Adhesive Steel-to-Steel Connections

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INTRODUCTION

Ongoing research on adhesive steel-to-steel connections is highlighted. This study, currently under way at the University of Massachusetts–Amherst, is led by Dr. Kara Peterman, Associate Professor in the Department of Civil and Environmental Engineering. Dr. Peterman's research interests include behavior of cold-formed and hot-rolled steel structures under service loads and extreme loads due to natural hazards. Among Dr. Peterman's accolades for her teaching and research are the University of Massachusetts–Amherst College of Engineering Outstanding Teacher Award, the McGuire Award for Junior Researchers from the Structural Stability Research Council (SSRC), the AISC Terry Peshia Early Career Faculty Award, and the AISC Milek Fellowship. The four-year Milek Fellowship is supporting this research on the holistic design and behavior of adhesive steel-to-steel connections. The research team is partway through year two of the four-year study. Selected highlights from the work to date are presented, along with a preview of future research tasks.

BACKGROUND AND MOTIVATION

The research team seeks to fill knowledge gaps and realize the great potential for adhesive structural steel connections. Experience with adhesives exists primarily in aerospace, nautical, and automotive industries, with some in cross-laminated timber and concrete construction, and more limited work with structural steel. Potential benefits for adhered steel-to-steel connections include improved performance of mechanical connections, connection flexibility, and reduction or elimination of stress concentrations.

A literature review highlights potential applications, anticipated benefits, and knowledge gaps. Applications related to the proposed research have included bridge retrofit, light-framed construction, and steel connections. Bridge retrofit work includes a Hu et al. (2006) study on adhered steel angles to mitigate out-of-plane, distortion-induced fatigue cracks. Two successful field tests on skewed bridges and large-scale laboratory tests demonstrated environmental durability and reductions in strains, with some loosening of the adhesives after millions of cycles of loading (Hu et al., 2006). In their investigation of bridge retrofit schemes using fiber-reinforced polymer (FRP) plates adhered to steel, André et al. (2012) observed debonding of the adhesive from the steel and failure within the adhesive itself. Peterman et al. (2017) also observed failures between adhesives and polymers in research on thermal break strategies for steel building systems. Serrette et al. (2006) explored cold-formed steel shear walls bonded to steel sheets or oriented strand board. The shear walls were attached to the stud wall framing with adhesive and fasteners. Peak wall resistance and stiffness were increased, but energy dissipation decreased. The researchers pointed to the need for additional research on the adhesive and connection detailing (Serrette et al., 2006). Steel double-lap splice connections studied by Sadowski et al. (2010) utilized a rivet, adhesive, or a combination. The combined connection demonstrated increased connection strength, elastic stiffness, and ductility. Gasparini et al. (1990) investigated mechanical properties of adhered steel-to-steel connections, identifying research needs in behavior under sustained loading and tensile creep rupture. Ikegami et al. (1996) demonstrated variability in the behavior of adhesively bonded steel connections (e.g., lap splices, butt joints), noting dependence on the curing process. Meanwhile, de Morais et al. (2007) demonstrated improved connection strength with increased adhesive thickness in lap splice and butt joint connections.

The literature review identifies lack of standards for adhesives in steel construction as well as research needs. More data are needed on adhered steel-to-steel connections, their limit states, and behavior (e.g., creep). Research must address adhesives used in combinations of connecting elements or as grout, fill encasement, or thermal break. Development of systematic methods for performance evaluation will further advance adhered structural steel connections. Challenges include the need for a controlled environment, different adhesives for different applications, lack of specifications, and varied mechanical performance based on curing.

PROPOSED RESEARCH AND DELIVERABLES

The research team is providing fundamental knowledge needed to advance adhesives for slip-critical bolted

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connections, prefabricated modular construction, bridge girder splices, and anchorage. Questions about installation procedure, structural behavior, creep performance, and performance under elevated temperatures are being addressed. The proposed work synthesizes existing knowledge, leverages the expertise of an industry advisory panel, identifies viable adhesives and applications, conducts experimental testing to address knowledge gaps in mechanical properties and structural behavior, and develops design recommendations (Figure 1).

Numerous opportunities exist for adhesives in structural steel construction. Adhesives may be integrated into bolted and welded connections and do not introduce stress concentrations or require any changes in the bolt or weld configurations. Adhesives may allow greater control of connection failure mode and energy dissipation. Adhesives may also be used to fill connection gaps or as anchor rod grout or connection encasement.

Research to address knowledge gaps and pursue opportunities leads to five major deliverables. The first deliverable is the information about the structural behavior of adhered steel-to-steel connections. The second is the validation of adhesives for these connections. Validation is tied to the determination of performance objectives and minimum properties for the adhesives. The third deliverable is a set of recommendations providing guidance on selection, design, and detailing of connections with structural adhesives. Accompanying the design recommendations is the fourth deliverable, a centralized and searchable database of available structural adhesives. Finally, underlying the research outcomes is the fifth deliverable, the experimental data.

The experimental work plan is a systematic investigation at material, connection, and subsystem levels (Figure 2). Material-level testing addresses tension, compression, and creep. Double-lap splices and anchors will be explored in connection-level testing. At the subsystem level, steel deck diaphragms and steel-sheet sheathed cold-formed steel (CFS) shear walls will be tested.

Material-Level Testing

Material-level testing focuses on strength characterization of the adhesives. The impact of curing methods and surface preparation on the mechanical properties will also be assessed. The research team plans to utilize available standards for adhesives and adapt standards as needed for tension, compression, and creep (Figure 2). Elastic yield strength and ultimate strength will be evaluated following ASTM D638, the test standard used for plastics (ASTM, 2022). Tension coupons will be machined from properly cured adhesive stock. The team will assess impact of cure time, cure temperature, and surface preparation on adhesives under tensile loading. Procedures such as ASTM D1002 (ASTM, 2019) for "Apparent Shear Strength of Single-Lap Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)" will be followed. Relevant standards [ASTM D2293 (ASTM, 2002), ASTM D2294 (ASTM, 2016)] will be utilized for creep testing of lap joints (adhesives in shear) under tension and compression loading. The team expects to investigate three adhesives and two curing methods. The results for the material-level testing will lay the foundation for test phases to follow.

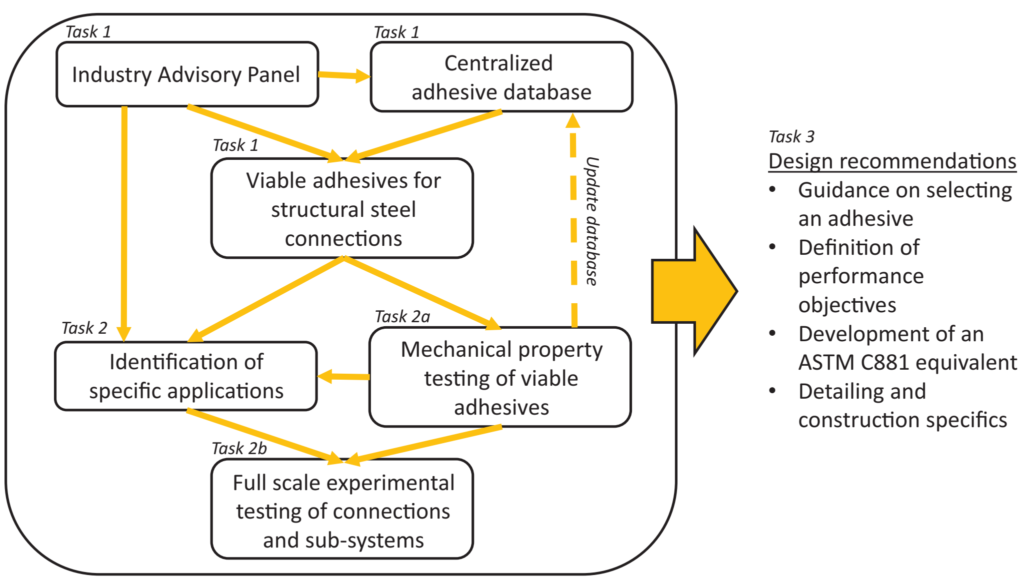

Fig. 1. Research tasks and deliverables.

Connection Testing

Connection tests will further inform design guidance for applications such as adhered anchor rods, steel deck diaphragms adhered to steel joists, and steel-sheet sheathed cold-formed steel (CFS) shear walls. Double-lap splice connections will be used to capture adhesive-steel interactions at a component level (Figure 3). Based on the literature and identified research needs, parameters will include thickness of the adhesive, combinations of adhesives with slip-critical bolts, and elevated temperatures. For the anchor rods, isolated adhered anchor rod pull-out tests will be conducted (Figure 4). Adhesive thickness may again be a parameter. Where thickness is dictated by the available fill space, the test results will provide upper and lower bounds on performance. These tests will use the same curing methods and adhesives as in the material-level tests. All specimens will be loaded with monotonic displacement control.

Subsystem Testing

The subsystem testing will focus on steel deck diaphragms adhered to steel joists and steel-sheet sheathed cold-formed steel (CFS) shear walls. The research team has chosen these subsystems to highlight the potential benefits of adhesives for prefabricated panels or modules for construction. Replacing or reducing the number of fasteners with adhesives may improve fabrication and installation time. Adhesives and methods will be chosen based on the materials and connection level testing. These experiments will leverage the existing cantilever diaphragm rig at UMass Amherst (Figure 5). Steel deck diaphragms will be adhered to steel joists as shown schematically in Figure 6. In its current configuration, the rig is set for 15 ft by 15 ft specimens but can be modified to accommodate 10 ft by 10 ft specimens. Expected research deliverables include information about the feasibility of adhered connections for CFS shear walls and deck diaphragms, as well as the behavior of these subsystems.

LITERATURE REVIEW, DATABASE, AND TEST PLANNING

Work to date has included a literature review, database, test planning, and creep testing that is under way. The literature review has confirmed that there is ample information on aerospace, automotive, and naval uses, but not much related to building applications. Large-scale tests (e.g., Serette et al., 2006; Hu et al. 2006) are also rare. The review has provided structural adhesives to populate the database, information on testing procedures, pointers to gaps in knowledge, and the groundwork for test planning.

For test planning, the literature has informed test procedures and properties of ideal adhesives. Ideal adhesives should include a high lap shear strength, long pot life or handling time to facilitate fabrication of joints, and low elongation at high loads. Ideally, the adhesives should also have a high glass transition temperature and a practical in-service temperature range. The curing method should be appropriate for large-scale work, whether in the fabrication shop or in the field. Meanwhile, relevant test standards have been reviewed and work on prototypes completed.

The database utilizes an online web application designed for sharing computational documents. The Jupyter Notebook features plots such as distributions of lap shear strengths and handling times for the adhesives in the database. The "live" Notebook updates plots with any changes in the database.

Challenges experienced by the research team include variability in manufacturer information and curing methods. Not all manufacturers release the same information in their data sheets; the research team is missing information for some adhesives. This introduces difficulties in

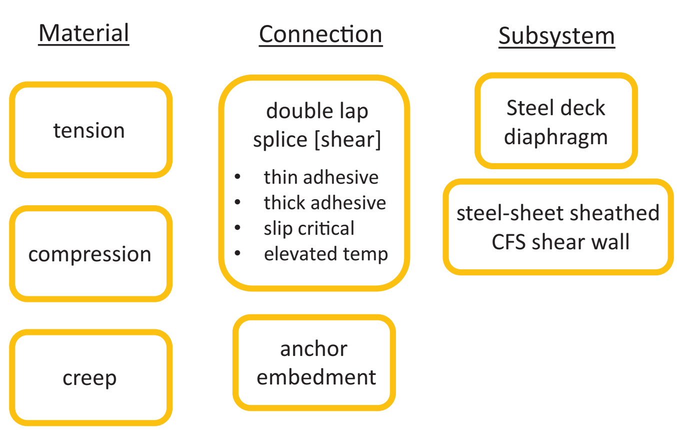

Fig. 2. Material, connection, and subsystem levels of investigation.

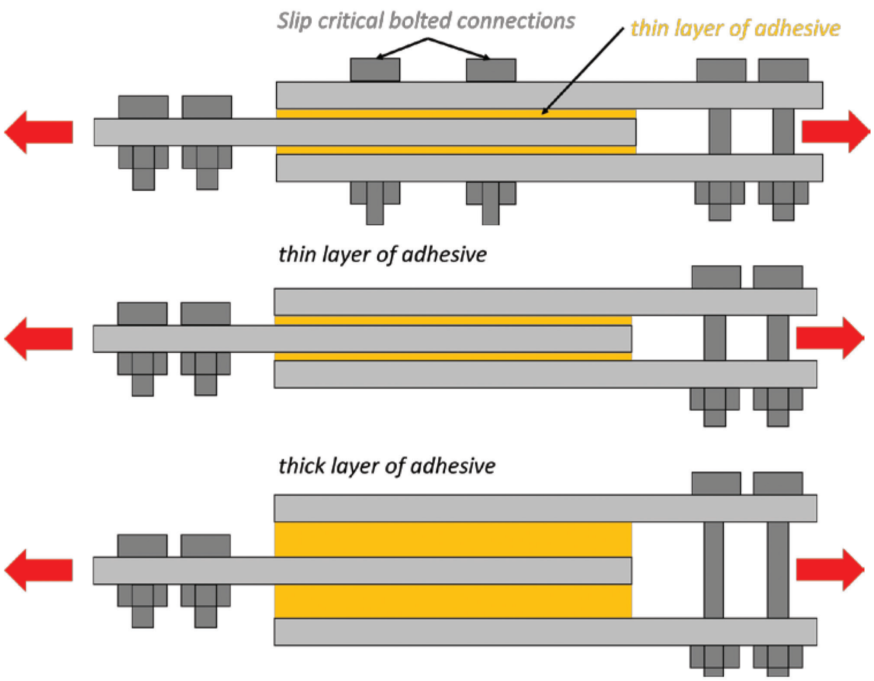

Fig. 3. Double-lap splice connection test configurations.

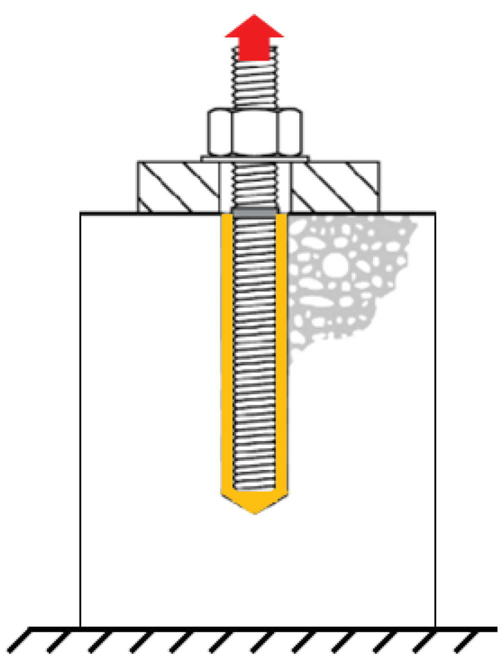

Fig. 4. Anchor rod pull-out test configuration.

Fig. 5. Cantilever diaphragm testing rig at UMass Amherst.

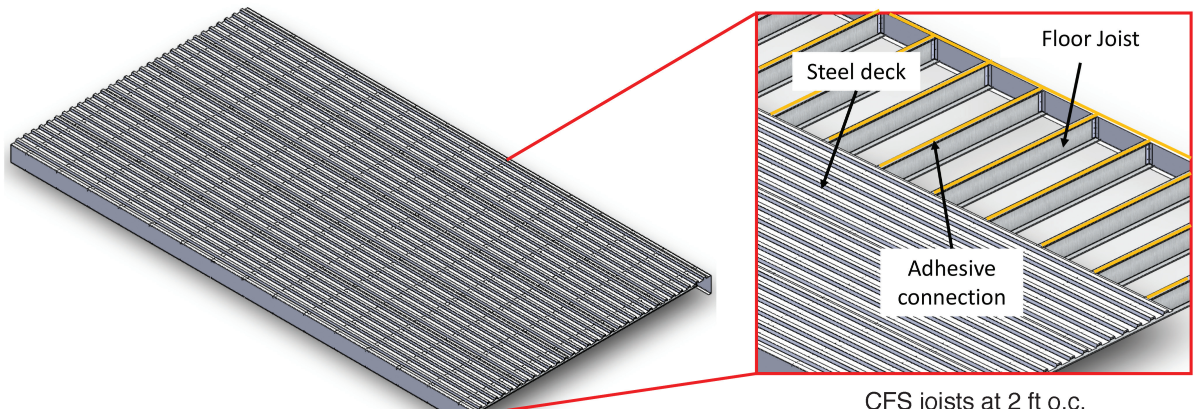

Fig. 6. Steel deck diaphragm-joist subassembly.

comparing adhesives. Different curing methods maximize different properties such as cure time, glass transition temperature, strength, or in-service temperature range. Synthesis of available products and methods continues.

COMPLEMENTARY RESEARCH EFFORTS

This research has also been informed by complementary work by the Virginia Department of Transportation (DOT) and the Federal Highway Administration (FHWA). Jason Provines, Virginia Transportation Research Council (VTRC), leads the DOT work focused on adhesives for gap filling and joint sealing at bridge girder ends. The adhesive joints are primarily under compressive loading. Ryan Slein and Fang Wang are in Phase 2 of their research, having completed a Phase 1 experimental study comparing performance of adhesive-enhanced bolted connections with conventional double-lapped shear bolted connections. Creep of adhesives and relaxation of bolt pretension were also investigated.

These groups shared research at a workshop hosted by UMass Amherst. Workshop outcomes included comparisons of adhesive selection processes and experimental protocols. The workshop highlighted the challenges in specifying adhesives for universal structural steel application. While the UMass and FHWA research teams had overlapping research goals (primarily shear connections), and thus overlapping adhesive selection, the VTRC team focused on entirely on compression joints and examined a different suite of structural adhesives. In translating research outcomes to practice, and to meet this challenge, the UMass team will be working to establish acceptable performance criteria to be used under certain load conditions.

FUTURE WORK

Work continues on the testing, database building, and design recommendation development. Looking ahead to one of the major deliverables, the research team expects to develop equations and recommendations that parallel existing guidance. For example, ASTM C881 (ASTM, 2020), "Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete," provides performance objectives for adhesives for specific applications. Applications range from load-bearing applications to non-load-bearing sealants. Each application type is defined along with performance targets to be achieved in order for an adhesive to be rated for that application. The adhesive rating system will be informed by the experimental testing and guidance from the industry advisory panel.

ACKNOWLEDGMENTS

Thank you to Dr. Kara Peterman for her contributions to this article. The work of PhD student Kate Sullivan is also recognized. The research is sponsored by the American Institute of Steel Construction (AISC) through the Milek Fellowship, with technical and financial support from the American Iron and Steel Institute (AISI) and the Steel Deck Institute (SDI). The researchers would also like to thank Advisory Committee members Caroline Bennett (University of Kansas), Devin Huber (AISC), Chris Garrell (AISC/NSBA), John Hooper (MKA), Ronnie Medlock (High Steel Structures), Bonnie Manley (AISC), Ryan Slein (FHWA), Tom Sputo (SDI), Brian Volpe (Cives Steel), Duff Zimmerman (Cooper Steel), Joe Zona (SGH), and Aamer Syed (Sika). Any findings or recommendations are those of the researchers and do not necessarily reflect the views of the sponsors.

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