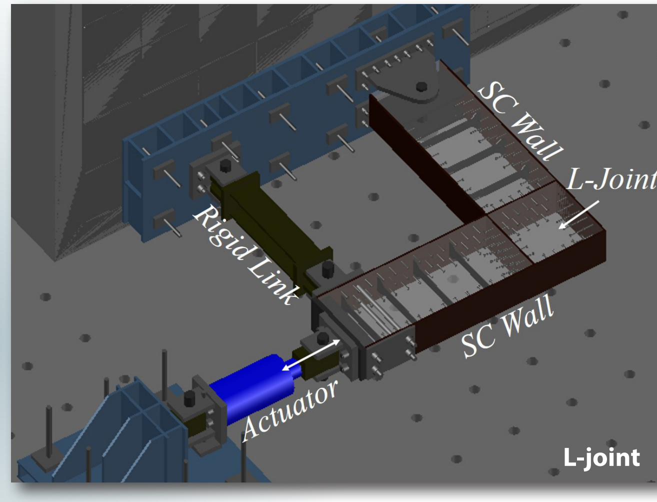

Figure 2: SC wall to wall connection test setup

SC Wall to Wall Connections

Two most common SC wall-to-wall joint configurations (T and L) have been investigated experimentally as shown in Figures 2 and 3. Numerical models have been developed (as illustrated in Figure 4) and benchmarked to predict experimental behavior and failure mode. Parametric studies were conducted using the benchmarked models. The experimental and analytical results were used to develop simple design equations or approaches.

Investigations indicate that: (i) the role and contribution of tie bars and shear studs in the SC wall-to-wall joint region behavior is not significant. (ii) The shear strength of the SC wall-to-wall joints can be estimated conservatively using ACI 349 code recommendations for shear strength of RC joints. And, (iii) SC wall-to-wall connections can be designed to develop yielding and plastification in SC walls before non-ductile joint shear failure during extreme events.

SC Wall to Basemat Connections

SC wall-to-concrete basemat anchorage connections were evaluated by conducting both experimental and analytical studies. The investigations focused on connections made using welded rebar anchors.

The direct shear strength of the welded rebar anchors was evaluated experimentally as shown in Figure 5. Full-scale tests were conducted on: (i) one #18 welded rebar anchor, and (ii) two #11 welded rebar anchors at 8 in. spacing.

Experimental investigations were conducted to evaluate the in-plane shear strength of SC wall piers with full strength anchorage to the concrete foundation as shown in Figure 6. 3D finite element models were also developed and benchmarked using experimental results as illustrated in Figure 7.

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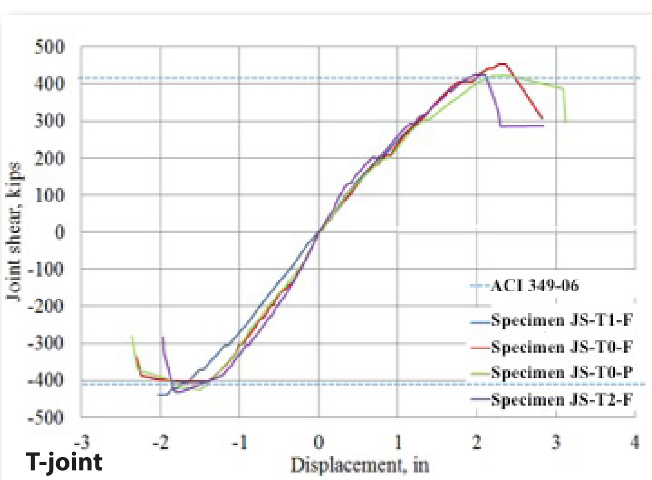

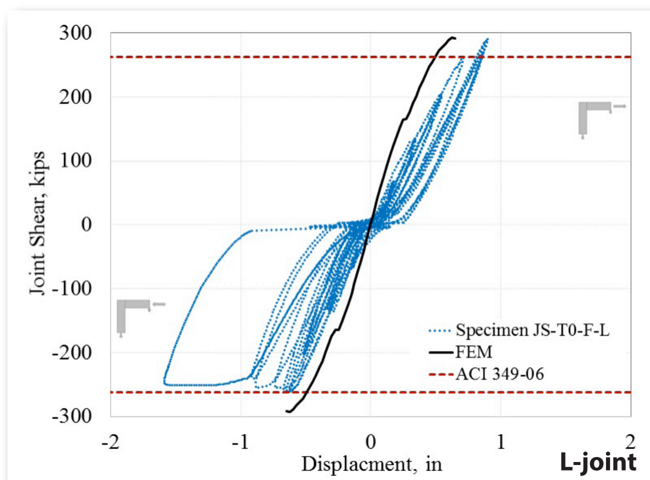

Figure 3: Joint shear – displacement responses

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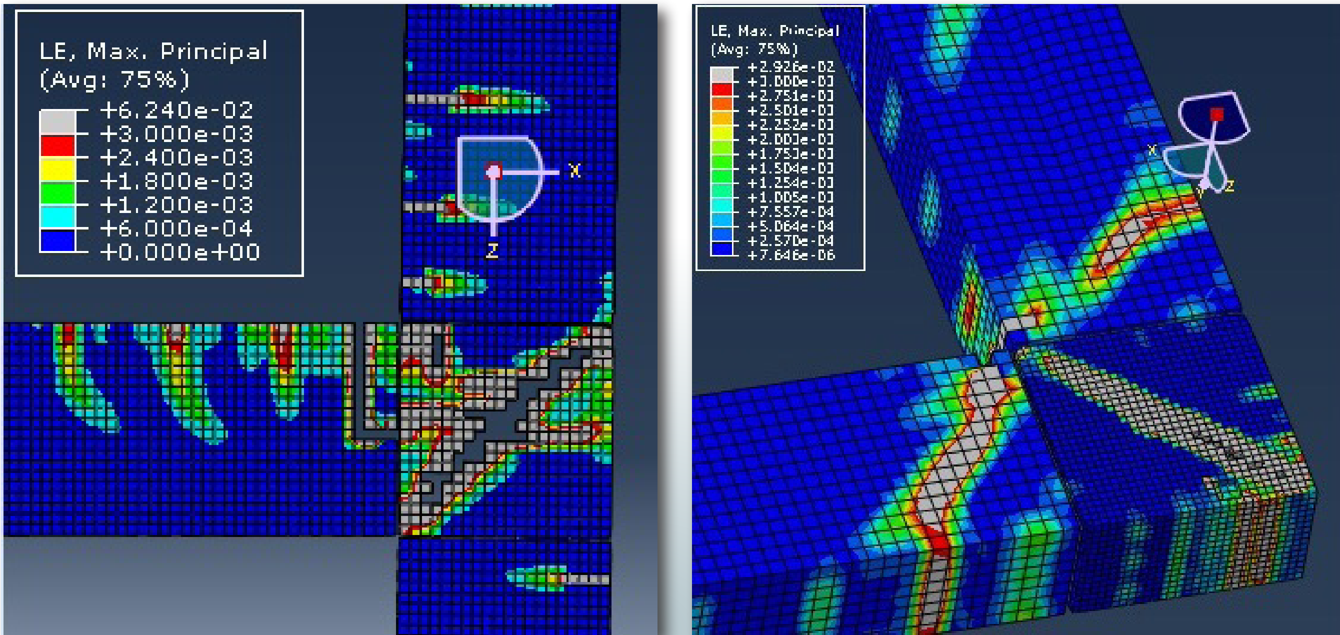

Figure 4: Analytical models

The experimental and analytical studies indicate that (i) SC walls can be anchored to the concrete basemat or foundation using welded rebar-coupler anchor systems. (ii) The direct shear strength of welded rebar-coupler anchor system is governed by the shear fracture strength of the welded coupler calculated using ACI 349 App. D equations and the measured material and geometric properties. (iii) Full strength anchorage of SC walls can be designed using the rebar-coupler anchor system and its direct shear strength. (iv) The in-plane shear strength of SC wall piers with full strength anchorage is governed by the yielding, local buckling and rupture of the steel faceplates accompanied by crushing and spalling of the concrete infill. And, (v) the stiffness, strength, and deformation capacity of SC wall piers with full strength anchorage can be predicted reasonably using benchmarked 3D finite element models of the SC walls and the embedded anchorage system.

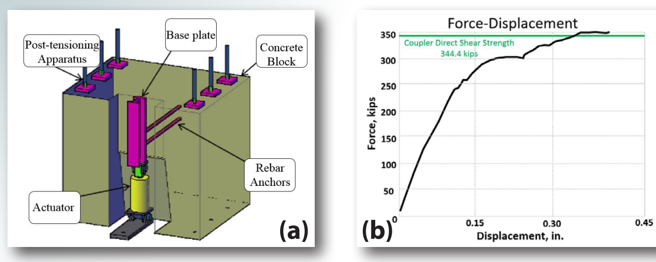

Figure 5: Direct shear test – (a) test setup and (b) applied force – displacement response

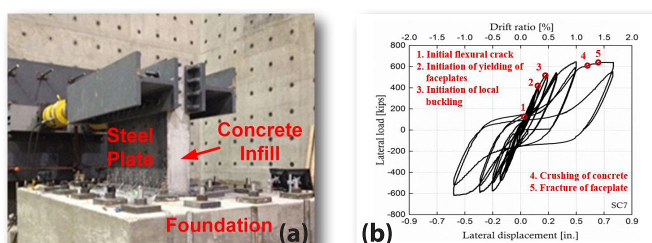

Figure 6: In-plane shear test – (a) test setup and (b) applied force – displacement response

Ongoing Work

The SC wall-to-slab test series is currently being finalized. This series will complete the development and evaluation of modular connection technologies for SC walls of SMRs. The results from all these investigations will provide standardized connection details and design guidelines for reference and acceleration of the design, review, licensing, and construction of small modular reactors utilizing composite SC walls.

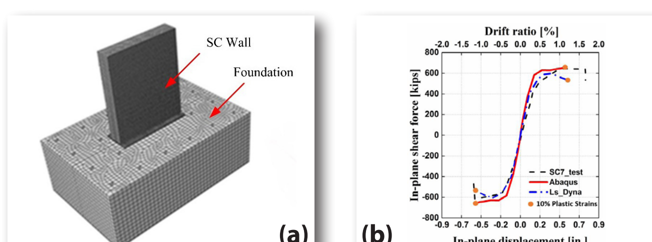

Figure 7: (a) In-plane shear analytical model test and (b) Analytically predicted response

Ultra-High Performance Concrete and Advanced Manufacturing Methods for Modular Construction

Y.L. Mo
University of Houston

Small modular reactors (SMR) allow for less onsite construction, increase nuclear material security, and provide a flexible and cost-effective energy alternative. SMRs can be factory-built as modular components and shipped to desired locations for fast assembly. This project has successfully developed a new class of ultra-high performance concrete (UHPC), which features a compressive strength greater than 22 ksi (150 MPa) without special treatment and self-consolidating characteristics desired for SMR modular construction. With an ultra-high strength and dense microstructure, it will facilitate rapid construction of steel plate-concrete (SC) beams and walls with thinner and lighter modules, and can withstand harsh environments and mechanical loads anticipated during the service life of nuclear power plants. The self-consolidating characteristics are crucial for the fast construction and assembly of SC modules with reduced labor costs and improved quality.

The detailed mechanical properties and long-term durability of UHPC will be established in this project. In addition, large-scale structural testing on steel plate UHPC (S-UHPC) beams is being performed to evaluate structural capacity and identify minimum cross tie ratio. As the bond between UHPC and steel plate is essential for ensuring structural integrity under shear and flexure, it will be measured and examined in this project through a digital image correlation system and smart piezoelectric aggregate sensors. Large-scale testing and finite element simulation will also be performed on S-UHPC wall panels. Based on these results, a set of design guidelines for steel-plate UHPC modules will be developed.

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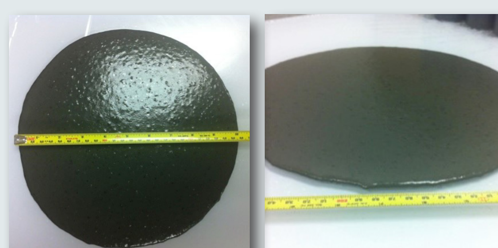
	Concrete for NPP Construction: Conventional Approach	**UHPC for SMR Construction:** Achieved in this Project
Compressive Strength:	5.8 ksi (40 MPa)	≥ 22 ksi (≥150)
Rheology:	Need External Vibration for Workability	Self-consolidating: 26cm Spread Value Based on Mini-slump Test
		

Figure 1: UHPC compared with conventional concrete for nuclear power plant construction

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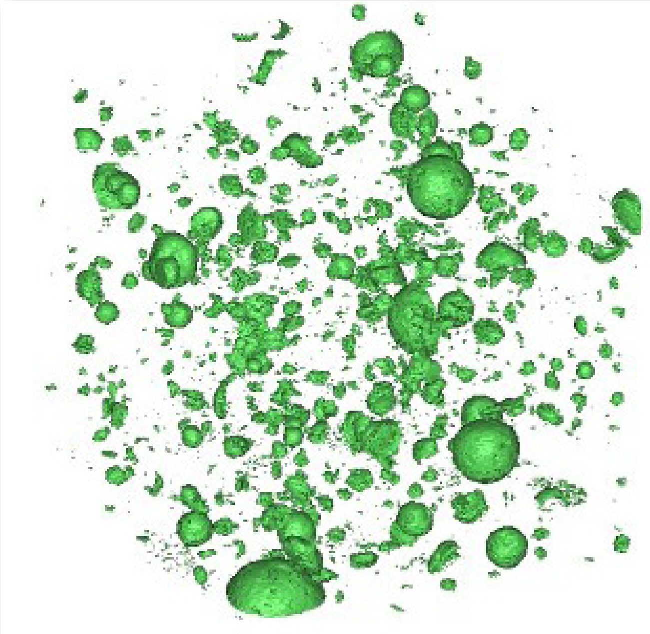

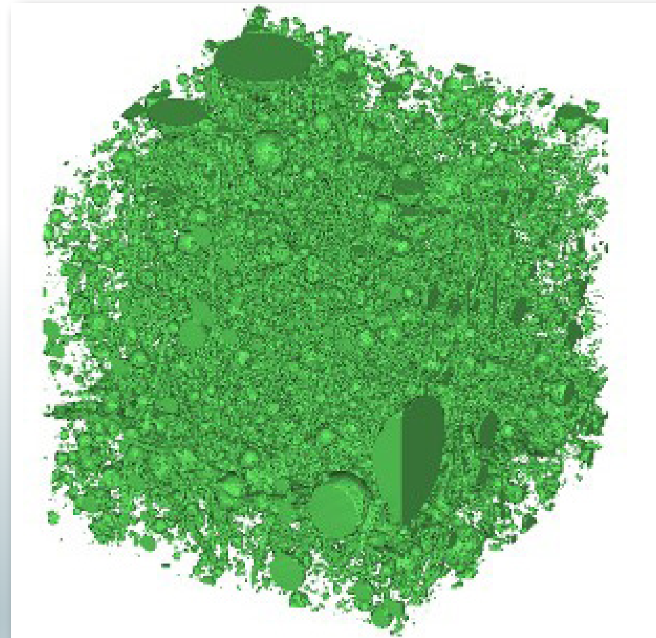

Figure 2: Reconstructed 3D images of pore structure (in green color) for UHPC (left) and conventional concrete (right)

Recent results and highlights

For the first time, a new class of UHPC materials has been developed (Figure 1) based on a systematic approach specifically for construction of SMRs and other reactor types. The approach integrates micromechanics theory, design of experiments, hydration chemistry, and rheology tailoring methods, and time-dependent computed micro-tomography (micro-CT) that can characterize material 3D microstructure formation and degradation. The new UHPC possesses a compressive strength exceeding 22 ksi (150 MPa) without special heat and pressure treatment, and by using a conventional concrete mixer and ingredients commercially available in the U.S.

The mixture design for UHPC is based on the principle of optimizing the particle packing density of the constituent ingredients in the UHPC mixture. Furthermore, through ingredient proportioning and chemical admixtures, the yield stress and plastic viscosity of UHPC during fresh state was tailored such that a self-consolidating property could be achieved.

High-resolution micro-CT was conducted to probe the 3D microstructure of UHPC compared with that of conventional concrete. Through micro-CT image analysis, the pore structure in the solid cementitious material was isolated from the phase of hydrated products, aggregates and unhydrated particles to quantify the development of each phase or component. The packing of the particles and the resulting 3D pore structure in UHPC could thus be quantified. The micro-CT analysis revealed how the particle packing and the resulting pore structure lead to the ultra-high compressive strength of the UHPC mixture. A denser microstructure and significantly less pores were found in UHPC compared with conventional concrete (Figure 2). The results also provided insights on the improved durability of UHPC due to its denser pore structure.

The capability of producing self-consolidating UHPC in mass quantities was investigated and compared to accepted self-consolidating concrete standards by the American Society for Testing and Materials (ASTM) and the European Federation of National Associations Representing for Concrete (EFNARC). With a slightly adjusted mixing procedure using large-scale gravity-based mixers (compared with small-scale force-based mixers), the self-consolidating UHPC has been successfully processed at six cubic yards (Figure 3); the product met both minimum compressive strength

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Figure 3: Large-Scale Production of UHPC

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requirements and self-consolidating concrete standards. S-UHPC beams (15 ft. long, 12 in. wide and 16 in. deep) were then constructed using the self-consolidating UHPC without any external vibration.

When the concrete is replaced by UHPC in a SC beam, it is critical to evaluate its structural behavior with both flexure and shear-governed failure modes. Specifically, the minimum shear reinforcement (i.e. cross tie) ratio needs to be determined for the S-UHPC beams to exhibit a ductile failure mode. S-UHPC beams have been designed and constructed. The beams will be tested to identify the minimum cross tie ratio for a ductile behavior in SC structures.

Impact and value to nuclear applications

The value of UHPC for reactor application is that it can significantly enhance the fabrication and manufacturing methods of modular constructions. UHPC is expected to have superior durability and mechanical characteristics over conventional concrete that is of great interest to safe operation of nuclear power plants.

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