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High Speed 3D Data for Configuration Management

TetraVue, Inc.

Construction of complex facilities, such as nuclear power plants (NPPs), has evolved to require sophisticated processes and data management capabilities to help ensure that the plants as constructed will perform as designed throughout their life cycle. A key element in realizing the value of a Configuration Management (CM) or Building Information Model (BIM) approach is the ability to track all design elements and to update the design when there is a deviation between the design and the as-built. This tracking process requires detailed, accurate measurements of the facility and all of its components. Historically, as-built measurement and design updates have been seldom done, misplaced, or otherwise not available. Even with the most current technology for three-dimensional (3D) laser scanning, the cost and time required to acquire the necessary as-built information is the primary barrier to completing a CM implementation. Overcoming this barrier in NPPs is especially difficult because of the high density of components found in confined spaces in the plants and because of the need to track all of the plants' components with high fidelity.

To address this challenge, TetraVue has a new high-resolution 3D capture technology that promises to eliminate the need for 3D instrument setups and greatly reduce the workflow required for capturing the as-built coordinates and imagery. The high-resolution coordinate and image data streams permit algorithm improvements that have the potential to allow camera pose tracking and registration of the individual frames to the plant coordinate system with a significant reduction in the size of the surveyed control network and to eliminate separate setups for 3D laser scanners. The concept of video acquisition rather than scan and survey acquisition promises the potential of changing the weeks of capture and processing time currently required for 3D laser scanners to days or less. This small business innovation research (SBIR) project intends to demonstrate the feasibility of achieving engineering-grade as-built data with an improved prototype 3D camera and optimized software processing pipeline.

Current Status

During Phase I, TetraVue used an existing prototype 3D camera to record 3D coordinate and image data at an existing power plant. Figure 1 illustrates how the process functions. Each individual frame of the video stream is comprised of a high-resolution (2 Mpx) greyscale image and a corresponding range map (shown in false color indicating distance from the camera). For each frame, a meshed model can be created for a small volume of area to be recorded. The prototype camera recorded data at 10 fps, recording large areas in a few seconds. Unlike

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For more program information, including recent publications, please visit www.energy.gov/ne

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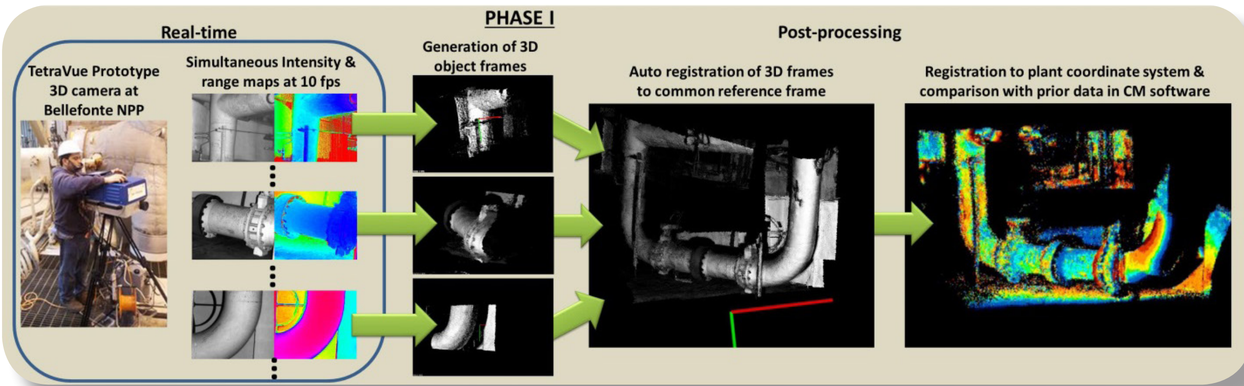

Figure 1. Phase I has demonstrated path to collect frames of intensity and range maps, convert to 3D frames, register these frames together, and then compare with design or prior as-built information in an NPP. This demonstration will be made robust and practical in Phase II.

other approaches, the imagery and 3D measurements are acquired using the same mega-pixel class sensor and so there are no registration errors between the image and the geometry. Post-processing software was used to find common features in each frame, identify the camera motion between frames, and register the frames into a common coordinate system, creating a 3D model and mesh of the larger volume. This registered point cloud was imported into Construction Systems Associates' (CSA's) PanoMap® software and compared with previous 3D laser scan data of the same area (shown to the right with the color scale indicating differences of the point cloud coordinates). The maximum error in measured coordinates was 2 in., which is consistent with the operating resolution of the early 3D prototype camera at the 5–10 m ranges. The effort was able to show how the high-resolution TetraCorder product could be walked through a plant without individual setups using the real-time imagery and 3D measurements to register all components to the plant coordinate system without global positioning system (GPS) or inertial measurement unit (IMU) data.

During Phase II of this SBIR project, TetraVue is improving the camera hardware to achieve cm-class resolutions and accuracies from a single frame and improving the registration algorithms to take advantage of the combined high-resolution image and coordinate streams and create point clouds of areas up to 100 m in extent. The required post-processing time to create the point cloud and then import the point cloud into the PanoMap configuration management software will be reduced to 4X times the acquisition speed. The goal is for the as-built data to be available in near real-time to the user or decision maker.

TetraVue has constructed an improved 3D camera to better meet the requirements of collecting the 3D as-built information of a construction project or existing plant. The result is shown in Figure 2, a handheld 3D camera that has an integrated display to show the status and 3D data as collected and controls typical of a camcorder. No work has been performed for electronics miniaturization so the handheld unit is quite heavy (10 lb), requiring two-hand operation. The data processing pipeline to capture and record the HD video stream is a Linux-based computer and graphics card combination that is housed in a separate backpack. The processing pipeline has been implemented in a low-power field-programmable gate array (FPGA) in a separate project, but that design path was not used for this 3D prototype camera. The backpack also houses a battery to allow operation of the camera without external power for 1 hour at a time, which is enough time to collect data on 72,000 m2 with 90% overlap. The camera operates at

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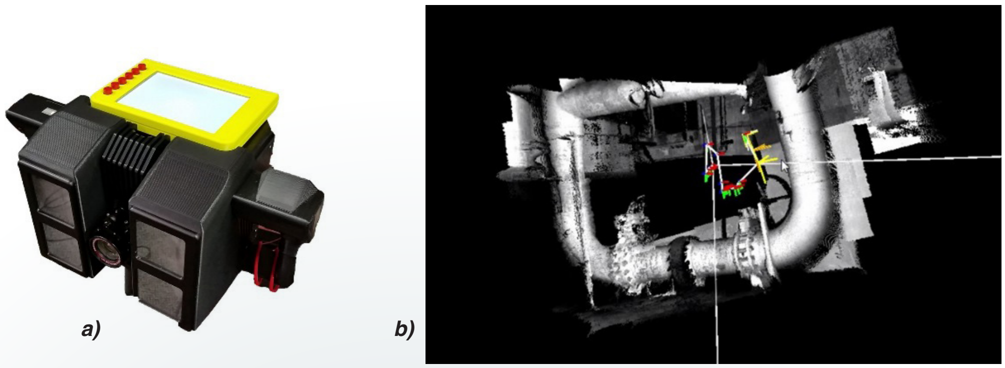


a) b)

Figure 2. Phase II handheld 3D video camera (a) will be coupled with optimized registration software to create near real-time as-build models of large plant areas. Preliminary testing with DotProduct's Phi3D software created a registered point cloud (b) in less time than it took to take the data (4 sec registration for 10 sec of data).

30 fps, collecting nearly 60 million 3D points per second at ranges up to 20 m with 20% reflective surfaces and 30 m with 90% reflective surfaces.

In addition, work is underway to optimize 3D registration algorithms to take advantage of the unique features of a high-resolution 3D camera as well as to keep up with the large data volume that can be captured. This includes both open source as well as commercial products. For example, TetraVue has used DotProduct's Phi3D software to register the previous Phase I data shown above in Fig. 1. The 10 sec of data is processed in 4 sec, with the resulting 3D point cloud shown in Fig. 2. Accuracy and robustness needs to be improved, particularly now that the handheld 3D prototype camera is complete, but this result highlights the potential of the speed at which 3D as-built data can be acquired and made available to the engineer and owner-operator.

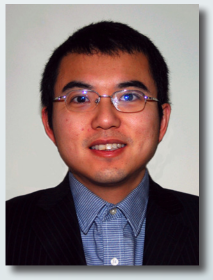
Conclusion

A key factor that prevents the more widespread use of 3D as-built data in CM is the relatively high cost and long delays between acquisition and availability using today's single spot 3D scanners, total stations, and surveys. Three-dimensional video promises to reduce the acquisition time by at least 10 X while also making 3D model information available in near real-time, rather than the current days or weeks of post-processing. During this SBIR Phase II project, TetraVue has completed an improved handheld 3D prototype camera that can acquire measurement-grade 3D coordinate data along with greyscale high-definition video. In the remainder of the project, optimized registration algorithms will be combined with the 3D video data to create high-resolution, high-speed 3D models that will be imported into CSA's PanoMap® configuration management software, making the information available in near real-time.

Beyond this SBIR project, TetraVue has identified the engineering and design changes required to first create an engineering-grade measurement 3D camera that would look and feel similar to a professional HD camcorder, providing either high resolution 3D video or automatically registered 3D models of large areas. Subsequent HD3D camera products can be further reduced in size and cost for use as the basis of 3D vision systems of robots, vehicles, and other smart machines.

Environmental Cracking and Irradiation-Resistant Stainless Steel by Additive Manufacturing

Xiaoyuan Lou
GE Global Research



Direct metal laser melting (DMLM) technology is the key additive manufacturing (or 3-D printing) method that can create near net shape metal components with complex geometry directly from the computer model. The development of DMLM technology for nuclear applications can provide the capability to fabricate parts rapidly that may be required to enhance the integrity of reactor internals. Such opportunities may be observed during plant refueling outages where DMLM parts can be custom designed and deployed within the outage interval. It can also provide its unique capability to generate complex geometries quickly with improved performance for new component design in Generation IV reactor applications.

While a large amount of work has been conducted to additively fabricate stainless steel, most of the work has been focused on some basic attributes such as geometry/shape creation, porosity, and residual stress along with component yields and process monitoring. For nuclear-specific applications, very little work has been done to understand the nuclear specific material properties, including stress corrosion cracking behavior in reactor environment, and material degradation under irradiation, which are the major obstacles for achieving regulatory approval and commercialization. In particular, the fundamental relationship between the produced microstructure by laser process and these nuclear specific properties is still largely unknown. In this 2-year program, GE Global Research, Oak Ridge National Laboratory (ORNL), University of Michigan, and GE-Hitachi Nuclear Energy aim to understand the nuclear-related properties, including mechanical performance, stress corrosion cracking (SCC), and irradiation resistance of the additively manufactured stainless steel. This program develops a novel SCC and irradiation-resistant stainless steel using additive manufacturing process to save on both deployment schedules and overall life-cycle costs with improved plant reliability, and demonstrates the feasibility and benefits of this process in nuclear applications.

Current Status

In the nuclear industry, SCC is the most important material failure mechanism that can influence the safe and reliable operation of nuclear reactors. Crack formation

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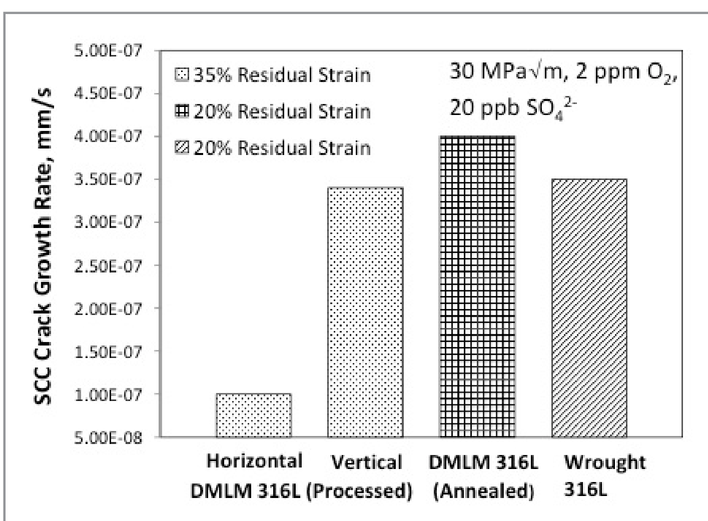

Figure 1. Stress corrosion crack growth rate comparison among different stainless steels.

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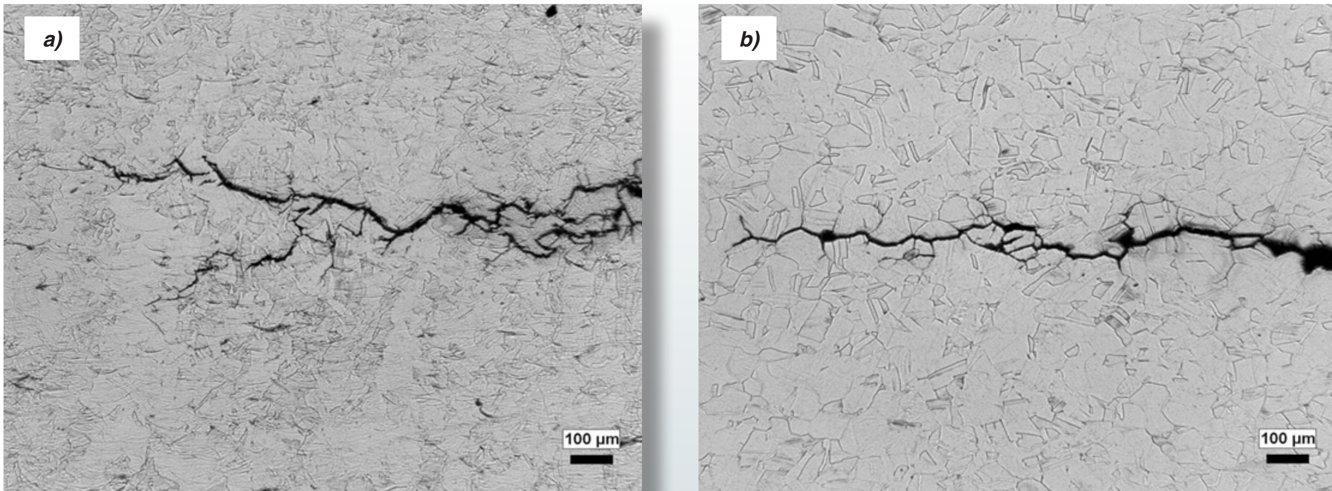

Figure 2. Cross-sectional image of stress corrosion crack on DMLM316L stainless steel after SCC test.

on the structural components in a reactor environment can result in unexpected sudden failures. Although austenitic stainless steel is widely used in nuclear reactor applications, it is well known that stainless steel is susceptible to SCC in high-temperature water. Cracking is accelerated by temperature, residual plastic strain in the alloy, sensitization, water conductivity, and electrochemical potential. In addition, near core components are constantly exposed to a high dose of neutron irradiation. Neutron irradiation can induce various changes in the material's microstructure and lead to increased susceptibility of alloys to stress corrosion cracking, which is commonly referred to as irradiation-assisted stress corrosion cracking (IASCC). Understanding the SCC and irradiation behaviors of the advanced DMLM materials are the keys to evaluate their usability and service life. The program has established the baseline understanding of the SCC behavior of the commercial DMLM 316L stainless steel in a simulated boiling water reactor (BWR) environment. Figure 1 shows a comparison of SCC crack growth rates in commercial heat DMLM 316L (two conditions: stress relief processed and annealed) and wrought 316L SS. Although the stress-relieved DMLM 316L contains increased residual plastic strain (generally, higher residual plastic strain results in higher SCC crack growth rates), its horizontal orientation shows less than one-third the crack growth rate of wrought material under the same testing condition in the high-temperature water. Its vertical orientation showed higher SCC susceptibility than the horizontal orientation.

Figure 2 shows the cross-section of the stress corrosion crack after the test on both stress-relieved and annealed materials. As shown in Figure 2a, the material with stress relief microstructure showed a transgranular type stress corrosion crack. The crack tends to form many secondary cracks and branches, which may be due to the residual strain distribution and grain structure. In the meantime, the fully annealed DMLM316L stainless steel, as shown in Figure 2b, showed a typical intergranular crack as its wrought counterpart. The detailed mechanism that causes the difference in SCC behavior is still under investigation. A clear understanding of these differences in material performance can help develop a better DMLM stainless steel for nuclear application.

The program also conducted the basic understanding on materials' mechanical properties. Figure 3 shows a comparison of the mechanical properties of the commercial heat DMLM 316L, wrought 316L, and Nitronic 50 (a nitrogen strengthened stainless steel). The yield strength of DMLM 316L is much higher than that of Nitronic 50. Clearly, the microstructure features produced by laser melting affect both SCC and mechanical properties of DMLM material.

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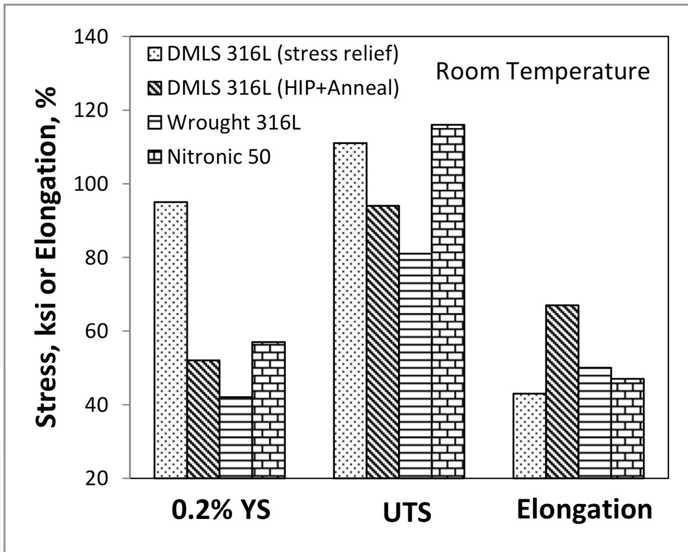


Figure 3. Mechanical property comparison among different stainless steels.

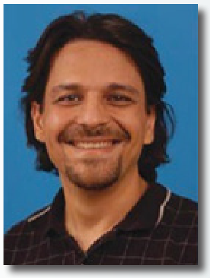
To understand and control the microstructure during DMLM to improve SCC and irradiation properties, both the GE team and the ORNL team are working on optimizing their laser process using their state-of-the-art DMLM systems to control the microstructure of the final products from DMLM. GE's existing codes for simulating the solidification microstructure of metallic product by DMLM were modified to be used for stainless steel. The accuracy of this model was validated by experiment. This simulation tool has been used to design the fabrication matrix for the desired microstructure. Thermodynamic calculation was also conducted to predict phase formation under fast solidification. The goal is to vary the material's microstructure and understand the link between microstructure and SCC/irradiation resistance.

The team from University of Michigan has designed the specimen geometry and sample holder for proton and ion irradiation test. The baseline DMLM 316L stainless steels under various heat treatments have been fabricated for the baseline irradiation test.

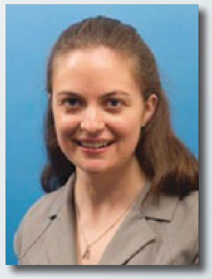
Conclusion

Extensive work has been carried out in the past 3 months since the kick-off of this program. Through the close collaboration of industry, a national laboratory, and a university in this program, the developed technology is in a very good position to gain regulatory acceptance and commercialization. The technology under development can provide the capability to save on both deployment schedules and overall life-cycle costs with improved material reliability in nuclear environments. The fundamental understanding of the relationship among microstructure, SCC, and irradiation properties can also advance the knowledge in materials science and impact a much broader community.

Prefabricated High-Strength Rebar Systems with High-Performance Concrete for Accelerated Construction of Nuclear Concrete Structures



Dr. Yahya C. Kurama
University of Notre Dame



Dr. Ashley P. Thrall
University of Notre Dame

This project involves innovative research that offers the promise of dramatically reduced field construction times and fabrication costs for reinforced concrete (RC) nuclear safety-related structures through the use of (1) high-strength steel deformed reinforcing bars (rebar), (2) prefabricated rebar assemblies with headed anchorages (Figure 1), and (3) high-strength concrete. The focus is on shear walls (including their connections and around large penetrations/embedments), which constitute the most common lateral load-resisting system in non-containment nuclear reactor buildings. The specific research goals are to (1) develop a transparent limit/cost-benefit analysis framework; (2) develop an optimization methodology for structural design; (3) conduct experimental evaluations of nuclear shear walls and wall-foundation joints; (4) develop validated numerical simulation models; (5) develop validated design procedures, tools, and criteria; and (6) develop field construction procedures that are consistent with current methods.

The experiments to be conducted for the validation of design methods and simulation models include testing of (1) high-strength materials (Figure 2); (2) deep cantilever beams (representing slices from a shear wall length, Figures 3–4); and (3) capstone shear walls (Figure 5).

Impact and Value

High-strength rebar with high-strength concrete can result in a higher-performing structural composite, reduce the total rebar volume, and simplify rebar cages. Prefabricated headed rebar cages can reduce construction times and the tight quality controls of

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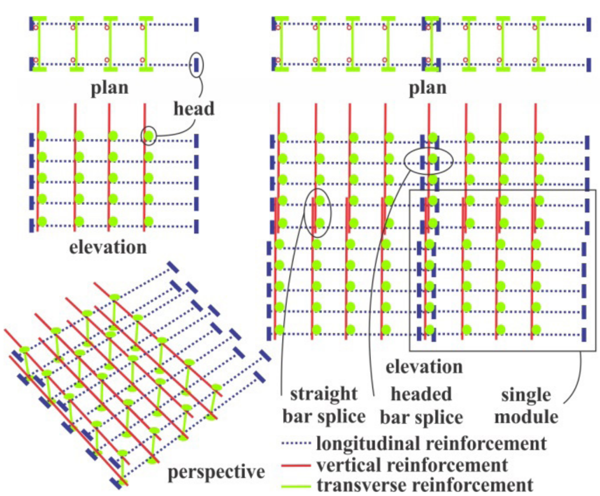

a) b)

Figure 1. Prefabricated rebar cages: (a) single module, (b) four field-tied modules.

a) b) c)

Figure 2. Properties of high-strength concrete: (a) slump, (b) compression cylinders (before testing), (c) tension cylinder (after testing)

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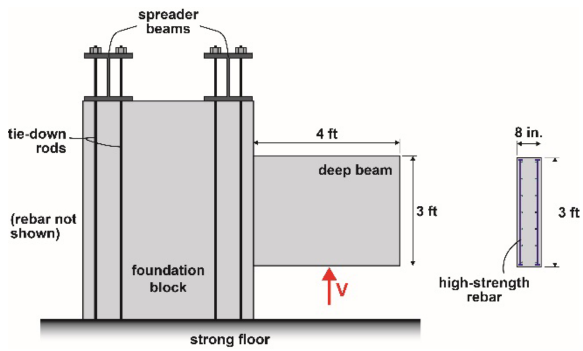

Figure 3. Preliminary elevation (left) and cross-section (right) views of deep beam specimens

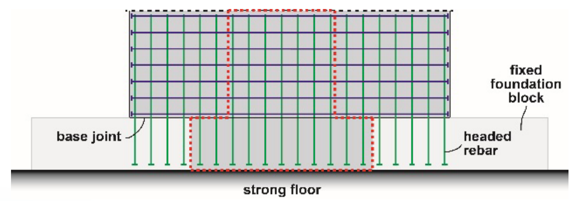

Figure 4. Vertical wall slice from capstone wall as basis of a deep beam specimen.

prefabrication can deliver a more reliable product. Further, reduced rebar congestion can provide better field inspection and easier concrete placement. Combined, these innovations have the potential to dramatically accelerate construction schedules and reduce fabrication costs while also facilitating more reliable quality control of nuclear safety-related structures. By building on existing research on high-strength materials, the proposed technologies have the potential to be utilized in the near-term, with results directly applicable to impact the relevant design codes. Ultimately, cost savings from the successful achievement of the project goals can lead to lower electricity costs in the United States.

Collaboration

The project is synergizing the expertise and resources of four researchers across academia, a national laboratory, and industry, and is also educating Ph.D., Master's, and undergraduate students. The research is led by the University of Notre Dame, with support in numerical modeling from Sandia National Laboratories, and nuclear industry insight and practical design/detail guidance from AECOM.

Current Status

The following tasks have been successfully accomplished within the first quarter since the beginning of the project in October 2015: (1) selection of high-strength materials suitable for high-performance RC nuclear structures, (2) development of full-scale prototype nuclear shear wall design properties, and (3) determination of reduced-scale specimen properties and variables to be tested in the subsequent tasks of the project.

High-Strength Materials

The current state-of-the-practice in RC nuclear structures uses conventional strength materials of 60 kilo-pounds per square inch (ksi) rebar and 5 ksi concrete. It was determined that 100 ksi rebar and 15 ksi concrete not only represent significant increases compared to these conventional materials, but are also readily available in the U.S. market and represent a high potential for acceptance by governing design codes. Concrete mixtures have been designed and

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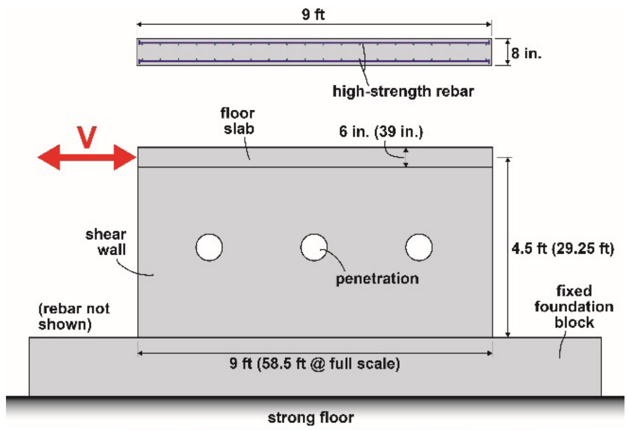


Figure 5. Preliminary cross-section (top) and elevation (bottom) views of reduced-scale capstone shear wall specimens.

ASTM testing of fresh and hardened concrete properties is being conducted, such as slump (Figure 2[a]), compression strength and Young's modulus (Figure 2[b]), and split cylinder tension strength (Figure 2[c]).

Reduced-Scale Specimen Properties

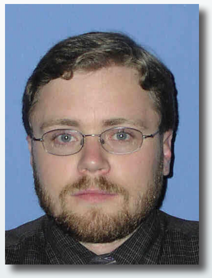
Based on the development of a generic full-scale prototype nuclear shear wall design, reduced-scale specimen properties have been determined for experimental testing. This testing will occur on (1) deep cantilever beams to understand the effects of various fundamental design parameters (e.g., concrete strength, rebar strength, reinforcement ratio, moment-to-shear ratio) on the shear and flexure-shear behavior of RC shear walls with high-strength materials (Figures 3–4); and (2) capstone shear walls to understand the behavior of more complete specimens subject to reversed-cyclic shear and flexure-shear loading (Figure 5).

Ongoing Work

Pre-test numerical analyses of the deep beam and capstone shear wall test specimens are being conducted to predict peak loads, rebar and concrete peak stresses/strains, and crack patterns. The project is also moving forward with the testing of the deep beam specimens. Ultimately, the measured results from the deep beam and capstone wall tests will be compared with the numerical models, culminating in the improvement and validation of these models. The validated numerical models will then be used to refine future tests and perform parametric analytical studies using a broader number and range of design parameters.

Advanced Onsite Fabrication of Continuous Large-Scale Structures

Corrie I. Nichol
Idaho National Laboratory



Large structures such as pressure vessels and containment structures for gigawatt-sized reactors present significant transportation challenges, as do pressure vessels and even containment vessels for small modular reactors (SMR). This limits the placement of any reactor or SMR to areas accessible from large navigable water ways. This project is conducting initial development work toward a novel method for onsite fabrication of continuous large-scale structures such as pressure or containment vessels for the nuclear industry. This approach is also applicable to the petrochemical, chemical processing, and other industries that use large-process structures.

This project will investigate techniques and additive manufacturing methods to construct large-scale structures onsite from smaller format raw materials. The methods proposed not only have the potential to form the basic construct of such components (for example the shell), but also to form the necessary additional features such as nozzles as the structure is fabricated.

The near-term objectives of this project are to (1) determine the feasibility to precisely control deposition via thermal spray, material representative of pressure vessel steel, and (2) determine the suitability of thermal spray and other arc-based additive manufacturing processes for large scale-vessel or structure fabrication.

The ultimate goal of this research is to develop a method of producing large-scale structures onsite, as illustrated in Figure 1.

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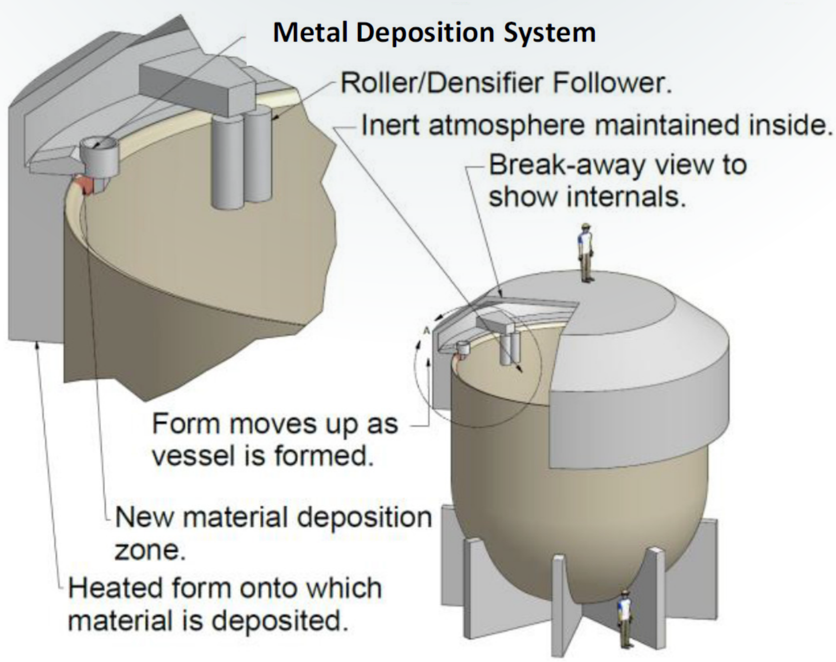

Figure 1. Concept of fabrication of large pressure vessel.

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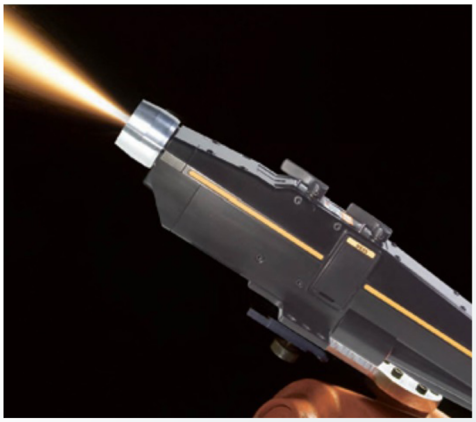

Figure 2. Spray system (Pictures from http://www.praxairsurfacetechnologies.com/components-materials-and-equipment/coating-equipment/thermal-spray-coating-systems/arc-spray).

Current Status

Research and investigation on potential surrogate processes has led to the selection of a dual arc spray deposition system for initial investigation of deposition parameters and process control. The equipment selected is commercially available, and is manufactured by Praxair TAFA®. The specific equipment selected is the model 9910i CoArc Arc Spray System (Figure 2). This equipment melts and entrains molten material into a gas jet by imposing an electric current between two continuously fed wire spools. This will allow for a variety of materials to be sprayed, and will enable work to commence in a short time frame.

This process will likely not be suitable for final fabrication of vessels or other large-scale structures, but will rather enable the initial investigation of spray deposition parameters, and will enable the development of real-time process monitoring and control algorithms. This process is similar to the spray-forming process, which is expected to meet the needs of the final rapid manufacturing system.

The small-scale arc spray work will be conducted in an enclosure with appropriate filtration and airflow required in a spray deposition process. This spray hood is also designed to contain the hot material that will be used during the processing and development work. A photograph of this industrial spray booth is shown in Figure 3.

The spray booth will be further modified to accommodate the automated equipment that will be necessary for further development. Currently a 3-axis gantry robot (just visible in the picture) is housed inside this spray hood, and this will be leveraged for control and movement of the spray deposition head.

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Figure 3. Spray booth.

Impact and Value to Nuclear Applications

Fabrication and transportation of large reactor components such as pressure vessels for SMRs or pressure vessel sections for other reactors is limited by site location. The methods for additive manufacturing have been progressively developing, and this project seeks to leverage the benefits of additive manufacturing in reactor fabrication. This has many potential benefits, including the ability to fabricate vessels from metal matrix composites, or a base material with clad metal structures that combine a corrosion-resistant alloy or a high-strength engineered alloy at the working interface with a less-expensive carbon steel backing. This process also enables raw materials to be brought to the construction site in an easily transportable form, where they are melted prior to or during the spraying process. This also eliminates the need to weld multiple small sections to form the vessel, eliminating the potential to form undesirable tensile residual stress states at welded interfaces.

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

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