Steel Structures Research Update

Additive Manufacturing for Structural Steel Applications

JUDY LIU

INTRODUCTION

Research under way on large-format metallic additive manufacturing for structural steel applications is highlighted. Dr. Ryan Sherman, Associate Professor in the School of Civil and Environmental Engineering at the Georgia Institute of Technology, leads this study. Dr. Sherman's research on steel bridge and ancillary highway structures encompasses large-scale laboratory testing, field monitoring, material characterization, and finite element simulation. Research interests include fatigue, fracture, and additive manufacturing for civil engineering infrastructure. The Terry Peshia Early Career Faculty Award (AISC), the Robert J. Dexter Memorial Award Lecture (Steel Bridge Task Force), and Georgia Tech's Student Recognition of Excellence in Teaching are among Dr. Sherman's accolades. An AISC Milek Fellowship, awarded in 2023, supports this research, building on work with Lincoln Electric Additive Solutions and funded by the Federal Highway Administration (FHWA). As part of that effort, AISC Undergraduate Research Fellow Shirin Raschid Farrokhi investigated fatigue performance under the mentorship of PhD candidate Hannah Kessler. Kessler, the 2025 Reidar Bjorhovde Outstanding Young Professional recipient, also conducted tension, impact, and fatigue testing for the FHWA project and, with PhD student Zachary de Haaff, has been integral to the research team. Selected highlights from completed and planned research are presented.

BACKGROUND

Additive manufacturing (AM) presents opportunities for steel construction, but questions about material, connection, and component behavior and design must be addressed. Advantages for steel AM include automation and the ability to create and optimize complex geometries with reduced material waste. Such advantages have been demonstrated in aerospace, maritime, and other industries. Potential applications in steel construction range from new construction to repair and rehabilitation (Kessler and Sherman, 2025). Research is needed to address knowledge gaps and advance AM for structural steel applications.

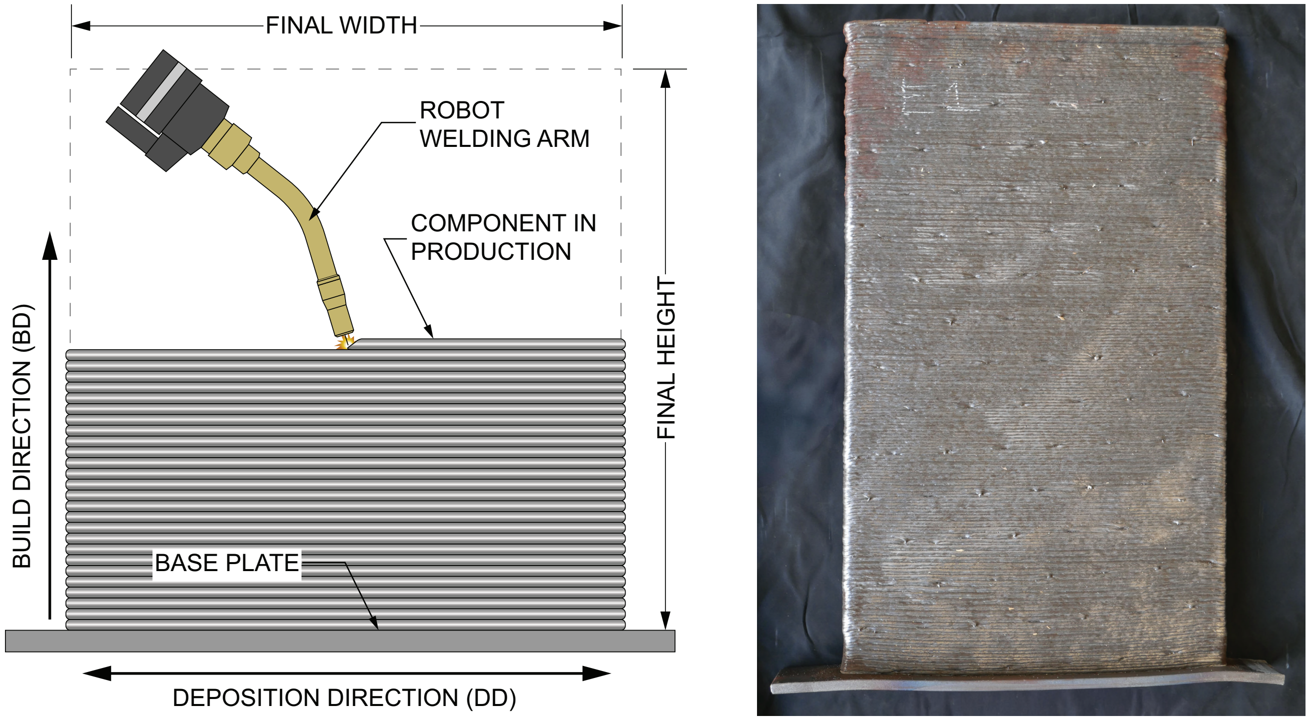
The team has been researching wire arc AM (WAAM). WAAM is a directed energy deposition (DED) process that uses the same metallic wire feedstocks used for welding. A completed study has answered questions about material and fatigue behavior. Specifically, the team has created material property datasets for WAAM ER70S-6 and ER80S-Ni1 filler metal components through tension, Charpy V-notch (CVN) impact, and fatigue performance tests. They have studied the influence of the as-built, or as-fabricated, surface finish, as well as material property anisotropy with respect to build and deposition directions (Sherman et al., 2023, 2024).

The tension and impact test programs examined the effects of interpass temperature, orientation, and location within the AM build. The robotic welding arm deposited layers of metal horizontally and built vertically on those layers (Figure 1). Tension coupons from the AM build were parallel to the deposition direction (DD), parallel to the build direction (BD), and oriented at 45° (Figure 2). CVN specimens were parallel to the deposition direction or the build direction. CVN specimens were also located within the middle half-thickness (½ T) or at a quarter-thickness (¼ T), as shown in Figure 2. Relatively low and high interpass temperatures were studied. Details for the test programs may be found in Kessler and Sherman (2024, 2025).

Tension test results showed dependence on interpass temperature. Loading direction had little influence on strength. For both filler metal classifications and interpass temperatures, yield and tensile strengths did not exhibit any significant anisotropy. However, the percent elongation at fracture was affected by the load orientation. Results showed higher percentage elongation for gauge lengths and loading parallel to the deposition direction (DD) than those with gauge lengths and loading parallel to the build direction (BD) and at 45° between the BD and DD. Low interpass temperatures correlated to higher yield and tensile strengths than for the high interpass temperatures (Sherman et al., 2024). More results may be found in Kessler and Sherman (2024, 2025).

CVN impact test results exceeded ASTM A709/A709M Grade 50 (ASTM, 2024) limits for both members requiring

Judy Liu, PhD, Research Editor of the AISC *Engineering Journal*, Professor, Oregon State University, School of Civil and Construction Engineering, Corvallis, Ore. Email: judy.liu@oregonstate.edu



(a) Schematic *(b) Photograph*

Fig. 1. Build and deposition direction.

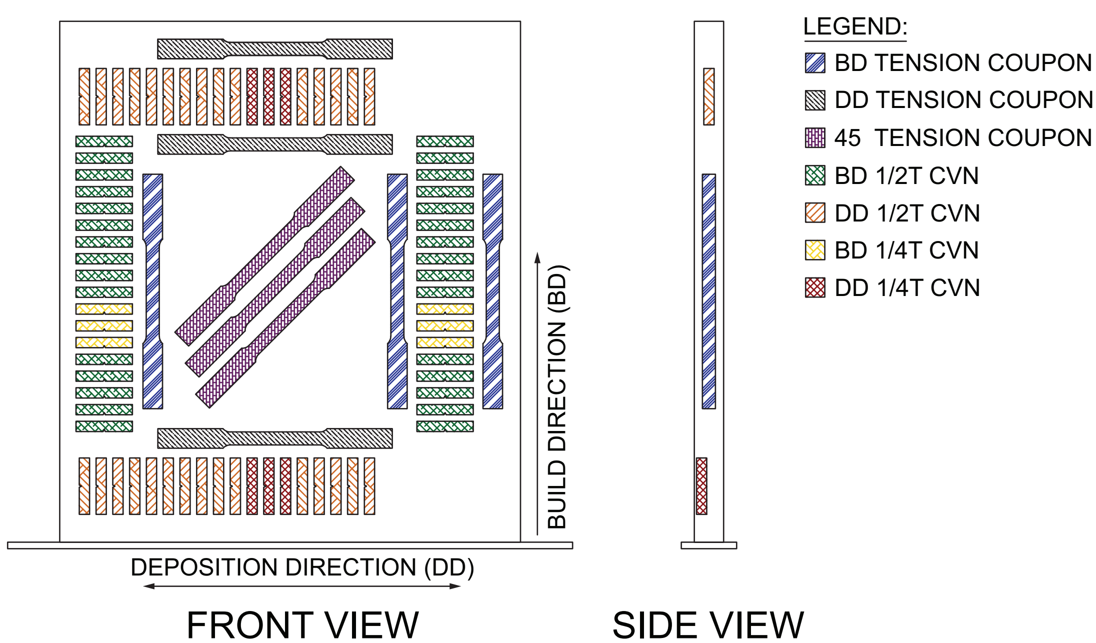


Fig. 2. Tension and CVN specimen orientations and locations through the thickness.

and not requiring fracture critical control practice for all service temperature zones (Sherman et al., 2024). More results may be found in Kessler and Sherman (2024, 2025).

The test program also addressed the knowledge gap for fatigue behavior of ER80S-Ni1 feedstock. Fatigue studies had been conducted for WAAM ER70S-6 (e.g., Sherman et al., 2023). ER80S-Ni1 has corrosion resistance to atmospheric weathering and is a matching feedstock for weathering steel applications such as bridges and other transportation infrastructure. The primary objectives of this study were to characterize fatigue behavior of WAAM ER80S-Ni1 for machined and as-built surface finishes at multiple interpass temperatures; to correlate fatigue life to fatigue detail categories from the AASHTO LRFD Bridge Design Specifications (2020); and to determine the influence of as-built, or as-fabricated, surface finish on fatigue performance. The AM build and fatigue specimens, with the as-built surface finish maintained or removed within the gauge length, are shown in Figure 3. Results showed machined specimen fatigue lives above the upper-bound curves for AASHTO detail Category A. For the as-built specimen, fatigue lives were between Categories C and D. There was no dependence on interpass temperatures for machined or as-built specimens. Given the clear dependence on surface finish, a machined surface finish was recommended for a higher level of fatigue performance (Farrokhi and Sherman, 2024; Kessler et al., 2025). AM builds with as-built surface finishes could also be sized for the desired stress range.

RESEARCH THEMES AND OBJECTIVES

The Milek Fellowship work continues research needed to realize the potential of large-format metallic additive manufacturing (AM) for structural steel applications. The two major themes for the research are connection considerations and component demonstration. For connections, the team is characterizing the behavior of bolted and welded AM connections, using component testing to establish mechanical properties as well as fatigue performance. Component demonstration will be through computational analyses and large-scale testing. The researchers will potentially examine structural steel applications such as an AM component or an AM repair.

The connection research objectives span strength limit states to fatigue performance. Small-scale component tests establish bolt bearing, tearout, and block shear rupture strengths. Testing of AM to base metal joints provides tensile and impact properties for multiple interpass temperatures. Fatigue tests quantify the performance of AM material and the influence of pretensioned high-strength bolts.

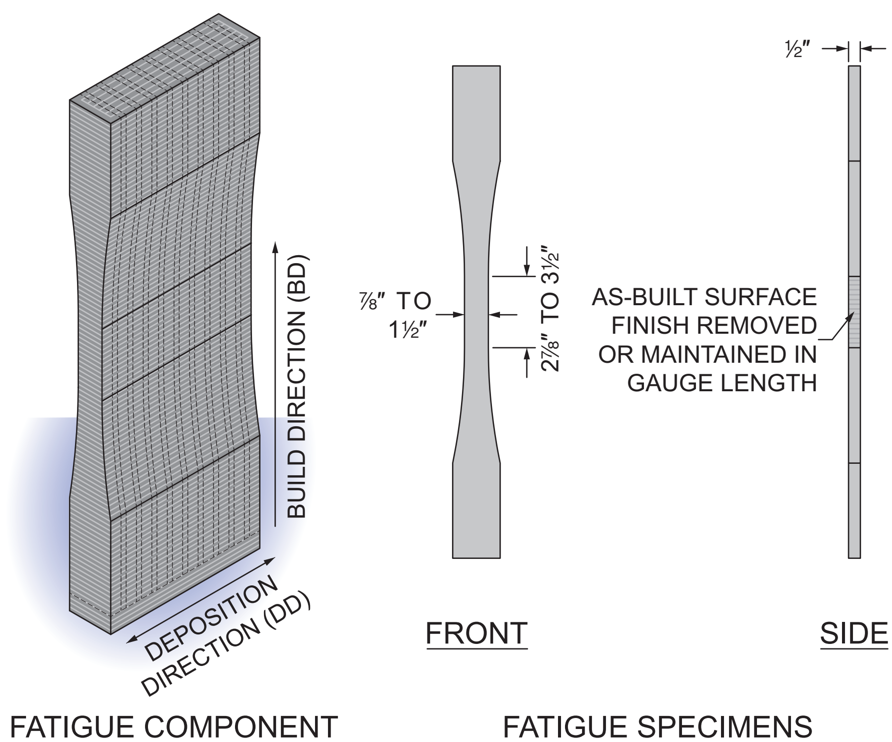


Fig. 3. Fatigue component fabrication schematic with specimen front and side views.

The component demonstration objectives focus on application and validation. The researchers seek to develop a model workflow to guide designers from concept to fabrication. Large-scale experimental testing will be used to validate design and performance of an optimized AM structural steel component or possibly an AM repair.

The research is organized into five primary tasks: bolted connection strength, welded joint properties, fatigue performance, model workflow development, and large-scale structural evaluation. At the time of writing, the work had been focused on experimental test program development for the first three tasks.

Bolted Connection Evaluation

Bolted connection limit states and AM parameters are studied. The test specimens are designed and detailed for the desired limit state—for example, net section rupture. Machined and as-built specimens are loaded parallel to the build or deposition direction.

The test setup simulates a tension member with a bolted connection. The hydraulic actuator and test frame impose uniaxial loading through double-shear connections to the specimen (Figure 4). The test area is the lower portion of the specimen, connected to the fixture base anchored to the strong floor. Instrumentation includes digital image correlation (DIC) on the test area.

The bolted connections are designed for the limit states of bolt bearing, bolt tearout, net section rupture, and block shear rupture. Connections for the WAAM ER70S-6 specimens use ⅞-in.-diameter ASTM F3125/F3125M Grade A325 (2025) bolts. The base module has overall dimensions of ½ in. × 6 in. × 12½ in. (Figure 5). The 15⁄16-in.-diameter bolt holes are located as needed for the desired limit state. The bearing and block shear specimens maintain the original 6 in. × 12½ in. geometry. For bearing, a single bolt hole is centered with a 2½ in. end distance. For block shear rupture, two bolts are symmetrically placed with 2½ in. spacing and a 2½ in. end distance. The tearout and net section rupture specimens use reduced sections for higher stresses in 3-in.-wide test areas. For the tearout specimen, the bolt hole is shifted closer to the end, with a distance of 1⅛ in. For net section rupture, the bolt hole is located 2 in. from the end.

In these tests, AM parameters investigated are surface finish and loading direction. Surface finish is either machined or as-built. Machined specimens are tested for all limit states. The machined specimens are built to a 1 in. thickness and machined to ½ in. thick. As-built specimens are also tested for the net section rupture. All specimens are tested for loading parallel to the build direction or to the deposition direction. There are three replicates for each combination of limit state, surface finish, and loading direction.

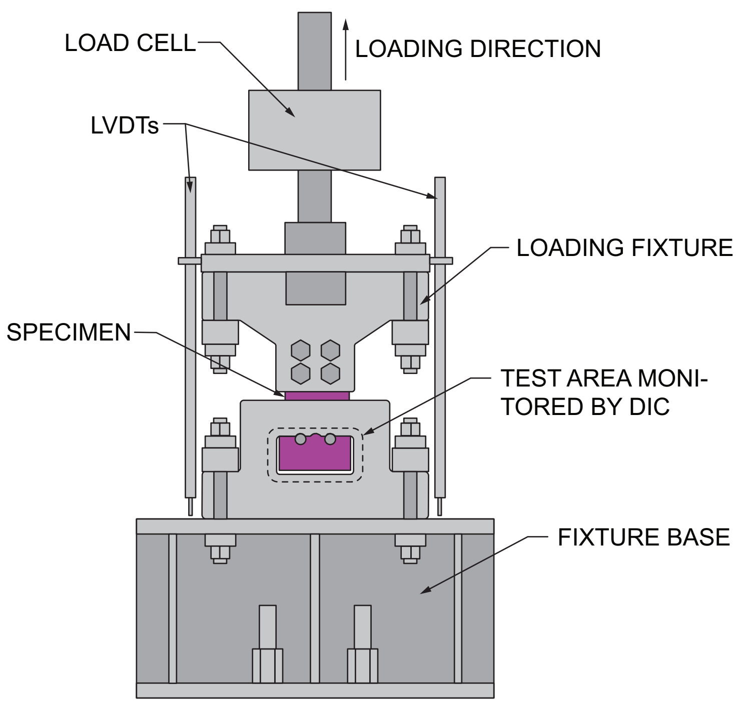


Fig. 4. Bolted connection test setup.

Welded Joint Evaluation

Tensile, CVN impact, and bend properties are evaluated for WAAM ER70S-6 builds welded to structural steel plates. The AM build direction is perpendicular to the weld to the ASTM A572/A572M Gr. 50 (2021c) plate (Figure 6). Two welded assemblies are planned; one AM build has a lower interpass temperature than the other.

Tensile properties are evaluated for different directions and locations in the welded assembly. The specimens, taken from the mid-thickness, are used to evaluate the tensile properties of the AM build, the A572 base metal, and the heat affected zone (HAZ) at the weld. Loading and specimen axis are parallel to the build direction or the deposition direction (Figure 6). Per assembly, there are three replicates for most combinations of specimen type (AM, base metal, HAZ) and build direction. The one exception is that there is only one HAZ specimen per plate in the deposition direction. The tensile test uses a universal testing machine (UTM), following ASTM E8 (2021a).

CVN impact properties are also evaluated. Most specimens are from mid-thickness (½T) of the assembly with some from the quarter thickness (¼T) location. The change in location is used to assess potential variation through the thickness. The specimens are sampled to test impact properties of the AM material, A572 base metal, and the HAZ. The specimen notches are broached at Georgia Tech to ensure they are within the HAZ. Per assembly, there are 15 tests for each combination of specimen type (AM, base metal, HAZ) and the ½T location. There are three tests per assembly for each specimen type and the ¼T location. Testing follows ASTM E23 (2018).

Bend tests are conducted on the welded joint builds. Specimens are from mid-thickness (½T) of the assembly. The specimens are sampled to test the bend properties of the face and side of the welded joint. There are three tests per assembly for each specimen type, face bend and side bend. Testing follows AWS D1.1 and D1.5 (2025a, 2025b).

Fatigue Performance Evaluation

Fatigue tests align with prior research and also explore the behavior of holes with and without bolts. Loading for all specimens is in the build direction. As-built and machined WAAM ER70S-6 specimens (Figure 7) are tested for stress ranges of 16–20 ksi and 30–38 ksi, respectively. Each combination of surface finish (as-built or machined) and stress range is tested with and without pretensioned, high-strength bolts. The as-built test combinations have three replicates; the machined tests are repeated for two replicates. The test procedure with the UTM follows the ASTM E466 (2021b).

Component Demonstration Research

With the unique AM opportunities for structural steel come challenges in predicting performance and establishing design procedures to meet specifications. The team plans to demonstrate the process with a computational parametric study and large-scale laboratory testing. Specifically, the demonstration includes a workflow model and laboratory testing of WAAM ER70S-6 structural steel applications.

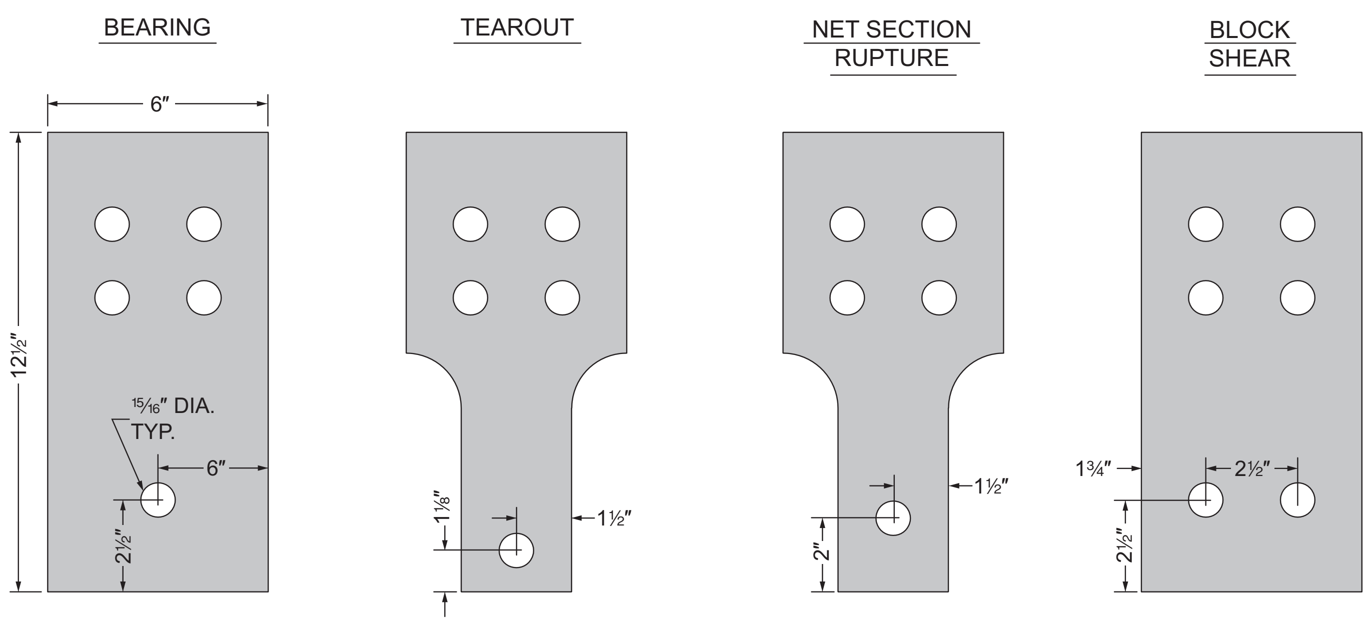


Fig. 5. Bolted connection specimens.

A model workflow delineates the design process. The freedom with AM necessitates new design guidance, tools, and methods beyond conventional prescriptive provisions for steel building and bridge design. Unique and potentially intricate geometries require finite element analysis (FEA) along with performance-based design provisions for schematic and design development. As a demonstration, the team plans to develop FEA and an optimization process for an AM structural steel component. Optimization of topology and shape may use objective functions such as minimizing strain energy or maximizing stiffness within a specified volume or weight of material. Results from the component evaluations inform material models used in the FEA.

Large-scale experimental evaluation will provide further demonstration of the process. Potential demonstration components include an AM beam-to-column connection node

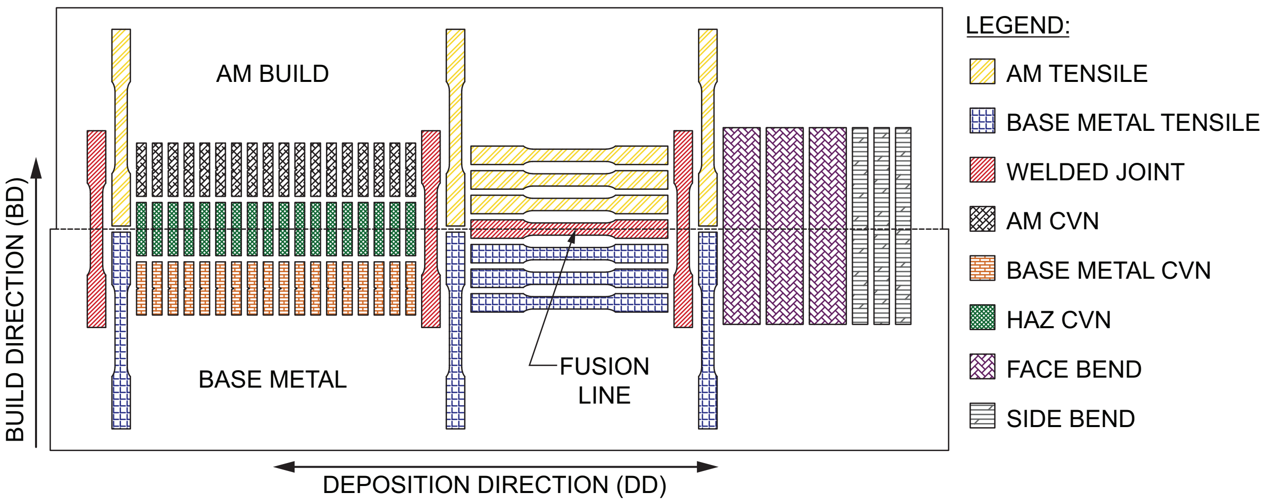


Fig. 6. Welded joint tensile and CVN specimen orientations and locations in AM build, steel base metal, and weld or HAZ.

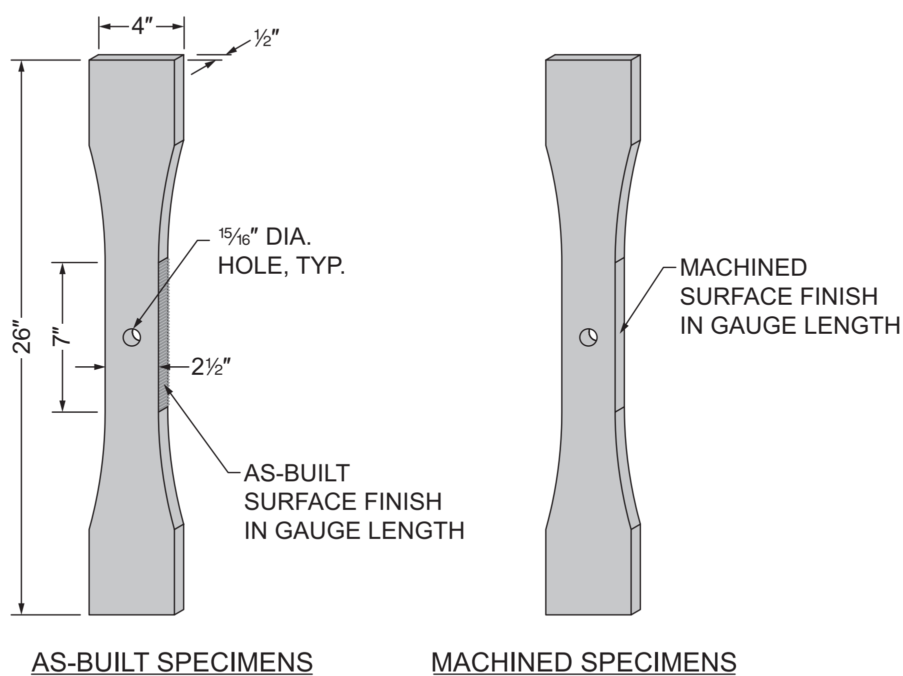


Fig. 7. Specimens with as-built and machined surfaces for fatigue performance tests.

and an AM corrosion repair of a beam end. Destructive testing results will be used to validate the design process.

An example of an ongoing, large-scale AM demonstration project is the AISC AM Pedestrian Bridge, featured at the 2025 NASCC in Louisville, Kentucky. As part of the AISC AM Exploratory Task Force, a range of structural steel industry stakeholders collaborated to design and fabricate a full-scale pedestrian bridge that highlights the opportunities AM provides the industry. The bridge merges traditional rolled steel products with the use of AM components, creating geometries and opportunities not feasible without AM. The research team at Georgia Tech will further this demonstration project by conducting controlled load testing of the AM bridge, helping to inform future integration into the steel industry.

INDUSTRY INVOLVEMENT AND EXPECTED OUTCOMES

Insights from industry experts throughout the project strengthen the impact of the research. Dr. Sherman serves as the chair of the AISC AM Exploratory Task Force, and the Milek Fellowship research team is advised by an industry oversight group. Fabricators, erectors, producers, engineers, researchers, and service providers in these groups provide insights and suggestions that guide research into practice. Research deliverables will include AM material and fatigue performance datasets, guidelines for bolted and welded connections, a model workflow, and large-scale AM demonstrations for new construction and repair. Among the expected benefits are innovative options for optimized and complex connection details, accelerated construction, repair and rehabilitation.

ACKNOWLEDGMENTS

Thank you to Dr. Ryan Sherman and PhD candidate Hannah Kessler for their many contributions to this article. The work of PhD student Zachary de Haaff and former undergraduate researcher Shirin Farrokhi is also acknowledged. The Federal Highway Administration (FHWA) supported the prior research under contract 693JJ321C00032. The Milek Fellowship research is funded by the American Institute of Steel Construction (AISC), with in-kind support provided by Lincoln Electric Additive Solutions. The researchers would also like to thank the AISC oversight committee: Joe Zona (Simpson Gumpertz & Heger Inc. Consulting Engineers), Brad Fletcher (Atlas Tube Inc.), Ronnie Medlock (High Steel Structures LLC), Lee Shoemaker (Metal Building Manufacturers Association, Thomas Associates, Inc.), Brian Volpe (Cives Engineering Corporation), Curtis Decker (Lincoln Electric), Carlos de Oliveira (Cast Connex), Devin Huber (AISC), Chris Garrell (National Steel Bridge Alliance), Luke Faulkner (AISC), Rob Connor (Purdue University), and Amit Kanvinde (University of California–Davis). Any findings or recommendations are those of the researchers and do not necessarily reflect the views of the sponsors.

REFERENCES

AASHTO (2020), *LRFD Bridge Design Specifications*, 8th Ed., American Association of State Highway and Transportation Officials, Washington, D.C.

ASTM (2018), *Test Methods for Notched Bar Impact Testing of Metallic Materials*, ASTM E23-18, ASTM International, West Conshohocken, Pa.

ASTM (2021a), *Test Methods for Tension Testing of Metallic Materials*, ASTM E8-21, ASTM International, West Conshohocken, Pa.

ASTM (2021b), *Standard of Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials*, ASTM E466-21, ASTM International, West Conshohocken, Pa.

ASTM (2021c), *Standard Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel*, ASTM A572/A572M-21e1, ASTM International, West Conshohocken, Pa.

ASTM (2024), *Standard Specification for Structural Steel for Bridges,* ASTM A709/A709M, ASTM International, West Conshohocken, Pa.

ASTM (2025), *Standard Specification for High Strength Structural Bolts and Assemblies, Steel and Alloy Steel, Heat Treated, In. Dimensions 120 ksi, 144, ksi, and 150 ksi Minimum Tensile Strength, and Metric Dimensions 830 MPa and 1040 MPa Minimum Tensile Strength*, ASTM F3125/3125M, ASTM International, West Conshohocken, Pa.

AWS (2025a), *Structural Welding Code—Steel*, AWS D1.1/D1.1M:2025, American Welding Society, Miami, Fla.

AWS (2025b), *Bridge Welding Code*, AWS D1.5/D1.5M:2025, American Welding Society, Miami, Fla.

Farrokhi, S.R. and Sherman, R.J. (2024), "Understanding the Fatigue Behavior of Wire Arc Additively Manufactured Steel: Report of Fatigue Testing Results," Georgia Institute of Technology, Report to the American Institute of Steel Construction.

Kessler, H.D., Farrokhi, S.R., and Sherman, R.J. (2025), "Fatigue Performance of Wire Arc Additively Manufactured ER70S-6 and ER80S-Ni1," *Journal of Bridge Engineering*, ASCE, Vol. 30, No. 10. https://doi.org/10.1061/JBENF2.BEENG-7229.

Kessler, H.D. and Sherman, R.J. (2024), “Tension and Charpy V-Notch Impact Properties of Wire Arc Additively Manufactured ER80S-Ni1,” *Structures,* Vol. 61, https://doi.org/10.1016/j.istruc.2024.106134.

Kessler, H.D. and Sherman, R.J. (2025), “Tension and Charpy V-Notch Impact Properties of Wire Arc Additively Manufactured ER70S-6,” *Journal of Materials in Civil Engineering*, ASCE, Vol. 37, No. 5, https://doi.org/10.1061/JMCEE7.MTENG-1873.

Sherman, R.J., Kessler, H.D., Frank, K.H., and Medlock, R. (2023), “Evaluation of Large-Format Metallic Additive Manufacturing (AM) for Steel Bridge Applications: Final Report of Tensile, Impact, and Fatigue Testing Results,” Georgia Institute of Technology, Atlanta, Ga.

Sherman, R.J., Kessler, H.D., Frank, K.H., and Medlock, R. (2024), “Evaluation of Large-Format Metallic Additive Manufacturing (AM) for Steel Bridge Applications [Tech Brief],” Federal Highway Administration, FHWA-HIF-24-008, Washington, D.C.