Steel Structures Research Update

# Investigation of Bearing and Tearout of Steel Bolted Connections

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## INTRODUCTION

Recently completed research on bearing and tearout of steel bolted connections is highlighted. This study, conducted at the University of Tennessee, Knoxville, was led by Dr. Mark Denavit, Associate Professor in the Department of Civil and Environmental Engineering. Dr. Denavit's research interests include structural steel connections, stability analysis and design, and innovative seismic systems. Among Dr. Denavit's accolades are the Terry Peshia Early Career Faculty Award (AISC) and the Sarada M. and Raju A. Vinnakota Award (SSRC). AISC supported this research on steel bolted connections. Selected highlights from the completed work are presented.

## RESEARCH MOTIVATION AND OBJECTIVES

This research evaluated the behavior and design of steel bolted connections subjected to the limit states of bearing and tearout. The work was motivated by questions about the effective strength approach for bearing-type bolt groups and the accuracy of current tearout strength provisions. A user note introduced in the 2010 AISC *Specification* states that the effective strength of an individual bolt may be taken as the minimum strength computed for bolt shear rupture, bearing, and tearout limit states. The sum of the individual bolt effective strengths is the bolt group strength. Consideration of the interaction of bolt shear rupture, bearing, and tearout is further complicated by tearout strengths that can vary by bolt. Meanwhile, studies on concentrically loaded bolt groups have produced alternative tearout strength equations (Clements and Teh, 2013; Kamtekar, 2012). Dr. Denavit's group sought to improve design of bolted connections by addressing knowledge gaps and developing more accurate methods that capture the influence of tearout.

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This study consisted of two phases exploring behavior and design of concentrically and eccentrically loaded connections. Objectives for the first phase included creating a database of experimental tests, evaluating design equations, conducting experimental testing to address knowledge gaps, and developing recommendations for design. In the second phase, the research team conducted tests on concentrically and eccentrically loaded bolt group configurations not previously studied experimentally. The tests further informed recommendations for design of bolted connections subjected to the limit states of bearing and tearout.

## PAST RESEARCH AND ALTERNATIVE EQUATIONS

The database of experimental results created by Dr. Denavit's group included 984 test specimens from 31 studies. Categories of connections included concentrically loaded lap splice connections, concentrically loaded butt splice connections, basic eccentrically loaded bolt groups, and single-plate bolted shear connections. Studies reporting bearing and tearout limit states were prioritized, though only 471 of 899 concentrically loaded specimens failed in bearing or tearout. For eccentrically loaded specimens, bearing failures occurred in approximately half of the tests. By design, tearout failures were not observed. Some limitations of the types of connections and configurations found in the literature motivated testing to address knowledge gaps. Additional database details can be found in Denavit et al. (2021).

The team also evaluated alternative tearout lengths. At the end of a plate or component, current provisions use the clear distance, $l_c$, measured from the edge of the bolt hole to edge of the material. Tearout failure planes, as shown schematically by the dashed lines in Figure 1, are longer than the clear distance. Kamtekar (2012) proposed an estimate of that tearout length, $l_{v1}$, defined by a line tangent to the bolt and the distance along that line from the edge of the bolt hole to the edge of the material. Clements and Teh (2013) proposed a tearout length, $l_{v2}$, equal to the average of the clear distance, $l_c$, and the edge distance, $L_e$, from the center of the bolt hole to the edge of the material. Evaluations of tearout capacity using these alternative lengths were compared to a small set of specimens with tearout failures and showed improved predictions (Elliot et al., 2019).

## CONCENTRICALLY LOADED BOLT GROUPS

Concentrically loaded bolt group tests were used to expand the database. The published experiments had focused on specimens with standard holes. In those cases, $l_{v1}$ is greater than $l_{v2}$, but at most by 7% when minimum edge distance requirements are satisfied. This new inventory of tests explored different types of holes, edge distances, and cases where $l_{v1}$ is greater than or less than $l_{v2}$.

### Test Specimens

Single-bolt splices were tested to investigate the behavior of concentrically loaded bolted connections and to evaluate the alternative tearout lengths. The 22 specimens consisted of a single interior test plate between two pull plates (Figure 2), connected with a ¾-in. snug-tight F3125/F3125M (2023) Gr. A490X bolt. The ASTM A572/A572M (2021) Grade 50 test plates were designed to fail in bearing, tearout, or splitting. Splitting started with a tensile fracture at the end of the plate.

The main parameters studied were type of hole and edge distance. Types of holes included standard holes, holes with minimum clearance, oversized holes, holes with ⅛ in. more clearance than oversized holes, and short-slotted holes oriented perpendicular to the load. The nominal edge distances were 1 in., 1.25 in., 1.5 in., and 2 in. The 2 in. edge distance was chosen because it is larger than the 1.91 in. calculated for the transition from bearing to tearout failure for the ¾ in. bolt in a standard hole. The 1 in. edge distance is the minimum for a ¾ in. bolt in a standard hole. The 1 in. edge distance is not permitted for oversized holes, but this case was still included for those holes to be consistent across tests. One specimen (no clearance, 1.25 in. edge distance) was duplicated to investigate repeatability. The standard hole, 1 in. edge distance specimen was also duplicated, with one specimen tested with bolts left untightened and grease applied to the faying surfaces.

The alternate tearout lengths were considered. For the standard hole and minimum/no clearance cases, $l_{v1}$ is greater than $l_{v2}$. For the oversized and short-slotted holes, $l_{v2}$ is greater than $l_{v1}$. More information on test parameters can be found in Denavit et al. (2021).

### Test Setup

The tests were conducted using a universal testing machine and complementary displacement measurement devices. The test plate assembly was attached to the machine by bolted filler and connection plates (Figure 2). The relative displacement between the pull plates and test plate was measured by two linear variable displacement transducers (LVDTs) mounted to the pull plates and bearing against tabs on the test plate. Optical markers placed on the bolt, test plate, and pull plates for Optotrak deformation measurements (Figure 2) confirmed the LVDT values and also provided elastic deformations in the plates.

For the test, a preload of 500 lb was applied to put the bolt into bearing. The test bolt was finger tightened before an impact wrench was used to obtain a snug-tight condition. All other bolts within the test set-up were finger tightened. The displacement-control test was conducted at a rate of 0.05 in./min to peak load and continued until almost complete loss of load-carrying capacity. The loss of load was typically due to rupture, signaled by one or two loud sounds.

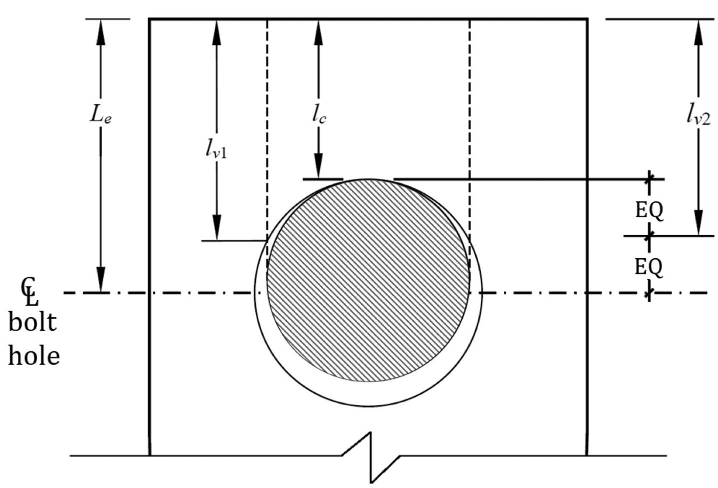


*Fig. 1. Tearout lengths.*

## Results and Discussion

Observed failure mechanisms include splitting tears and shear rupture along one or both sides of the hole (Figure 3). For specimens with short edge distances, the splitting tear continued from the end of the plate to the bolt hole. For test specimens with larger edge distances, the splitting tear did not extend to the bolt hole.

Tested capacities were compared to the predicted values. The strength was evaluated at the ¼ in. deformation limit state and at ultimate. Predicted bolt strengths were calculated using $l_{v1}$ and $l_{v2}$. The ¼ in. deformation predicted strengths are for the case when deformation at the bolt hole at service load is a design consideration. Test-to-predicted ratios with ¼ in. deformation strengths calculated using $l_{v1}$ and $l_{v2}$ yielded similar results across different hole types. For $l_{v1}$, the ratios ranged from 0.965 to 1.050, and for $l_{v2}$, between 0.922 and 1.073. The predicted strengths with $l_{v1}$ and $l_{v2}$ were also more accurate than those using $l_c$ (test-to-predicted ratios from 1.149 to 1.307). At ultimate, the mean test-to-predicted ratios by hole type were more similar between the current equation with $l_c$ and calculations using the alternative tearout lengths. Test-to-predicted values using $l_c$, for example, ranged from 0.948 to 1.078. However, greater variation was seen for the $l_c$ ratios evaluated across the edge distance values and hole type. Further details and analysis are provided in Franceschetti and Denavit (2021) and Denavit et al. (2021).

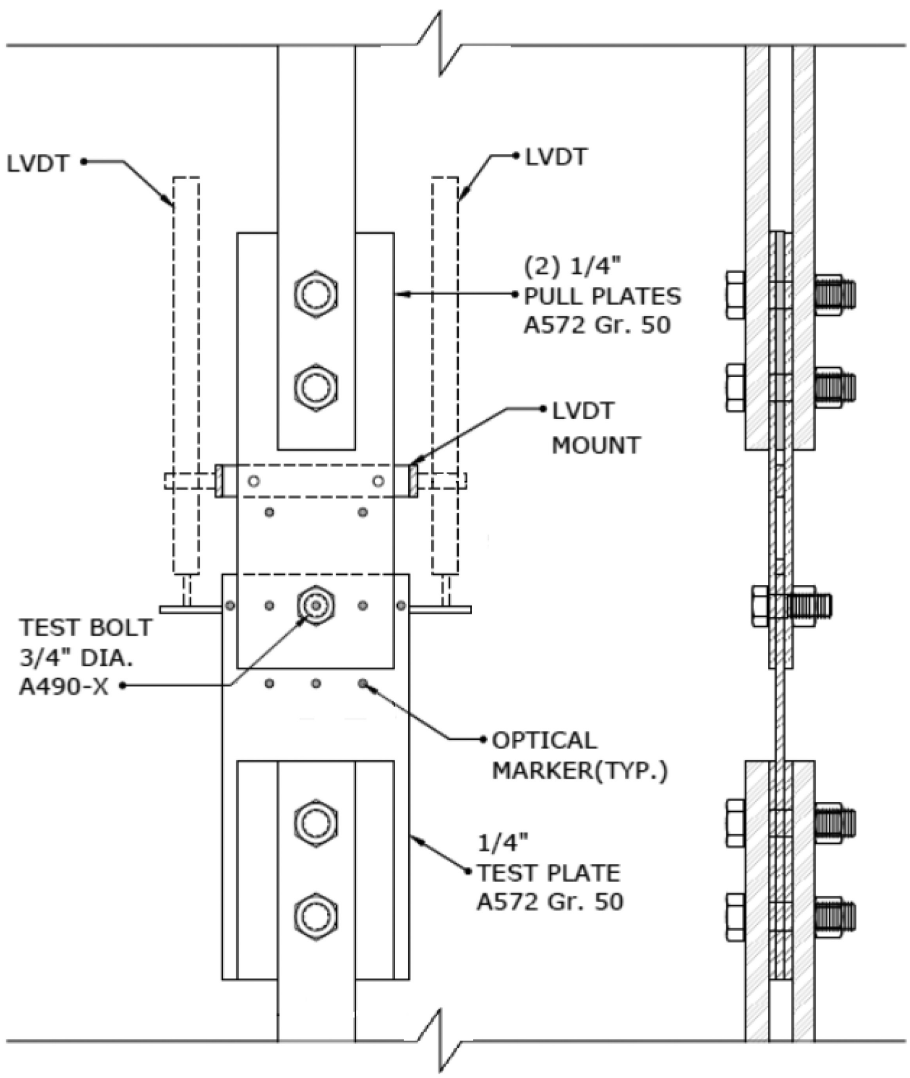


*Fig. 2. Elevation and side view of test setup.*

### Alternative Design Approach

The team also developed an alternative approach for design of concentrically loaded bolted connections. Effective strengths, which can be different for each bolt, are replaced with lower-bound values for edge and interior bolts. The alternative approach leverages the use of $t$ and $F_u$ in both the bearing and tearout equations, recognizing that the bearing-to-tearout strength ratio depends on bolt diameter, $d$, and clear distance, $l_c$. This ratio was calculated for the deformation limit state, a range of bolt diameters, and oversize and standard holes. The data was used to develop lower-bound tearout strengths, written in terms of bearing strength, for edge and interior bolts. The approach was adapted to consider bolt shear rupture as well. The derivation of the alternative approach is provided in Denavit et al. (2021).

## SINGLE-PLATE SHEAR CONNECTIONS

The single-plate shear connection portion of the study addressed gaps in the literature and questions about current design procedures. Most experimental studies on eccentrically loaded bolt groups, including single-plate connections, did not experience tearout failures because of edge distances or bolt shear rupture. Meanwhile, the approach for design of conventional single-plate shear connections is to neglect the eccentricity and evaluate bearing and tearout as concentric; this approach may be unconservative in some cases. A test program focused on single-plate connections susceptible to tearout failures evaluated the practice of concentric bearing and tearout for the conventional single-plate connections and best methods for predicting the strength of extended single-plate connections.

### Modified Instantaneous Center of Rotation Method

The team proposed a modified instantaneous center of rotation method applicable to tearout as well as bolt shear rupture and bearing. The instantaneous center of rotation method accounts for effects of eccentricity within a bolt group, including the resulting magnitude and direction of force at each bolt. The instantaneous center of rotation method had been validated against tests of connections governed by bolt shear rupture and bearing, primarily. The modified method explicitly incorporates the tearout limit state in the ultimate strength calculation of each bolt, using a clear distance calculated based on the direction of force. In cases with sufficient edge distances to preclude tearout, the current and modified methods produce the same results. The team demonstrated how smaller edge distances introducing tearout resulted in a shift of the center of rotation and a reduction in the connection strength. The team also compared their modified instantaneous center of rotation results to the design strengths tabulated for conventional single-plate connections in the AISC *Steel Construction Manual* (2017). They obtained identical results, indicating edge distances large enough to avoid tearout failures and suggesting that the current method for handling tearout for conventional single-plate connections may be appropriate (Denavit et al., 2021). However, experimental investigation is needed to validate the method.

### Test Specimens

The single-plate shear connection test matrix was used to further explore the impact of tearout and the viability of different approaches for handling the bearing and tearout limit states. Two conventional and eight extended single-plate connections were tested. The A572 Grade 50

*Fig. 3. Concentrically loaded specimen after testing.*

plates were ⅜ in. or ½ in. thick. Two-bolt and five-bolt connections used ¾ in. or 1 in. Grade A490-X bolts. The distance, $a$, from the weld line to the bolt line was set at 3 in. or 9 in. The vertical edge distance, $l_{ev}$, was set at the minimum value from Table J3.4 in the AISC *Specification for Structural Steel Buildings* (2016). The two conventional connections used a horizontal edge distance, $l_{eh}$, of two times the bolt diameter. The rest of the connections used the minimum value from Table J3.4.

The test specimens were beam-connection-column subassemblies, with the test connection at one beam end. Beam lengths were 18 ft and 26 ft, and sizes ranged from W8×21 to W18×143. A beam end target rotation of 0.03 rad was set based on the literature. The ASTM A992/A992M (2022) beams were also designed to avoid limit states (e.g., beam yielding) that had been observed in some previous studies. The beam design would ultimately prevent the specimens from reaching the target rotation.

### Test Setup

The test specimens were supported and loaded as shown in Figure 4. A frame and hydraulic actuator were located to apply a concentrated load 6 ft from the connection bolt line. Lateral bracing at the beam flanges was provided at intervals not larger than 6 ft. Each test column had single-plate connections welded to each flange (Figure 5) and was used in two test subassemblies. Instrumentation included the load cell and LVDT at the actuator, a load cell at the simple support, two LVDTs, and 12 optical tracking markers at the connection to provide data for calculating rotations. Initial cycles of loading to 2 kips were used to check the instrumentation and data. The specimens were then loaded in displacement control at a rate of 0.1 in./min until failure.

### Results and Discussion

Specimen behavior varied and generally did not align with predicted limit states and design strengths. Observed limit states included plate yielding, bolt hole ovalization, bolt shear rupture, tearout, beam yielding, and weld rupture. Test-to-predicted strength ratios, calculated using nominal properties, ranged from 1.71 to 6.11. A root cause for the stronger-than-anticipated connections and some unexpected limit states was the support condition at the column. The rotational restraint at that support shifted the point of zero moment away from the assumed column-face location toward the bolt line, resulting in a lower eccentricity than assumed in design. Additional observations and discussion are provided in Denavit et al. (2021).

## DIRECT ECCENTRICALLY LOADED BOLT GROUPS

In the second phase, concentric and eccentric load tests were conducted on configurations not tested previously. The direct eccentrically loaded bolt group tests were designed to address questions not answered by the single-plate shear connection tests and to validate the modified instantaneous center (IC) method. Configurations included concentrically loaded connections with skewed plate edges, plate corners, and connections with only interior bolts placed, as well as different eccentrically loaded bolt groups. Details of the

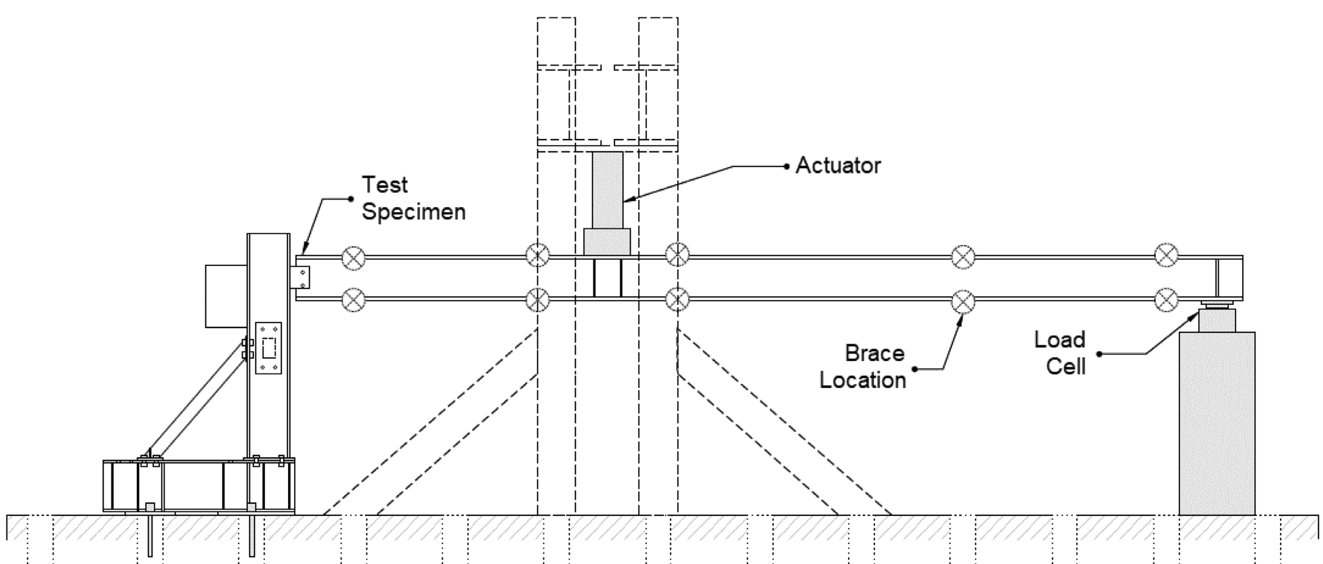


*Fig. 4. Test setup for single-plate specimens.*

concentrically loaded and eccentrically loaded connection tests are provided in Denavit et al. (2024). Highlights from the eccentrically loaded connection tests are briefly presented.

### Test Matrix and Test Setup

This test set focused on relatively large eccentricities for single- and two-row bolted connections. The single-row connection used five ¾ in. A490 bolts. The other connection configuration used the same size and grade of bolts, but in two rows of four. Spacing between bolts and rows was 3 in. Pairs of ¾ in. A572 Gr. 50 plates were connected to the web of an A992 W21×55 (Figure 6). Three edge distances (1.0 in., 1.5 in., and 2.0 in.) were used for each connection configuration for a total of six specimens.

The test setup utilized a wall-mounted actuator and support beam anchored to the strong floor (Figure 6). Three pairs of connector plates transitioned from the welded

Fig. 5. Column and single-plate connection at beam end.

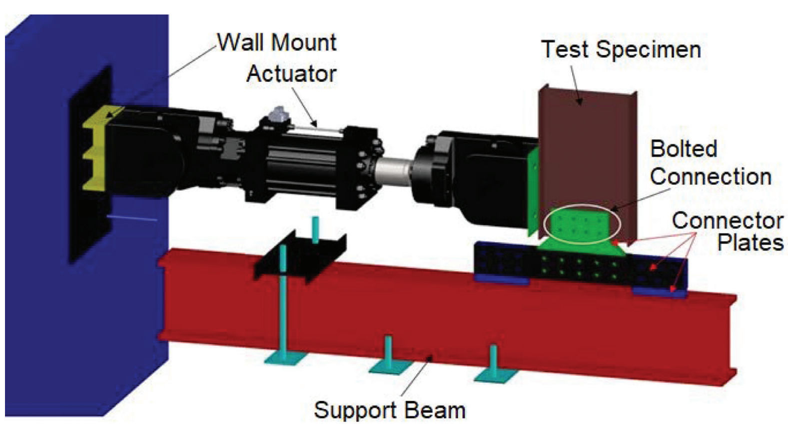


Fig. 6. Test setup for higher eccentricity specimens.

connection at the support beam to the bolted connection at the web of the W21×55 beam. Lateral support was provided by bracing not shown in Figure 6. Displacement-controlled loading was applied at an eccentricity of 9 in. and at a rate of 0.1 in./min. Optical trackers were again used for Optotrak measurements of deformation.

### Results and Discussion

The load-deformation responses were similar across the connections. Initial loading saw significant displacement at the low loads as bolts came into bearing, then an increase in stiffness when bolts were in bearing. A linear elastic response followed until yielding in the web resulted in reduced stiffness. The load-deformation plots for one-row bolted connections typically exhibited a sharp drop in load after the peak due to tearout fractures. Two-row specimens maintained their peak load, and the test was stopped before any significant decrease in load. In both connection configurations, the direction of force at each bolt hole is evident, amplified by the bolt hole ovalization, or elongation (Figure 7).

Strength generally increased with edge distance. This increase was more evident for the one-row specimens, as their strength was limited by tearout. In the two-row specimens, the increase in the strength with increased edge distance was more marginal. Yielding and rotation of the web around the two-row bolt group was an indicator of a different ultimate limit state for this connection [Figure 7(b)].

The results were compared to different analysis methods, including the modified instantaneous center of rotation method. The modified IC method correlated well to results for the three one-row specimens with bolt tearout failure. For the IC method not considering tearout, the predictions were unconservative—for example, a 0.614 test-to-predicted ratio at ultimate. The research team determined that the two-row specimens experienced a generalized block shear failure. Equations and discussion of generalized block shear are presented in Jönsson (2014).

## EFFECT OF BOLT HOLE CLEARANCE

Research under way is building upon this test program and exploring the impact of bolt hole clearance. Reynolds et al. (2020) extended the IC method to consider hole clearances and the bolt slip and bearing behavior. Their analytical study demonstrated potential strength reductions on the order of 9 to 18% in certain cases. Dr. Denavit's group is conducting experiments to verify the effects of bolt hole clearance predicted by Reynolds et al.

## CONCLUSIONS

A comprehensive study evaluated the behavior and design of steel bolted connections subjected to the limit states of bearing and tearout. Through a coordinated experimental and analytical investigation, the research team addressed knowledge gaps and developed methods that capture the influence of tearout. The research demonstrated that neglecting tearout produces unconservative predictions of bolt group capacity. A modified IC method was developed and shown to be more accurate than other methods for bolt groups governed by tearout. For eccentrically loaded two-row bolt groups, generalized block shear failure, a yielding of the material around the bolt group, was identified as the limit state. The bolted connection research continues and includes a study investigating the impact of bolt hole clearance.

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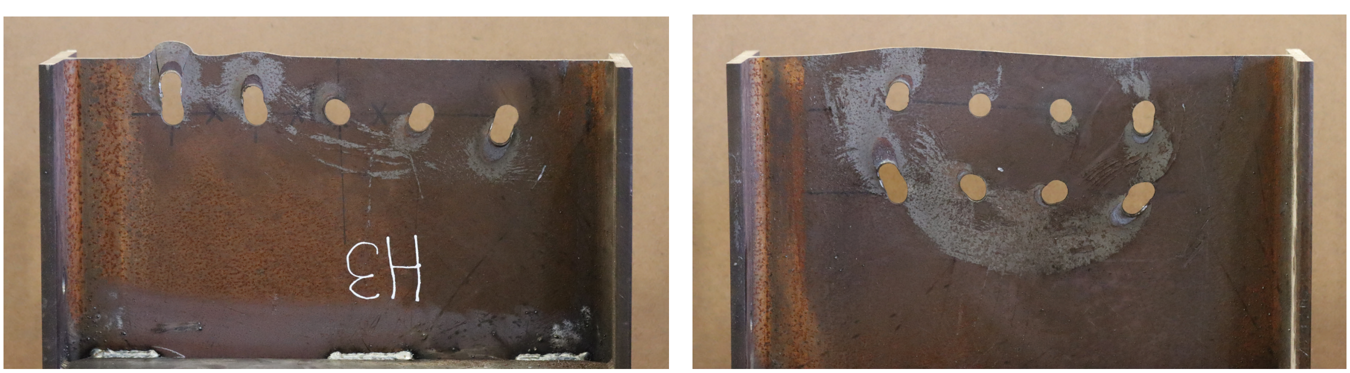

*(a) Specimen H3* *(b) Specimen H6*

*Fig. 7. Specimens after testing.*

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