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NASA LaRC Unveils NDE Simulation & Modeling Tools to Accelerate Adoption of Advanced Materials and Ensure Aging Infrastructure Safety

State-of-the-art NDE modeling and simulation tools are actively being used at NASA Langley. Several benefits are achieved by using such tools. First, the time needed to develop physical reference standards to demonstrate NDE capability is shortened, and associated costs are lowered. This is achieved by using the tools to optimize the design of physical reference standards before committing to expensive fabrication. Second, potentially lengthy trail and errors approaches to optimize NDE data acquisition parameters using expensive NDE equipment are shortened or eliminated completely. Last, the tools being used can overcome new inspection challenges encountered with newer materials and components, such as additively manufactured parts (for example, fracture critical metal spaceflight hardware made by laser powder bed fusion) and advanced composite components (for example, radomes, composite pressure structures, and composite overwrapped pressure vessels).

Modeling simulation tools are just one part of developing a robust NDE capability. The timeline for bringing these tools to full maturity ultimately depends on taking the tools out of the R&D environment and demonstrating their utility to inspect fracture and safety critical hardware in NASA's spaceflight hardware production and ground support equipment environments.

Use of Modeling to Facilitate Adoption of Advanced Materials:

Toward this goal, several areas are emerging where the use of simulation tools show the greatest benefit and promise. The first area is additive manufacturing, which takes advantage of the ability to fabricate parts with intricate internal geometries that are difficult or impossible to make by conventional subtractive manufacturing routes. The need to be able to 'see' intricate internal features and interrogate rough or coarse as-built surfaces in additively manufactured parts, without unacceptable losses in NDE sensitivity, places special demands on conventional NDE methods and equipment. In the worst case, the NDE method of choice may miss the critical defect type, many of which are unique to additive manufacturing (for example, trapped powder and layer defects). Similarly, the NDE method of choice may be unable to access or interrogate internal surfaces or embedded defects in the region of most interest with the required sensitivity as stipulated by overarching NASA requirements documentation such as NASA-STD-5009 *Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components*, NASA-STD-5019 *Fracture Control Requirements for Spaceflight Hardware*, and NASA-STD-6016 *Standard Materials and Processes Requirements for Spacecraft*.

On the horizon, structures completely designed and optimized by Artificial Intelligence for a particular functionality, could be extremely complex. Similarly, advanced composites may have internal complexity that can "hide" detail, even when the outside geometry is simple. Together, these structures that may consist of hybrid materials and complex microstructure will push the boundaries of what should be defined as a defect. Material and structural design has evolved to the point that localized damage, i.e. crack growth, could be considered late-stage failure. Therefore, to ensure adequate safety and risk reduction, we may need to identify precursor or incipient defects responsible for crack or damage initiation.

This is especially true for NDE methods such as eddy current, ultrasound, and thermography that usually have better resolution and specificity, as the sensors can be located closer to the location of damage initiation. According to Dr. Michael Horne, (Principal Engineer Associate, National Institute of Aerospace) who sits at NASA Langley, "The savings from these methods would be in time and money spent trying to create representative physical standards for NDE technique development. Simulation and modeling could help design the standard and down-select an appropriate technique."

With remote interrogation and fixed sensor modalities such as radiography and acoustic emission, modeling could be used to help interpret NDE results. Dr. Horne continues, "modeling that addresses 'what if?' questions, covering the gamut of possible failure mechanisms, could be compared to actual NDE data to better identify the failure modes and underlying causes." While modeling is typically applied after manufacturing, it is plausible that early-stage modeling during the design phase could be used to customize more effective and efficient NDE inspection configurations, such as partial angle CT or very sparse AE networks. Early-stage NDE modeling can be informed by failure analysis already in place, which likely includes CAD geometries and critical areas identified by modeling and simulation. This reduces the experimental time and expense of NDE by identifying regions unlikely to fail and, thus do not require a comprehensive and thorough evaluation. Admittedly, experiment will always be needed to either validate modeling of novel inspection techniques or investigate novel types of failure. However, NDE modeling has the potential to reduce design cycle expenses.

<u>A Practical Application: Using CIVA to Simulate Complex Weld Inspections on Aging Layered Pressure Vessels at NASA</u>

In the 1950s and 1960s, NASA acquired approximately 360 high-capacity ground-based metallic multi-layered pressure vessels (MLPV) for use at multiple centers across the agency. These vessels were fabricated prior to the adoption of American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) construction techniques applicable to MLPVs. As such, the vessels were considered 'non-code' when applicable versions of the ASME standards were finally adopted. These MLPVs, which are still in use today, now have to be qualified and certified to allay safety concerns and ensure weld integrity to support continued operations. To enable certification, a significant amount of structural analysis and material testing has been done to identify critical flaws, one of which is cracking in a circumferential 'V'-shaped shell-to-shell weld (Fig. 1). Ultrasonic inspection of the welds, which connect stacks of as many as thirty 6.5-mm (¼-in.) steel plates is very challenging, since the only usable sound path to inspect the weld is through the top of the weld itself because of the lack of access to the vessels' interior (Fig. 2). Consequently, inspection of inner weld areas joining adjacent shells is extremely difficult.

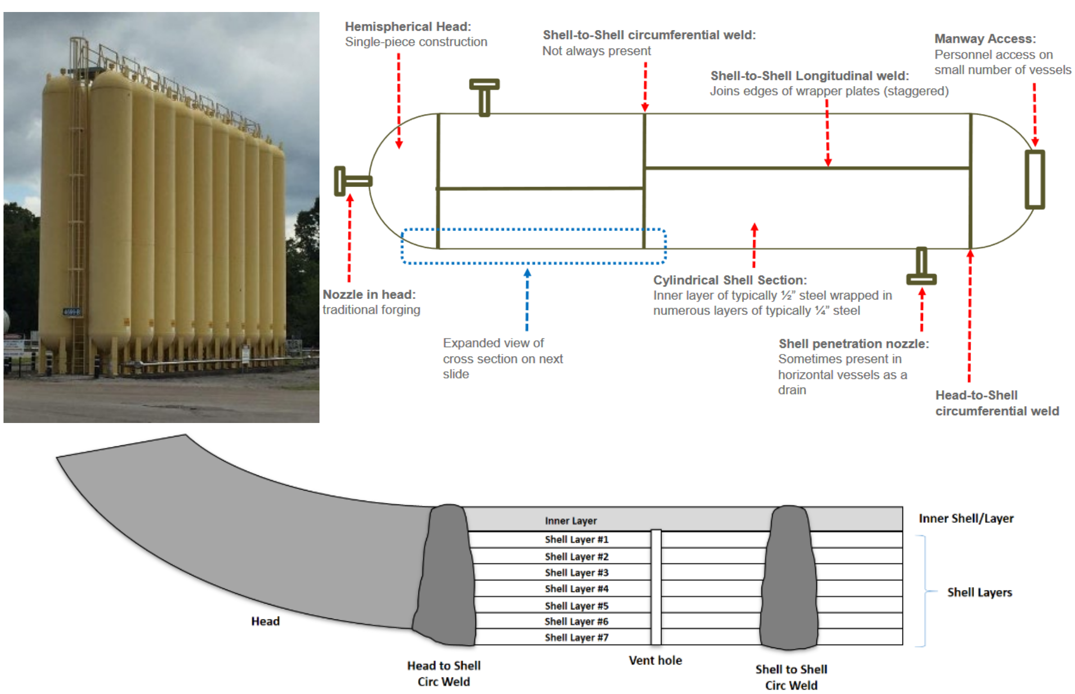

Figure 1. Layered pressure vessels at NASA (upper left) and diagrams showing the location of the

shell-to-shell circumferential welds (upper right and bottom) [1].

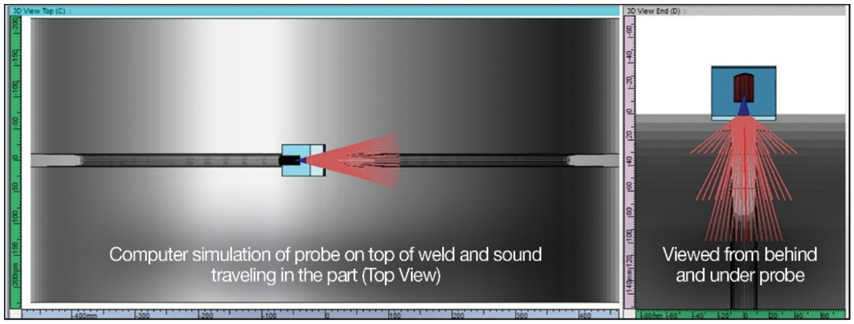

Figure 2. Ultrasonic inspection of a circumferential shell-to-shell weld in a layered pressure vessel [2].

According to Peter Juarez, a Research Engineer at NASA Langley, "the unique geometry of MLPV weld makes it an ideal candidate for iteratively simulating inspection scenarios and help interpret low fidelity real world data." For this task, the computational modeling and simulation software CIVA was selected to simulate various NDE methods. The CIVA ultrasonic module, for example, allows the user to simulate various inspection processes (pulse echo, tandem or time-of-flight-diffraction (TOFD)) and probes (conventional, phased arrays (PAUT), or electromagnetic acoustic transducers (EMAT)). At Langley, phased array ultrasonic inspections of an LPV were simulated using CIVA (Fig. 3) and the results were compared to ensure CIVA could represent this use case. Verification was performed by measuring the relative dB levels between two known flaws in the ultrasonic inspection data and comparing it to the relative dB between the same two flaws in the simulation data. Next, multiple scenarios were simulated with variations in flaw types, flaw orientation, part surface roughness, part geometries, and inspection methodologies/equipment. Through these efforts, Peter and his team were able to study the effects that flaw characteristics and geometry imperfections had on detectability, and recommend novel inspection methodologies for the more challenging flaw types.

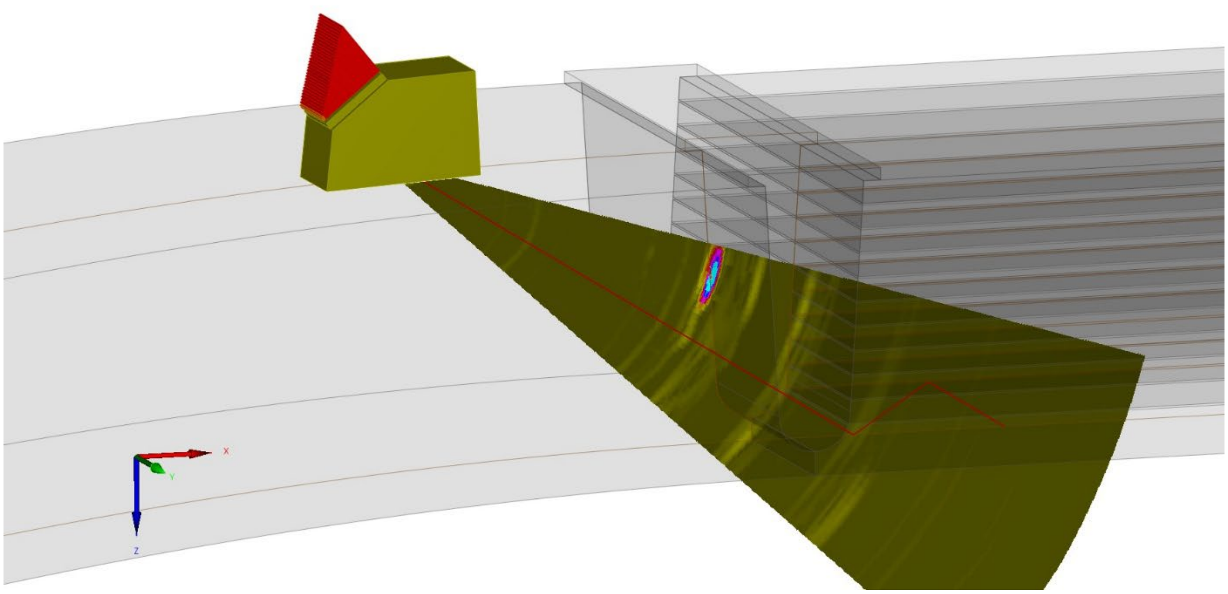

Figure 3. CIVA simulation of a layered pressure vessel.

More recently, OSMA's Pressure System program has made significant advancements in detecting weld flaws in MLPVs using a Zetec state-of-the-art phased array ultrasonic test (PAUT) Dynaray system coupled with custom designed 2D sensing units [2]. In the future, comparison of the Zetec PAUT data and CIVA modeling results could conceivably allow optimization of data acquisition parameters of Zetec devices and other search units (including optimization of pretest machining operations on LPVs to maximize coupling between the PAUT sensor and the LPV weld surface). Peter notes, "CIVA can be used to detect different flaws at different locations using different probes using the CAD geometry of the inspected part, and has a successful track record for optimizing UT inspections of equipment used in the nuclear power industry." Peter continues, "One of the powerful features of CIVA is to simulate inspection of welds such as those found in MLPVs, and determine the detectability of weld cracks at different orientations." Verifying the modeling results predicted by CIVA with experimental data obtained in the field is an area of possible future investigation. Brian Stoltz, a Damage Tolerance Engineer at NASA MSFC, adds, "Tying in parametric Finite Elements Analysis (FEA) probabilistic models would add further confirmation towards validating analytical and tests approaches currently used for MLPVs." In terms of MLPV failure analysis, comparison of PAUT data and modeling results could help identify precursor or incipient defects responsible for crack or damage initiation, and ultimately, to identify the failure modes and underlying causes over the course of the MLPV lifecycle. Lastly, modeling could facilitate the development of suitable physical reference standards for future MLPV designs.

Potential synergies between NASA, the Navy, and the Space Force are now being explored to improve the safety and reliability of MLPV assets. , as well as related assets such as castellated beams that support overhead cranes used by NASA and others. It is anticipated that benefits would accrue through NASA R&D data sharing and provided training. Clifton Arnold, the OSMA Program Executive for Pressure Systems, Propellants & Pressurants, and Lifting Devices, concludes, "OSMA is now transitioning out of its R&D effort to an implementation phase for MLPV management." Next on NASA's agenda is a multi-year pilot project to identify and baseline critical weld flaws in in-service MLPVs. This project will allow the Agency to selectively repair or replace MLPVs with known and verified critical flaws. Additionally, CIVA shows great potential in modeling weld flaws in other assets, such as castellated beams that support overhead cranes used by NASA and others. He adds, "All of the tools available to identify flaws in NASA's MLPV fleet have been considered, and now the challenge becomes tracking critical flaws using down-selected technologies and methodologies, whether they be by test or analysis."

References

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