

High Strength Structural Steel in Building Applications

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INTRODUCTION

Ongoing research is taking steps forward in the adoption of high strength structural steel in building design and construction. This University of Cincinnati (UC) study is led by Dr. Rachel Cross, Associate Professor in the Department of Civil & Architectural Engineering & Construction Management. Dr. Cross's research interests include structural steel design and behavior, performance-based fire design of steel buildings, seismic analysis and design, and multi-hazard resilience. Dr. Cross is an AISC Terry Peshia Early Career Faculty Award recipient, recognized for contributions and high potential in structural steel research and teaching. Graduate student Kara Stall is one of AISC's inaugural Peggy A. McCartney/B&B Welding Company, Inc., PhD Fellows. The fellowship supports full-time PhD students committed to academia and participating in AISC-funded research—in this case, material characterization and implementation strategies for high strength structural steel in building applications. Selected highlights from the work to date are presented, along with a preview of future research tasks.

BACKGROUND AND MOTIVATION

The interest in high strength steel in building design and construction is clear, but current design guidance and specifications are not. Benefits include structural performance as well as weight and cost savings. Such benefits have been realized in bridge design, for example. However, the “success with high-strength steel in U.S. bridges has been slow to translate to the building market.” (AISC, 2019). In 2017, an Ad Hoc Task Group on High Strength Steel was charged with guiding AISC committees to improved clarity and pathways in the AISC *Specification for Structural Steel Buildings* (2022) for adoption and innovation in application of high strength steel in building construction. The Task Group (TG) reviewed technical literature on high strength structural steel (named HS3 by the TG); studied HS3

applications across building, bridge, and other industries domestically and internationally; examined new material adoption pathways and standards worldwide; and developed recommendations (AISC, 2019).

High strength steel properties and uses vary by sector. In building construction, HS3 is any steel with specified minimum yield stress, F_y , of 65 ksi or greater. HS3 processes include high strength low-alloy (HSLA) for rolled shapes, quenching and tempering or self-tempering (Q&T or QST), and thermo-mechanical control processes (TMCP). High strength is typically 80 ksi or greater in bridge construction today. Specifically, high-performance steel (HPS) has been developed for improved weldability and fatigue performance. HPS is commonly used in built-up shapes (from plate) that may be hybrid members, with a lower grade in the web plate compared to the flange plates. This concept that “key members in a structure may use different grades of steel to meet a particular need ... has seen limited use in bridge construction, but is a relatively new thought for building construction outside of seismic applications.” (AISC, 2019)

Obstacles to implementation include material behavior and questions about the validity of current design specifications. HS3 stress-strain behavior differs from mild steel in a lower yield to tensile strength ratio, a smaller or absent yield plateau, and a shorter strain hardening region, as shown in Figure 1. This may affect the tension member limit state of yielding on the gross cross section, for example. Whereas gross cross-section yielding may be clear for mild steel members, the limit states and strengths may change over relatively low deformation levels in high strength steel members. In addition, the modulus of elasticity of HS3 does not change relative to conventional steel, so use of the material is best realized in force-controlled applications. Members that are deflection-controlled would likely not benefit significantly by shifting to HS3 materials.

The practice of expressing residual stresses in terms of F_y presents another challenge. Studies on high-strength welded built-up and rolled shapes (e.g., Rasmussen and Hancock, 1995; Ban et al., 2012) show that residual stresses can be $0.2F_y$ or lower, even in welded sections. Simplified expressions—for example, $0.3F_y$ based on mild steel—may overestimate residual stresses and underestimate HS3 member capacity.

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This issue extends to element width-to-thickness limits. Compact, noncompact, and slender element criteria are also functions of F_y . These limits were developed considering steel with F_y less than or equal to 50 ksi. HS3's residual stress and strain hardening characteristics may affect local buckling and motivate changes to these limits (AISC, 2019).

Provisions related to plastic hinging and inelastic rotations may also need to be revisited. AISC 360, Appendix 1.3.2a, stipulates that the specified minimum yield stress, F_y , shall not exceed 65 ksi for members subject to plastic hinging (AISC, 2022). This restriction reflects a limitation of the studies used to develop plastic analysis and design provisions. Some small-scale bend test results supported a proposed increase to $F_y = 70$ ksi, but the AISC Task Committee reviewing the proposal decided that large-scale tests would be needed to demonstrate member-level ductility (AISC, 2019). Related HPS girder research (e.g., Barth et al., 2000; Green et al., 2002) demonstrated that the increase in yield stress and yield-to-tensile ratio, the decrease in strain-hardening modulus, and lower deformation ductility adversely affect the inelastic rotation capacity.

HS3 material and member behavior affect compression and flexural member design. For example, the existing column curves may not adequately predict HS3 member capacity. Also, high strength members may become more slender (globally and locally), requiring more careful attention to torsional and flexural torsional buckling behavior. For slender elements, the strength reduction approach may need to be adapted for higher strength steel given material behavior and residual stresses. Similar considerations exist for

flexural members, as local buckling and lateral-torsional buckling provisions are based on residual stress and assumptions about material behavior (AISC, 2019).

The Task Group conducted a survey of steel designers, which confirmed interest in HS3 as well as current barriers. All 27 respondents agreed they could use steel with yield strength from 65 to 145 ksi. Top choices for structural shapes were W-shapes, plate, and HSS. Trusses and composite columns were most popular applications, and the respondents saw the most potential for HS3 in high-rise buildings (more than 20 stories), arenas, convention centers, and stadiums. Some shared positive experiences, including a switch from 50 ksi to 65 ksi for columns, braces, and truss members to save over 100 tons of material on a high-rise residential project. Current barriers included technical issues already identified and other concerns. Survey participants noted lack of information about cost, market availability, and product applications, as well as limitations on use. Some commented on ductility, toughness, strength versus serviceability, and education needed for steel fabricators and erectors. Respondents also requested research and design guides (AISC, 2019).

With HS3 opportunities and challenges in mind, the Task Group looked to the example of high-performance steel in bridges. In 1992, a consortium developed high performance steel grades 50W, 70W, and 100W (50 ksi, 70 ksi, 100 ksi, respectively) with improved weldability and toughness. The 1998 Transportation Equity Act for the 21st Century partially funded use of new grades in highway bridges. Built-up bridge girders with 70W steel have seen fairly widespread

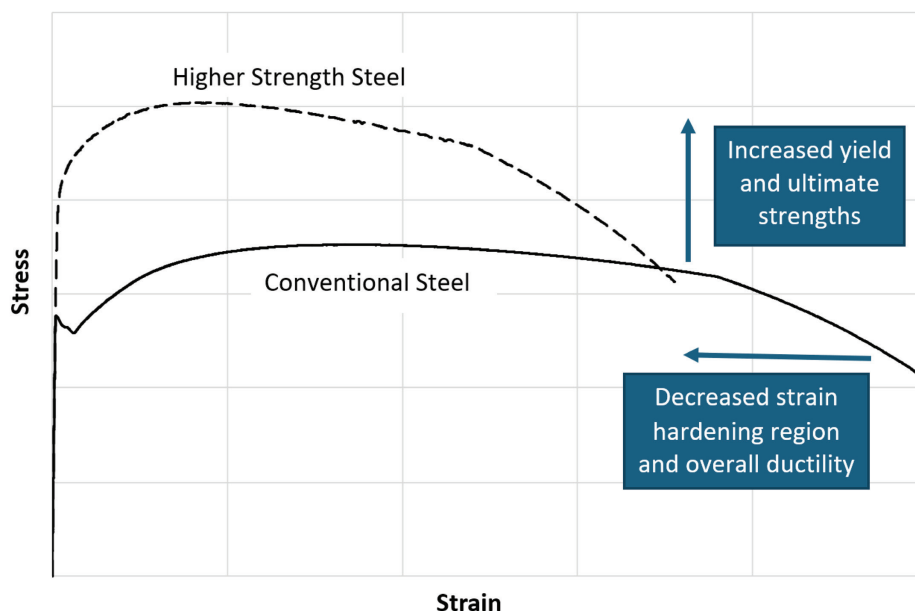


Fig. 1. Representative stress versus strain behavior of high strength steel relative to conventional steel.

adoption, along with some hybrid girder design using 50W webs and 70W flanges. Some of the primary takeaways for the Task Group were to focus on specific HS3 grades, utilize research, and recognize that implementation is not a simple swap of one grade for another; some “reengineering is required to reap the rewards” (AISC, 2019).

The Task Group developed recommendations across education, advocacy, fabricator needs, *Specification* Task Committee efforts, and research. Education efforts should include cost and availability information as well as success stories and case studies. Advocacy involves incentivizing demonstration projects, partnering with funding agencies and other organizations. To address fabricator needs, the Task Group recommended identifying fabricator challenges while developing and sharing best practices. The Task Group also recommended that the *Specification* Task Committees collaborate with counterparts in other countries to inform *Specification* updates and develop paths forward for new materials, specifically HS3. In research, development of performance criteria, investigating HS3 design solutions, and improved provisions are priorities. Research topics supporting improved specifications include imperfections, residual stress, column behavior and column curves (AISC, 2019).

Current Uses and Benefits

Building case studies have highlighted best uses and benefits for using HS3. Benefits may include smaller members with lower weight and costs, smaller foundations, and reduced carbon emissions. Some notable uses of high strength steel are in two New York City buildings—One World Trade Center’s perimeter steel moment frame and 217 West 57th Street’s steel mega-columns. 217 West 57th Street reported a 30% savings in weight of steel. Bay Adelaide Centre, East Tower, Toronto, used high strength steel in columns and short-span transfer girders, recording greater than 9% weight savings.

HS3 columns for 150 North Riverside, Chicago, resulted in 6% savings in total steel tonnage (Finnigan et al., 2015). The North Riverside building was the first use of 70 ksi rolled steel members in the United States. Columns with shop-welded moment connections were designed with 65-ksi steel, eliminating standard pre-heat requirements (AISC, 2018).

The Union Station Tower in Chicago, Illinois, was the first to use 80 ksi steel in the United States. The HS3 perimeter columns helped to reduce the building’s total steel weight by almost 20% compared to conventional steel (Yoders, 2020). With the smaller section sizes, the design team was able to achieve more tenant space. The case study supported a focus on force-controlled columns, maximizing benefits of the increased yield strength.

RESEARCH OBJECTIVES AND PLAN

This research builds on the growing interest in high strength steel for building applications and supports implementation through foundational work for improved design specifications and guides. The overarching goal is to close the knowledge gaps in material and member behavior while informing design with HS3. For material and member behavior, specific research objectives are to identify specific grades of interest, perform lab testing to investigate stress-strain behavior as well as residual stress and ductility assumptions, and evaluate the applicability of current column curves for HS3 wide-flange shapes. For design, the team will recommend changes as needed to the AISC *Specification* for HS3 members. The team will also identify key building components that would benefit from use of HS3 and evaluate material, cost, and carbon savings from using HS3 in place of conventional steel (50 ksi).

The research is organized into four major tasks across material behavior, member behavior, and design. Task 1, Development of Material Matrix and Selection of Testing Material, includes surveys as well as a review of the literature. Task 2, System-Level Comparison of HS3 and Conventional Steel, is based on designs of prototype buildings. Task 3, Material Characterization of HS3, includes tensile coupon and compression tests, residual stress measurements, and three-point bend tests. Task 3 results inform finite element models in Task 4, Development of HS3 Column Curves.

DEVELOPMENT OF MATERIAL MATRIX AND SELECTION OF TESTING MATERIAL

The research team conducted a literature review on HS3 properties and behavior, the state of practice with regards to HS3 case studies and current standards, and published studies informing the experimental program. They also conducted their own surveys on HS3 materials and applications. Selected portions of the literature review and surveys are highlighted.

The literature review informed the experimental program. The team studied standards and common practices for tensile testing, compression testing, residual stress measurements, and three-point bend testing. Multiple methods exist for residual stress evaluation. Residual stress measurement techniques include destructive (sectioning), semi-destructive (e.g., center hole drilling), and nondestructive (e.g., neutron diffraction) methods. Sectioning was chosen based on its common use and acceptance (Ziemian, 2010). Sectioning is also the method used in the two studies with published residual stress data for HS3 hot-rolled I-sections (Spoorenberg et al., 2013; Tankova et al., 2021). Residual stresses for the 65 ksi specimens in both studies demonstrated some dependence on the cross-section

geometry; Spoorenberg et al. (2013) tested heavy sections with flanges several inches thick.

The team developed an HS3 material matrix with mechanical properties, material use, production methods, and current producers. Mechanical properties included yield and tensile strength, elongation, and impact energy. Material use corresponded to rolled shapes, plate, etc. Production methods included HSLA, Q&T or QST, and TMCP.

Surveys on material use and applications were sent to designers, producers, fabricators, and erectors. The material survey asked about experience with each ASTM specification in the material matrix and with which grades of steel. Designers were asked if they used the material in gravity columns, lateral columns, beams, truss members, and/or built-up sections. Fabricators had the opportunity to note any difficulties or limitations with respect to fabrication with the specified material. Nineteen respondents included nine engineers, three fabricators, two producers, and a mix of project and quality managers. Only ASTM A913 (2019a) had been used by all engineers and in a variety of applications. All had used Grade 65, five used Grade 70, and one had used Grade 80.

The HS3 project survey requested information about current and past HS3 building projects. Name, location, and type of project (e.g., high-rise, long-span construction, stadium/arena); number of stories; and building use (e.g., office, industrial, residential) were collected. Designers were also asked for the grade of steel and for which members, their motivation for using HS3, the benefits provided by HS3, as well as any challenges. The team collected several responses for buildings ranging from 7 to 73 stories. The most common use of HS3 was in the gravity columns.

Working in consultation with the project advisory committee, the research team decided to focus on ASTM A913 Grade 80 rolled wide-flange shapes for this research. Results from the surveys indicated that designers were generally reticent to incorporate built-up members and would be more inclined to use rolled shapes. In addition, most interest was in column applications. Grade 80 was added to ASTM A913 in 2019 and to AISC 360 in 2022, but research on this material and its applicability to the existing member design equations is still limited. There are two different steel producers who supply this new material and agreed to collaborate. For these reasons, the research team and project advisory committee felt that studying ASTM A913 Grade 80 material would be most impactful toward implementation of high strength steels in building applications.

SYSTEM-LEVEL COMPARISON OF HS3 AND CONVENTIONAL STEEL

This task compares the use of HS3 and conventional steel in prototype buildings. The team is evaluating HS3 for

composite beams and columns and in columns of lateral systems (wind and seismic). However, the focus is on HS3 for the gravity columns, which are expected to have the greatest impact on cost and material savings.

These case studies utilize a diverse prototype building inventory. Prototype selection from the AISC Steel Solutions Center (AISC, n.d.) and other research projects (Gupta and Krawinkler, 1999; NEHRP, 2010) considered number of stories, building heights, story heights, and framing bay dimensions. The 3- to 35-story buildings vary in footprint—for example, 100 ft by 100 ft or 270 ft by 120 ft, and occupancy (residential, office, parking garage, etc.). Building use influences story height, which ranges from 10 ft to 15 ft, and typical bay dimensions—such as 30 ft by 30 ft or 62 ft by 30 ft. Three sample buildings are shown in Figure 2 to demonstrate the scope of building size and massing.

The prototype buildings were designed and compared. Baseline designs were created first for conventional steel ($F_y = 50$ ksi). There were two HS3 gravity column redesigns for each building with nominal 80 ksi and 100 ksi steels. (Note that 100 ksi rolled shapes are not currently produced but were designed nevertheless, assuming applicability of the existing column equations to illustrate the potential savings through use of high strength steel.) The designs were completed following the *International Building Code* (ICC, 2018). Column sizes and building weights were compared for reductions in steel tonnage. Building foundation designs are under way to quantify anticipated benefits of reduced foundation sizes. Material cost savings and carbon emissions reductions were also calculated.

Comparisons were made for HS3 yield strength, methodology, and number of stories. Three groupings were used for number of stories: 1–10 stories, 11–20 stories, and 21+ stories. Preliminary results showed average column tonnage savings (compared to conventional steel designs) of approximately 19 and 23% for buildings with 80 and 100 ksi columns, respectively. Buildings that fell into the 21+ story category recorded average column tonnage savings of approximately 25 and 31% for 80 and 100 ksi columns, respectively. An increase in yield strength corresponded to an increase in column tonnage savings.

Additional studies considered the influence of live load magnitude as well as story height to assess the impact on the HS3 in column applications. Composite columns using high strength steel were also studied. The use of HS3 in lateral-force-resisting systems [e.g., as columns in moment frames (MF) and concentrically braced frames (CBF)] is also being explored. At this time, it is not anticipated to use HS3 for the dissipative fuse elements of the seismic lateral-force-resisting systems (e.g., the braces in CBFs or beams in MFs), but the three-point bend tests to be conducted in the material testing portion of this project may inform these decisions. Findings of these comparative design studies will be presented in a future publication.

MATERIAL CHARACTERIZATION AND COLUMN CURVES

Work in progress includes the material characterization and development of HS3 column curves. Based on survey results, ASTM A913 Gr. 80 wide-flange shapes are the primary focus for these tasks.

Material Characterization

Laboratory tests are conducted to investigate material and member behavior. Specifically, the team is evaluating HS3 stress-strain behavior, residual stress distributions, and rotational ductility. The stress-strain and residual stress behavior are foundational to the development of column curves. The rotational ductility is necessary to assess the potential of the material in seismic applications.

The tensile coupons, compression specimens, and residual stress specimens were cut from the flanges and webs of the same group of W14 shapes: W14×283, W14×211, W14×176, and W14×398. The wide-flange selection was primarily based on availability from the two participating steel producers, but element slenderness and other cross-sectional properties were considered. The currently limited list of available shapes is expanding. Specified minimum yield strengths are 80 ksi for W14×283 and W14×211; 65 ksi for W14×398; and 50, 65, and 80 ksi for W14×176. The mix of yield strengths and shapes provided a conventional steel baseline and variations across yield strengths and cross sections.

The tension and compression tests together provide comprehensive information about HS3 stress-strain behavior. The tensile coupons were cut from flange and web locations

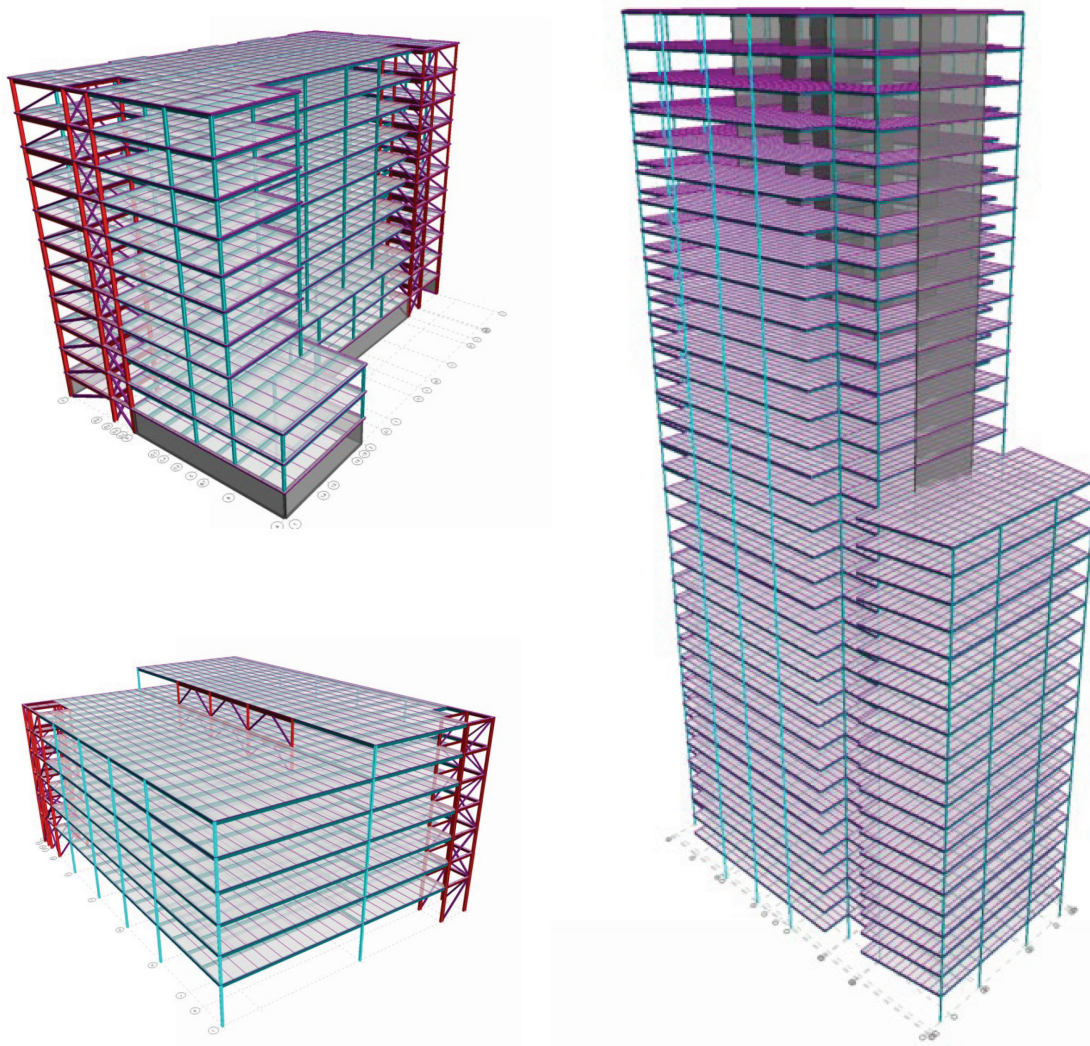


Fig. 2. Sample prototype buildings.

at dimensions and geometries that satisfy ASTM A370-24 (2024) requirements. For example, the flange coupons are cut from a location two-thirds from the flange centerline to the flange toe. Compression tests follow ASTM E9-19 (2019b) and have an approximate length to thickness ratio of 3.0. Compression test specimens were taken from the W14×211 and W14×176 flanges and web; specimens from the thicker W14×283 and W14×398 flanges would exceed the test machine capacity. Full-thickness specimens are needed to properly capture the quenched and tempered properties through the section. The tension and compression tests are conducted on a Tinius Olsen machine, following the appropriate loading protocol and procedures for measuring the stress-strain behavior (ASTM, 2024, 2019b). Photographs show the fractured coupon from one of the tensile tests (Figure 3).

The same W-shapes were used to assess residual stresses. The residual stress measurements for each wide-flange section are made using the sectioning technique (Ziemian, 2010, Stall et al., 2024). The original specimens are at least three times the W-shape's largest transverse dimension, plus the gage length of 10 in., plus 2 in. For the W14×398, the overall specimen length is 7 ft 6 in.; all others are 5 ft 6 in. Test pieces were cut from the original length before the strips were cut. The flanges and web are marked with 0.5-in.-wide strips (Figure 4). Stainless-steel locating points with indentations are epoxied to the ends of the strips to assist with measurements. Length measurements were taken prior to the test piece being cut, after the test piece was cut, and then after the strips were cut. Changes in length are used to calculate the residual stresses that have been released during the cuts. Stress distributions across the thicker flanges are captured by also sectioning through the flange thickness.

Rotational Ductility

Five three-point bend tests will be used to evaluate moment-rotation behavior and ductility. This portion of the study addresses knowledge gaps relevant to seismic applications and is not applied to the HS3 column curve development. Three 80 ksi specimens (W14×283, W14×211, and W14×176) will be compared to 50 and 65 ksi specimens (W14×176). Prior to testing, the wide-flange specimens are measured at nine locations along the length of the beam. Cross-sectional dimensions and imperfection measurements (camber and sweep) are taken. The 22 ft, simply supported test specimens are loaded at mid-span (Figure 5). Lateral bracing is provided at mid-span and near the supports. The beams are loaded past the formation of a plastic hinge to a peak on the moment-rotation curve. The peak is expected to be between 1.0 to 1.2 times the plastic moment, M_p . If possible, loading will continue until a drop in moment to below $0.8M_p$; local buckling may occur before targets are achieved.

Development of HS3 Column Curves

The experimental test results provide data for development of finite element models and column curves. The UC research team as well as researchers from other universities will use the stress-strain and residual stress measurement data in the development of finite element (FE) models for HS3 columns. These FE models are benchmarked to historical data and then analyzed using HS3 material characterization results. Effective stress-strain material models will be created and used in fiber-based models for a parametric study to create column curves.

Creating benchmarked finite element (FE) models is the first step in column curve development. Test data used



Fig. 3. Result of full-thickness tensile coupon testing.

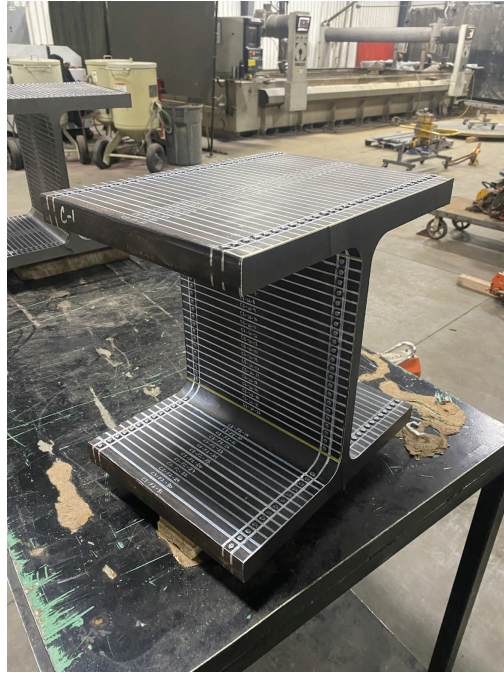


Fig. 4. A residual stress test piece before cutting the individual strips.

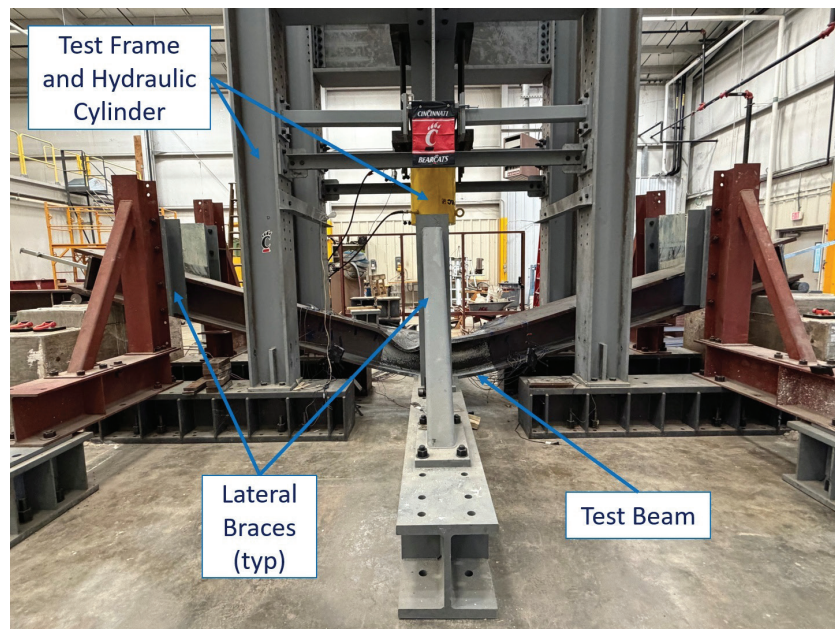


Fig. 5. Post-test photo of a three-point bend test.

for the first column curves (Bjorhovde and Tall, 1971) will also be used here. The published data include material stress-strain behavior, residual stresses, and geometric imperfections. Such data do not exist for hot-rolled HS3 columns. The column tests and models track load versus deflection through buckling and post-buckling. Analysis completed to date demonstrates that the FE models can predict the maximum compression loads within 4%.

Those benchmarked FE models will then be analyzed using the HS3 material characterization data. Models of the tested wide-flange shapes will incorporate the data from the tensile tests, compression tests, residual stress sectioning, as well as geometric imperfections. The HS3 modeling will be expanded to include additional wide-flange shapes for the development of phenomenological stress-strain curves (Alghossoon and Varma, 2023). For the HS3 column modeling, sections will include W12s as well as more W14s, W18s, and W27s, with flange ratios from 2.15 to 7.11 and web ratios from 5.21 to 18.9. The objective is to develop a generalized stress-strain curve capable of capturing local buckling behavior for any ASTM A913 (2019a) Grade 80 wide-flange section.

A parametric study will then be used to create an HS3 column curve. This study will utilize a fiber-based model, first benchmarked against the same data used for the FE models. Further benchmarking will compare fiber models to the wide-flange FE models used for the stress-strain curve development. Parameters include global slenderness ratios, as well as flange and web width-to-thickness ratios. Wide-flange members will be selected from available ASTM A913 (2019a) sections. The models may include Grades 50, 65, and 70, but priority will be given to sections currently manufactured in Grade 80.

Once the column curve work has been completed, the research team may recommend revisions to the AISC *Specification* for HS3 members. The prototype building designs will be revisited to demonstrate any additional savings with the revised column design procedure. Additional recommendations may stem from the prototype building work, with best practices for maximizing the benefits of HS3 members for structural performance, weight and cost savings, and reduced carbon emissions.

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