AMM Newsletter

Advanced Methods for Manufacturing

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The Advanced Methods for Manufacturing Newsletter

The U.S. Department of Energy's Advanced Methods for Manufacturing (AMM) Program held its annual program review on September 29, 2015, at the Lockheed Martin Global Vision Center to discuss the status of currently-funded AMM projects. The audience included personnel from academia, national laboratories, manufacturing, design, and construction organizations, which provided an excellent platform for further collaborations. Seventeen presentations were made, encompassing projects awarded through the Consolidated Innovative Nuclear Research and Small Business Innovation Research (SBIR) solicitations since 2012. All presentations can be found on the Nuclear Energy Enabling Technologies page.

The meeting began with results from research awarded in 2012 on Laser Direct Manufacturing by Lockheed Martin and Advanced Fabrication Using Hot Isostatic Processing/Powder Metallurgy by the Electric Power Research Institute. Other 2012 activities included Advanced Monitoring and Control of Laser-Gas Metal-Arc Welding at Idaho National Laboratory and Modular Connection Technologies for Steel-Plate Composite Walls presented by Purdue University.

The 2013 projects concentrated on concrete and concrete construction improvements related to modular builds. The Georgia Institute of Technology presented on Consolidating Concrete Construction for Modular Units and the University of Houston provided the status of their work on High-Performance Concrete and Advanced Manufacturing Methods for Modular Construction.

The current status of the 2014 projects was provided by Oak Ridge National Laboratory on Improving Weld Quality, by Purdue University on Improving Design Codes to Account for Accident Thermal Effects, and by the University of Houston on Periodic Based Seismic Isolators for Small Modular Reactors.

AMM awarded four cooperative agreements in 2015 that cover the entire range of AMM objectives. The projects' principal investigators were asked to provide a brief introduction to their research. The projects that were introduced included Advanced Onsite Fabrication by Idaho National Laboratory, Advanced Surface Plasma Nitriding by Texas A&M University, Investigating Environmental Cracking of Stainless Steel Produced by Additive Manufacturing by General Electric, and Prefabricating High-Strength Rebar for Accelerated Construction of Nuclear Power Plants by the University of Notre Dame.

The workshop also introduced four SBIR projects that are funded through AMM; TetraVue is developing a High-Speed 3-D Data Collection System for Configuration Management; Voxtel is producing a Geo-Referenced, UAV-Based 3-D Surveying System for Precision Construction; Mercorp is developing an Alternate Additive Manufacturing System to Produce or Join Nuclear Components; and Radiabeam is developing Nuclear Quality Components Using Metal Additive Manufacturing.

The workshop concluded with an invitation to all participants to provide questions or comments about current AMM projects and to provide feedback on other relevant manufacturing, fabrication, and construction activities.

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

Self-Consolidating Concrete Construction for Modular Units

Russell Gentry
Georgia Institute of Technology

Researchers at the School of Civil and Environmental Engineering at the Georgia Institute of Technology (referred to as Georgia Tech), along with colleagues at Westinghouse Electric Company, are developing a new concrete material system to increase the speed of construction and reduce the cost of the primary structures in modern nuclear reactors. The shield wall of the AP 1000 nuclear power plant is constructed with steel plate composite modules, which act as stay-in-place formwork for concrete fill. The walls in the shield can be 80 ft high or higher and many feet thick, thus requiring a tremendous volume of concrete. The Georgia Tech/Westinghouse team is developing self-consolidating concrete (SCC) mixes that can be placed rapidly in the steel plate composite modules without the need for extensive consolidation measures during concrete placement.

Current Status

The SCC being developed at Georgia Tech has a number of unique aspects. First, the concrete is tailored to control heat generation within the concrete; therefore, it can be placed in massive quantities as part of the shield wall construction. This has been accomplished by using a blend of supplementary cementitious materials such as fly ash, cement, and a high fine aggregate fraction. Second, the concrete has the high flowability characteristic of SCC mixes and the ability to maintain this flowability over long periods of time to facilitate continuous concreting operations. Most importantly, the SCC mix has been tailored to produce a self-roughening surface at the end of concrete operations (see Figure 1). The mechanisms that generate this self-roughening surface are the subject of an invention disclosure at Georgia Tech and are not discussed in detail in this article.

The self-roughening surface is critical in shield wall construction with SCC. At the end of a given concrete placement (e.g., at the end of the day), a cold-joint is formed in the concrete. This cold joint represents the boundary between one concrete placement and the subsequent placement, which may be placed the next day or the next week.

The transfer of forces across this cold-joint is achieved through a series of mechanisms, one of which is known as shear friction. In the shear-friction concept, the roughness of the cold-joint surface is critical because the shear coefficient μ is a function of the amplitude of the surface roughness. It is not possible to manually roughen the surface of SCC due to the fluid properties of the mix. In addition, it is not realistic to have construction personnel inside the steel plate composite formwork to manually create the roughened surfaces. Thus, the self-roughening SCC developed by the project will allow for more flexible planning of concrete placement operations in reactor construction.

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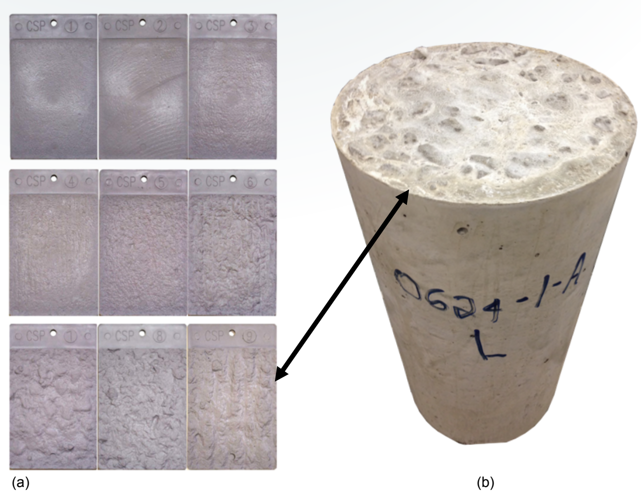

Figure 1. ***Self-roughing concrete surface: (a) represents the International Concrete Repair Institute surface profiles and (b) shows a typical self-roughening surface as formed on a standard 6x12 cylinder of concrete cast in the laboratory. The self-roughening surface corresponds to the roughest surface in the International Concrete Repair Institute reference surface profiles.***

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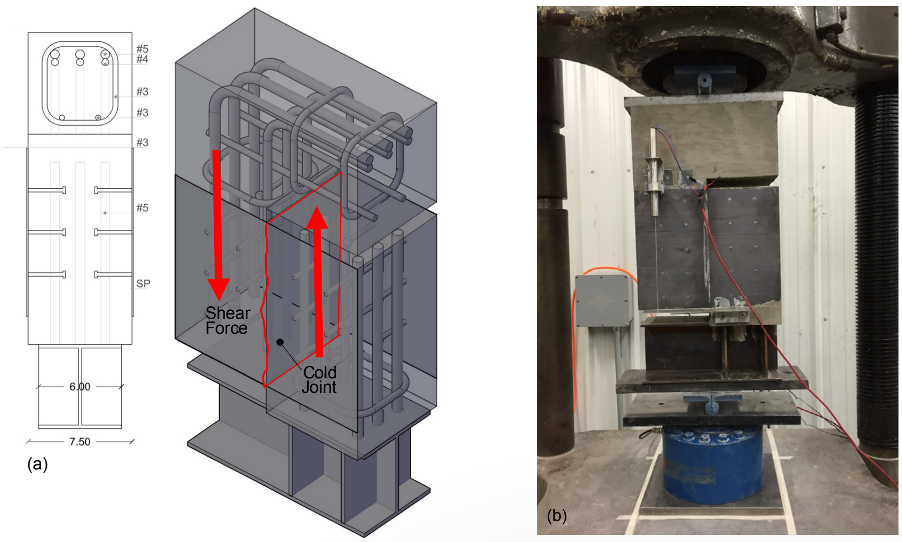

Figure 2. Small-scale push-off specimen: (a) specimen consists of two L-shaped concrete placements with a cold-joint boundary running vertically, with the two placements joined by steel composite plates on two opposite sides of the specimen and (b) the specimen is loaded in a compression fixture, which generates shear across the cold-joint boundary. The slip along the cold-joint boundary is measured with two linear variable differential transformers.

To validate the structural efficacy of the self-roughening SCC in steel plate composite construction, a novel small-scale test specimen has been developed at Georgia Tech (see Figure 2). This specimen, based on a push-off specimen developed originally for internally reinforced concrete, has been adapted for use with externally reinforced steel plate composite structures.

The relatively small scale of the push-off specimens has allowed the research team to test for a wide range of variables, including steel plate thickness, steel stud configuration, and concrete surface roughness amplitude. Test results from these small-scale specimens indicate that the self-roughening SCC is capable of transferring significant loads across the cold-joint boundary and, furthermore, that the shear capacity of the steel plate composite construction exceeds that of conventional internally reinforced concrete (see Figure 3).

Conclusion

The Georgia Tech/Westinghouse team is continuing their research by developing two sets of validation tests. In the first set of tests, one-third scale models of steel plate composite beams constructed with SCC and self-roughened cold joints were tested in the Structural Engineering and Materials Laboratory at Georgia Tech. The last validation test will be a full-scale test, using steel plate composite modules supplied by Westinghouse. Planning for this large-scale test is underway; it is anticipated that this test will take place in the first quarter of 2016. If successful, these validations tests will lead to commercialization of the new concrete mix and revisions to the code that controls the design of steel plate composite structures (AISC N690-12 Appendix N9).

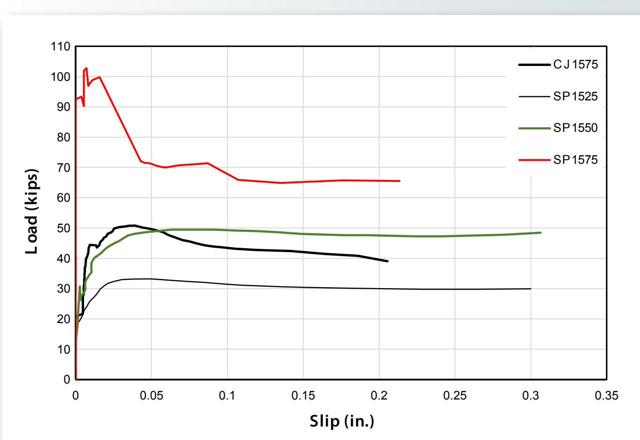

Figure 3. Load versus slip relationship for four different specimen configurations and tested as shown in Figure 2. Specimen CJ1575 (solid line) is a baseline specimen that is reinforced with internal concrete reinforcement. SP1525, SP1550, and SP1575 represent steel plate composite specimens with 0.25%, 0.50%, and 0.75% external reinforcement.

Improvement of Design Codes to Account for Accident Thermal Effects on Seismic Performance

Amit H. Varma & Kadir Sener
Purdue University

The Fukushima nuclear accident in 2011 has highlighted the importance of designing safety-related nuclear facilities for accident thermal scenarios combined with design basis and beyond design basis shaking. While the probability of both events occurring simultaneously is low, the Fukushima event has demonstrated that severe environmental conditions may trigger accident thermal loading and subsequent aftershocks, potentially as intense as the main shock, may occur during the accident thermal event.

There are no design codes or standards for steel plate composite (SC) walls in the United States; however, AISC N690-12, Supplement No. 1, recently released, includes Appendix N9 for SC wall design. Neither this appendix nor its counterparts in Japan (JEAC 4681 2009) and S. Korea (KEPIC-SNG 2012) will address the effects of accident thermal loading on seismic performance. Similarly, the much more established standard for safety-related reinforced concrete (RC) structures (ACI 349-06 2006) does not address the effects of accident thermal loading on the seismic performance of RC walls. Guidance is needed for regulators, designers, utilities, and Nuclear Steam Supply System vendors.

The effect of accident thermal loading on the seismic performance of SC or RC walls has not been investigated experimentally or numerically. Prior research has focused on either seismic behavior or accident thermal loading, but not on both in combination. The combination of accident thermal loading and the safe shutdown earthquake level for the plant design will present a significant design challenge for buried small modular reactors, because postulated accident scenarios will cause higher elevated temperatures for longer durations in the small and/or constrained spaces. For approval, the regulator will require extensive technical information and clear evidence of safety for the accident thermal plus safe shutdown earthquake level loading combination, which may compromise the licensing schedule.

This study focuses on the effects of accident thermal conditions on the seismic performance of innovative SC walls and conventional reinforced concrete RC walls. Figure 1(a) shows a typical SC wall. The exterior steel faceplates serve as reinforcement for the concrete section. The steel faceplates are anchored to the concrete using shear

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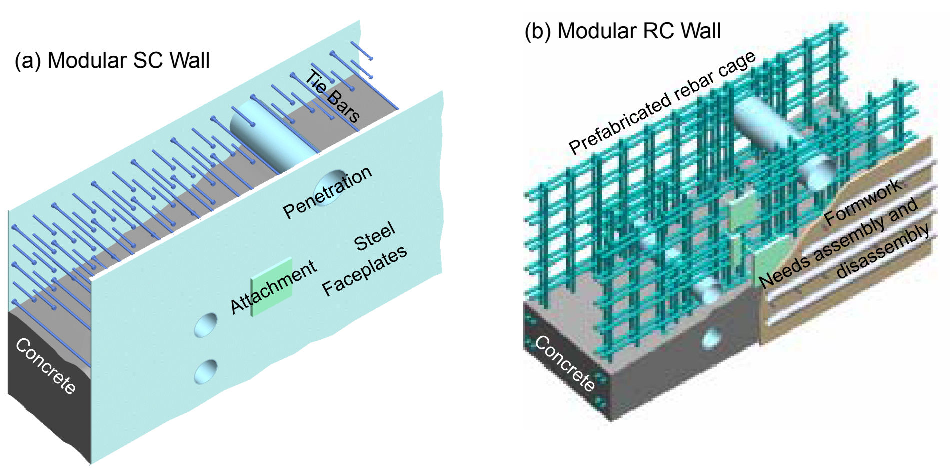

Figure 1. Small modular reactor modular construction.

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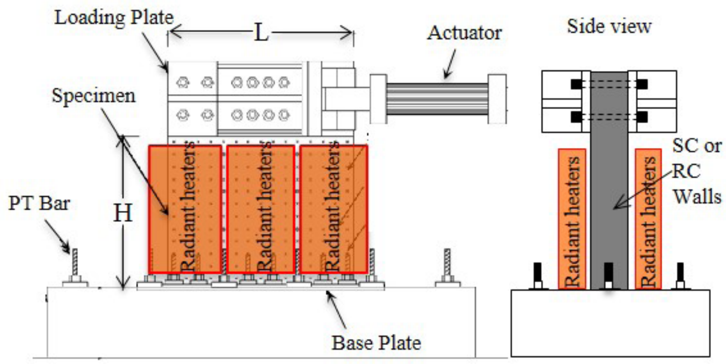

Figure 2. Test setup for conducting accident thermal plus lateral loading tests.

connectors (studs) and are connected to each other using tie bars or rods. The steel faceplates (with no protection) are directly exposed to the elevated temperatures resulting from accident thermal conditions. The differential temperatures between the steel faceplates and concrete infill, and the nonlinear thermal gradients lead to concrete cracking and potential overstressing of the steel faceplates (i.e., primary reinforcement), particularly during seismic events. Figure 1(b) shows a modular RC wall. For these walls, the nonlinear temperature gradient through the thickness of the concrete section will lead to concrete cracking and significant stress in the steel rebar in the absence of earthquake shaking.

Research Objectives and Tasks

The project involves experimentally investigating the seismic (i.e., in-plane shear) performance of structural walls subjected to accident thermal loading. Parameters included in the investigations will be (1) wall type (i.e., SC and RC), (2) maximum accident temperature, (3) duration of the accident thermal loading before seismic loading, and (4) structural details (e.g., reinforcement ratio and clear cover). Following the experimental program, numerical models will be developed and benchmarked for predicting the seismic performance of structural walls subjected to accident thermal loading and design basis and beyond design basis earthquake shaking. The benchmarked models will be used to conduct analytical parametric studies to evaluate the effects of a wide range of material, geometric, structural detailing, thermal loading, and seismic loading parameters, including those from the experimental program.

The test setup for conducting experimental investigations is shown in Figure 2; the figure shows the lateral loading setup with heaters in place. As shown, the walls will be subjected to cyclic lateral loading using two 1,000-kip capacity hydraulic actuators in displacement control. The walls will be anchored to a concrete foundation (or basemat) to develop their full shear strength. The concrete foundation will be post-tensioned to the laboratory strong floor to prevent uplift and sliding. As shown in Figure 2, the specimens will be subjected to heating (i.e., accident thermal histories) on their exterior surfaces using ceramic fiber radiant heaters.

Current Status

The project has reached several milestones, including the finalization of (1) a list of parameters considered for experimental testing; (2) details of the accident thermal history, including maximum temperature and heating duration; and (3) test matrix, setup, heating and loading protocols, sensor layout, and calibration records for instruments and sensors to be used for the tests.

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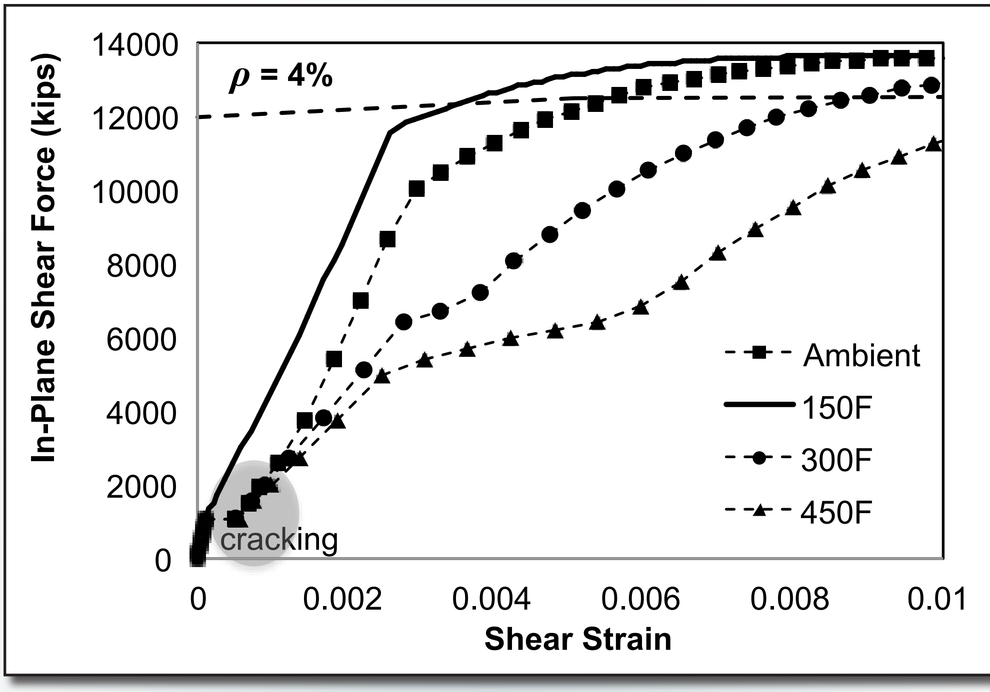


Figure 3. Effects of accident thermal loading on the in-plane shear behavior of SC walls.

Initial findings from the project include (1) typical temperature-time (T-t) curves for containment internal structures in pressurized water reactors, (2) thermal gradient histories that develop through concrete thickness, (3) concrete cracking due to severe gradient and internal restraint, (4) in-plane shear behaviour of the wall after concrete cracking, and (5) effects of external restraints on in-plane shear behavior.

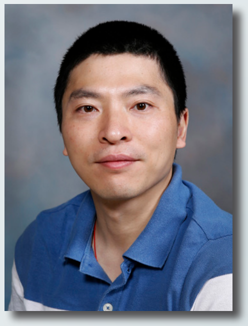
Preliminary numerical studies were conducted on SC and RC walls to be used for development and benchmarking of the future experimental program. Preliminary analysis results of this study show that the faceplate reinforcement ratio and temperature amplitude have remarkable influence on the behavior of SC walls. Thermal loading affected the in-plane shear stiffness and strength of SC composite walls. Figure 3 includes the in-plane shear, force-shear strain responses for SC walls with a 4% reinforcement ratio. It includes the response for ambient conditions at 150, 300, and 450°F maximum temperature. Heating for all three cases was applied for 3 hours. As shown, accident thermal conditions have a very significant influence on the in-plane shear stiffness, strength, and deformation capacity of walls for safety-related nuclear facilities. Similar results are obtained for RC walls.

Future Work/Impacts

This project is continuing according to the planned schedule and will proceed with constructing and testing SC and RC specimens in the near future. The project outcomes will include fundamental knowledge in terms of experimental results, benchmarked numerical models, and analytical results regarding the influence of accident thermal conditions and various parameters on seismic behavior (i.e., stiffness, strength, and ductility) of SC and RC walls.

Improving Weld Productivity and Quality by Means of Intelligent Real-Time, Close-Looped, Adaptive Welding Process Control through Integrated Optical Sensors

Jian Chen
Oak Ridge National Laboratory



Advanced manufacturing technologies for fabricating nuclear reactors (such as small modular reactors and advanced light water reactors) is extremely important for reducing the construction cost of nuclear plants. Because nuclear reactor structures are made of high-performance structural materials such as nickel base superalloys, stainless steels, and low alloy carbon steels, welding is one of the most important manufacturing technologies. The weldments of these materials must be of high quality due to the criticality of the demanding service. Today, welds are made in a prescribed manner, where welding conditions (such as welding current and welding speed) are predetermined based on weld qualification trials. It is very difficult, if not impossible, to proactively adjust the welding conditions in real-time to compensate for unexpected variations in real-world welding, causing the formation of welding defects. Post-weld quality inspections (such as ultrasound, x-ray, and dye-penetrant) are generally mandatory per code requirement. Repair and correction of weld defects after the weld is made is time-consuming and expensive (i.e., often much more than the cost of welding).

Current Status

This project aims to develop a novel, close-looped, adaptive welding quality control system based on multiple optical sensors. This system will enable real-time weld defect detection and adaptive adjustment to welding process conditions to eliminate or minimize the formation of major weld defects that are

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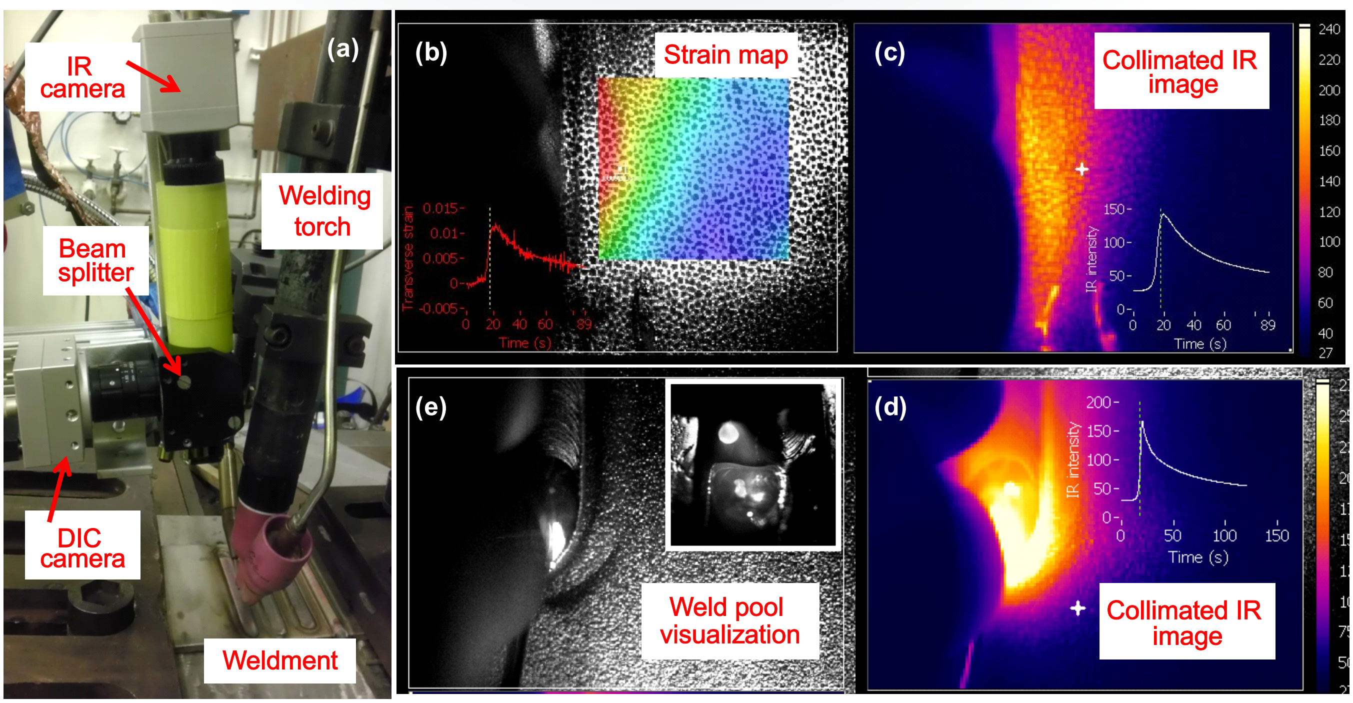

Figure 1. Integrated optical sensing technology for welding in-situ monitoring.

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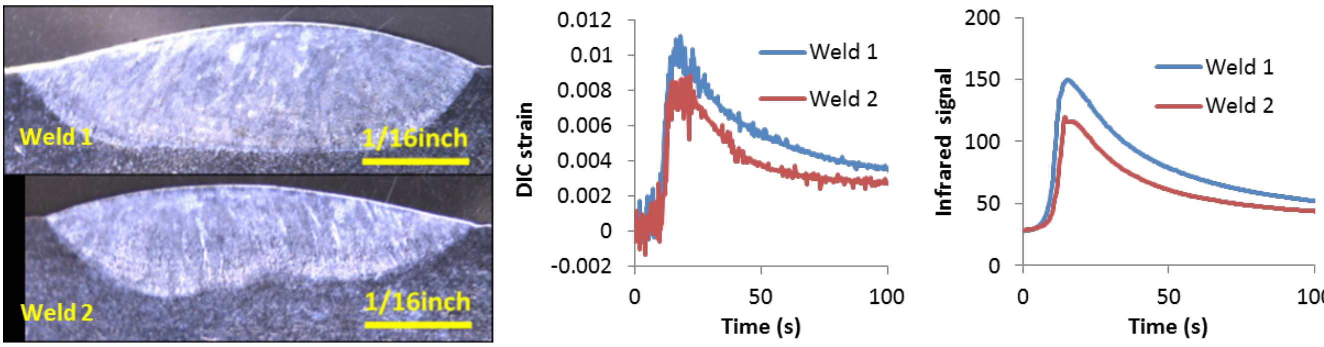

Figure 2. Variation of in-situ strain and IR signals positively correlates to a certain weld defect (Weld 1 - normal size; Weld 2 - undersize).

typically encountered in welding of high-performance engineering structural materials for nuclear structural components.

During the first fiscal year, we have been focusing on hardware integration and testing. New techniques have been developed to overcome the challenges encountered with real-time optical sensing during welding processes (such as the disturbance of high temperature and intense arc light). Figure 1a shows the experimental setup of our integrated sensing approach. In principle, the multi-optical sensing system includes a digital image correlation (DIC) sensor, an infrared (IR) thermography sensor, and necessary auxiliary illumination sources and filters. The sensing system has been successfully used in arc welding and laser welding applications. The system is capable of concurrently measuring, in real-time, changes in the strain field via DIC (Figure 1b), the temperature field via IR camera (Figures. 1c and 1d), and the weld pool surface profile (Figure 1e). Preliminary results have demonstrated that optical signals can be positively correlated to final weld attributes. Figure 2 shows an example of undersized weld detection. Weld 1 is a normal-sized weld and Weld 2 is an undersized weld. The real-time strain and IR signals adjacent to the fusion zone were measured in-situ. Data show that the peaks of both signals for the undersized weld are 20% less. Further experiments will be performed to investigate welding parameters, optical signals, and weld quality correlation, which will eventually be used for weld quality monitoring and control.

Conclusion

In 2015, the multi-optical sensing system was integrated to monitor, in real time, a material's strain field, thermal field, and weld pool profile during different welding applications. Preliminary results demonstrate the feasibility of correlating the optical signals to the final weld quality. Additional research will be conducted to extract more useful information from the signals and apply it to control the quality of the welding processes.

Periodic Material-Based Seismic Base Isolators for Small Modular Reactors

Y. L. Mo
University of Houston
Y. Tang
Argonne National Laboratory
K. Barry
Electrical Power Research Institute
K.C. Chang
National Center for Research on Earthquake Engineering, Taiwan

This research seeks to develop a periodic foundation for small modular reactors (SMR) using innovative periodic materials. The characteristic of a periodic material is based on the concept of a phononic crystal in solid-state physics. The distinct feature of these materials is they cannot transmit waves having frequencies within a certain range (i.e., called the frequency band gaps). This property is a very useful characteristic for seismic base isolation systems. With proper design, frequency band gaps can be adjusted to match the frequency ranges associated with strong seismic waves to filter out the strong earthquake motion. The focus of this article will be on the design of the periodic foundation, with a scaled SMR building as the superstructure. The design will later be verified through shake table tests to experimentally study the behavior of the specimens under different wave excitations.

Expected Outcomes

At the end of this project, a periodic foundation will be seismically designed for SMRs (Figure 1) and a set of design guidelines on periodic foundations for SMRs will be proposed to increase the safety margin of nuclear power plants.

Recent Results and Highlights

Optimum design of a three-dimensional periodic foundation can be achieved by suppressing the unit cell in the vertical direction (Figure 2). Because the size of the suppressed unit cell in the vertical direction (az) is smaller than the size in the horizontal direction (a), the Brillouin zone in this unit cell takes the shape of a rectangular prism. Subsequently, the first irreducible Brillouin zone (i.e., a collection of non-repeated wave vectors of the Bloch waves) has the shape of a rectangular pyramid (L-R-M-Γ-X-M), which is shown in Figure 2(b).

The dispersion curve in Figure 3 shows that the attenuation zone that correlates with translational mode in the horizontal direction was observed in the frequency range from 11.5 to 17.54 Hz. On the other hand, the attenuation zone that correlates with translational mode in the vertical direction was observed in the frequency range from 20.1 to 30.2 Hz. This geometry is very suitable for isolating seismic waves because a vertical earthquake generally has higher frequency content than a horizontal earthquake. Moreover, with suppression of unit cell size in the vertical direction, more unit cells can be placed, which contributes to higher wave reduction.

Another interesting result recently obtained in a one-dimensional periodic foundation was that combining two different unit cells with attenuation zones overlapping one another would result in the union of the attenuation zones. Unit Cell 1 (Figure 4(a)) was made of layers A and B, and had attenuation zones for horizontal excitation at 7 to 16.25 Hz, 19.3 to 32.5 Hz, and 34.3 to 48.85 Hz. Unit Cell 2 (Figure 4(b)) was made of layers C and D, and had attenuation zones at 7.58 to 21.72 Hz, 24.3

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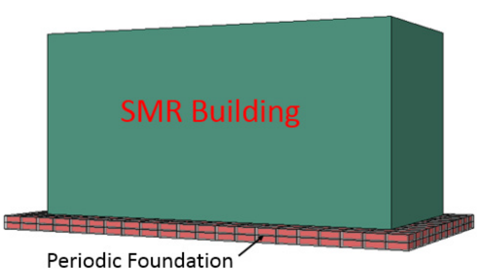

Figure 1. SMR building with periodic foundation.

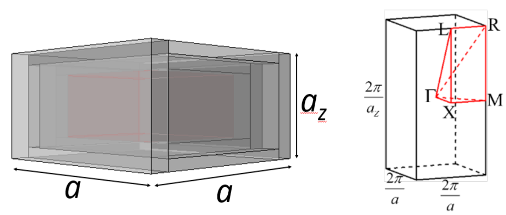

Figure 2. (a) Suppressed unit cell in vertical direction and (b) first irreducible Brillouin zone.

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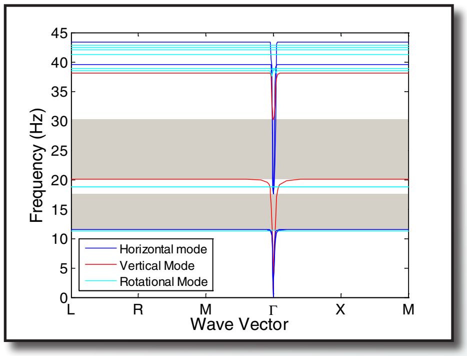

Figure 3. Dispersion curve of unit cell suppressed in the vertical direction.

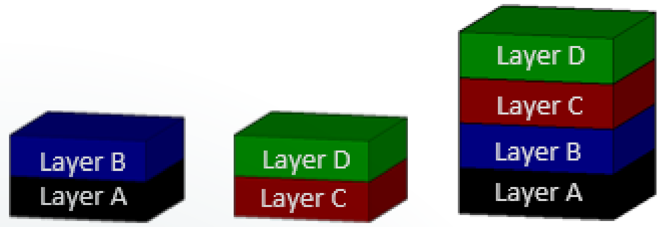

Figure 4. (a) Unit Cell 1, (b) Unit Cell 2, and (c) Unit Cell 3.

to 43.5 Hz, and 44.85 to 50 Hz. The attenuation zones of both Unit Cells 1 and 2 are covering one another. Figure 4(c) shows Unit Cell 3, which is composed of Unit Cell 1 and Unit Cell 2. The analytical result shows a wide attenuation zone (i.e., 7 to 50 Hz) and a large wave response reduction inside the zone (represented by a larger negative Frequency Response Function (FRF) value in Figure 5). Considering that the damping ratio of concrete and rubber are 4% and 10%, repectively, the amplification becomes much smaller and the wave response inside the attenuation zone is greatly reduced.

Impact and Value to Nuclear Applications

The value of this material for SMR foundation applications is that it potentially can be designed according to the seismicity of the region and/or according to the natural frequency of the SMR. Use of a periodic foundation for SMRs will reduce the input acceleration transmitted to SMRs, thereby maintaining the responses of these structures within acceptable limits. These two advantages will increase the safety of both the structural and nonstructural components of SMRs without the need for a special design and restrictions on the components.direction was observed in the frequency range from 20.1 to 30.2 Hz. This geometry is very suitable for isolating seismic waves because a vertical earthquake generally has higher frequency content than a horizontal earthquake. Moreover, with suppression of unit cell size in the vertical direction, more unit cells can be placed, which contributes to higher wave reduction.

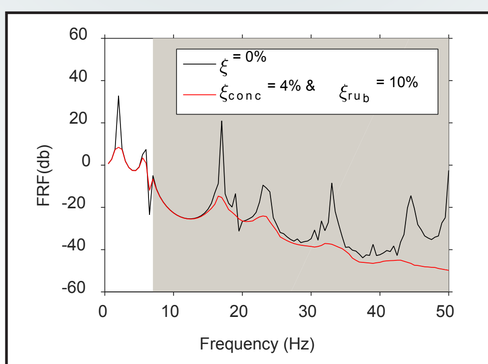

Figure 5. Attenuation zones of Unit Cell 3.

To submit information or suggestions, contact
Alison Hahn at **Alison.Hahn@nuclear.energy.gov**.