# TRANSPORTATION POOLED FUND PROGRAM
# QUARTERLY PROGRESS REPORT

Date: _June 30, 2024_

Lead Agency (FHWA or State DOT): ______Indiana DOT______________________________

**INSTRUCTIONS:**
*Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.*

| **Transportation Pooled Fund Program Project #** *(i.e, SPR-2(XXX), SPR-3(XXX) or TPF-5(XXX)* <br><br> ***TPF 5-436*** | | **Transportation Pooled Fund Program - Report Period:** <br> ☐Quarter 1 (January 1 – March 31) <br> X Quarter 2 (April 1 – June 30) <br> ☐Quarter 3 (July 1 – September 30) <br> ☐Quarter 4 (October 1 – December 31) |
|---|---|---|
| **Project Title:** <br> **Development of Criteria to Assess the Effects of Pack-out Corrosion in Built-up Steel Members** | | |
| **Name of Project Manager(s):** <br> **Tommy E. Nantung** | **Phone Number:** <br> **(765) 463-1521 ext. 248** | **E-Mail** <br> tnantung@indot.in.gov |
| **Lead Agency Project ID:** | **Other Project ID (i.e., contract #):** | **Project Start Date:** <br> 9/1/2019 |
| **Original Project End Date:** <br> **8/31/2022** | **Current Project End Date:** <br> **8/31/2024** | **Number of Extensions:** <br> None |

Project schedule status:

☐On schedule X On revised schedule ☐ Ahead of schedule ☐ Behind schedule

Overall Project Statistics:

| Total Project Budget | Total Cost to Date for Project | Percentage of Work Completed to Date** |
|---|---|---|
| **$680,000** | **$550,317** | **88%** |

***Quarterly*** Project Statistics:

| Total Project Expenses and Percentage This Quarter | Total Amount of Funds Expended This Quarter | Total Percentage of Time Used to Date* |
|---|---|---|
| **$18,246** | **2.7%** | **91%** |

*Based on revised project end date of 8/2024.

**Project Description**:

This study proposes to:

1) To develop AASHTO ready specifications for the evaluation of the effects of pack-out corrosion in built-up steel tension, compression, and flexural members.
2) Provide guidance on the need for repairs and corrosion rates that can be expected in various environments in order to assist owners in programming when repairs may need to be made.
3) Identify the most effective methods of repairs and provide suggesting verbiage that could be used when preparing special provisions for repairs.
4) Develop several case-study examples, including calculations that will be used for training users on the methodologies to be developed. It is anticipated that the research team will host a number of webinars or on-site training sessions to ensure technology transfer and implementation.

**Progress this quarter (includes meetings, work plan status, contract status, significant progress, etc.):**

- FEA parametric studies continued on flexural and axial members to evaluate the effect of pack-out corrosion on the strength and fatigue performance of such members.
- Continued work on parametric studies focused on compression members was intimated for a range of flexural members.
- Results (compression, tension, and fatigue) are being synthesized into draft AASHTO ready code and commentary.
- A high-level summary of the portion of the work focused on tension components is attached. The results presented in this attached will be used as the basis for the AASHTO language in preparation.

**Anticipated work next quarter**:

- Continue with the finite element parametric studies and based on the results of the prototype test, develop the detailed experimental program for compression flanges;
- Continue analytical and experimental studies on tension flanges with pack-out corrosion.
- Continue evaluating the strength and fatigue data.
- Continue to craft AASHTO-ready code and commentary for evaluation of members with pack-out corrosion for consideration by AASHTO COBS, S&E and S&M committees.

**Significant Results:**

1. None to date

**Potential Implementation:**

None to date

# TPF-5(436)

The following is a brief update on the overall progress related to influence of pack-out corrosion on the fatigue and tensile strength of steel members. The literature review, results of fatigue testing, strength testing are presented. Work is on going regarding the development of the AASHTO-ready specification language for the evaluation of the effects of pack-out on these limit states.

## Literature Review

A systematic review of the published research literature was undertaken to determine the state of understanding regarding crevice corrosion's effect on fatigue strength. No single document reviewed addressed the subject, yet a number of relative conclusions were drawn from complementary studies.

- Surface corrosion has a far greater influence on the reduction of fatigue strength in the more desirable, superior performing American Association of State Highway and Transportation Officials (AASHTO) fatigue categories. Those analyses compared the as-constructed controlling fatigue detail before and after damage resulting from the corrosion process, in terms of stress concentration magnitude. When the magnitude of the fatigue detail's stress concentrator remained greater than any stress concentrators created by corrosion, the fatigue strength has not been affected. Some publications placed that threshold around category D and E (Albrecht and Cheng, 1983; Albrecht and Naeemi, 1984; Albrecht et al., 1989), while other authors, including AASHTO place it closer to category B (Fisher, J. W., 1983; Barsom, 1984; AASHTO, 1992).
- Built-up members with category D rivet details tend to exhibit a fatigue performance nearer to category C (Out et al., 1984; Fisher et al., 1987; Zhou, Y. E., 1994). Category D is a good lower bound of member performance (Out et al., 1984; Fisher et al., 1990; Zhou, Y. E., 1994).
- A bond is created across faying surfaces by the buildup of corrosion product and has been shown to increase fatigue resistance (Fisher et al., 1990; Out et al., 1984, Zhou, Y. E., 1994; Soriano et al., 2022).
- Rough and irregularly corroded edge surfaces are primarily responsible for a reduction in fatigue strength (Out et al., 1984).
- Fatigue cracks from notches are rarely observed in real in-service corroding members (Fisher et al., 1991). It is surmised the rate of corrosion exceeds the rate of fatigue damage in those cases (Fisher et al, 1991, Calderon et al., 2019).
- When cracks did initiate in severely corroded members, they typically originate at a notch and not at the net section (Fisher et al., 1987).
- Strength tests indicate corrosion does not overly reduce ductility (Fisher et al., 1991).

- Notches detrimentally effect fatigue strength primarily through stress concentrations. Similar reductions from section-loss are from an increase in the nominal stress range. Corrosion notches are more detrimental to fatigue strength than uniform corrosion (Albrecht and Lenwari, 2008).

## Experimental Research

### Large-scale Fatigue Tests

Four large-scale fatigue specimens were fabricated from tension chords of an out-of-service deck truss approach span. The members had been in service approximately 75-years before being acquired by Purdue's Steel Bridge Research, Inspection, Training, and Engineering (S-BRITE) center. Eight months of continuous fatigue cycles resulted in a total of 91.6M cycles being applied to the specimens near the AASHTO category D (stress range, $S_r$ = 7-ksi) and C' ($S_r$ = 12-ksi) Constant Amplitude Fatigue Limits (CAFLs). All specimens were initially subjected to approximately 20M cycles at the category D CAFL with two of the four specimens receiving an additional ~5M cycles at the category C' CAFL as illustrated in Figure 1.

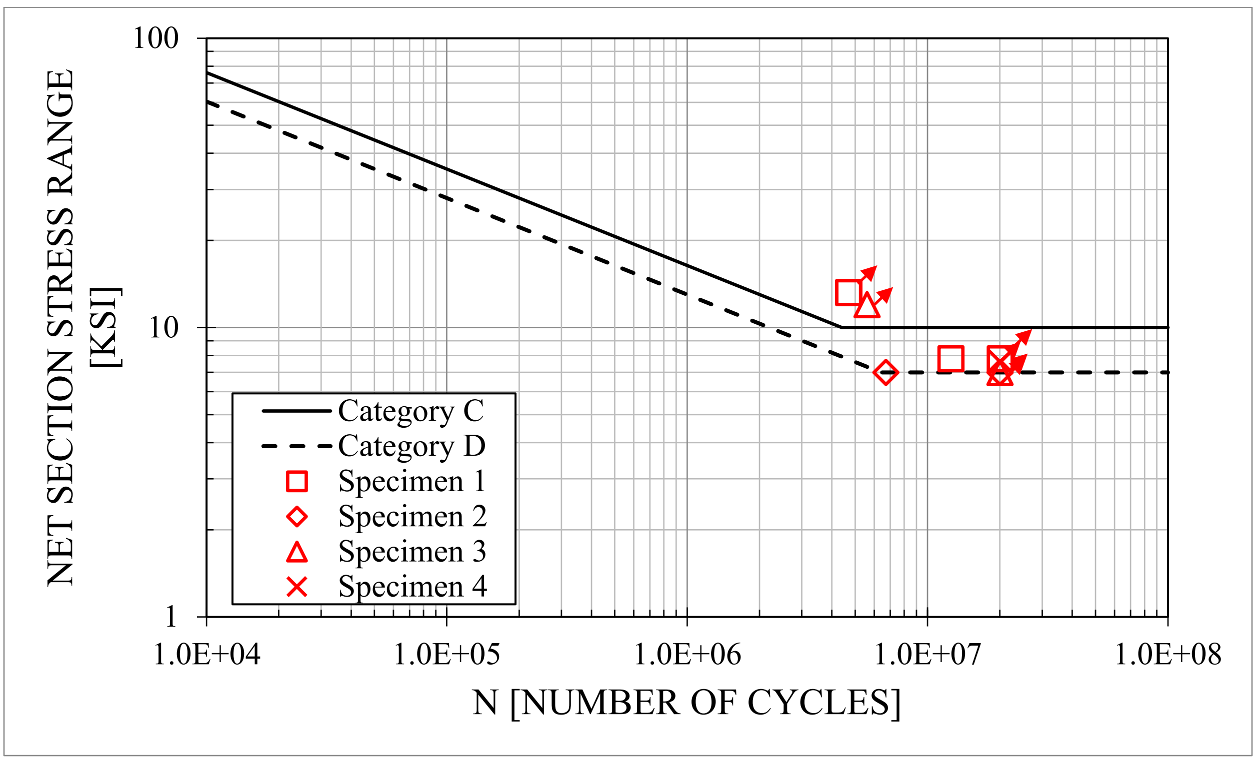


*Figure 1: Specimen Performance on the AASHTO Fatigue Curves*

Two cracks were discovered in cover plates subjected to the fatigue cycles, however they originated from locations of severe local notching and not areas of uniform section-loss. One crack, discovered at 6.7M cycles with a $S_r = 7.0$-ksi, self-arrested between the element's exterior edge and an inboard full depth corrosion pit. The second crack, discovered at 12.7M cycles with a $S_r = 7.0$-ksi, propagated another 0.5-inch in the subsequent 7.3M cycles, but didn't noticeably advance beyond 20M cycles. Seemingly halting to propagate, despite being subjected to another 5.8M cycles at the greater stress range of 12-ksi and a trajectory toward a rivet hole.

## Large-scale Strength Tests

Upon conclusion of fatigue testing, two of the four specimens were then subjected to a strength test, including the faulted condition where the cover plate was severed as if it had cracked entirely near mid span. The purpose of this testing regime was to evaluate the remaining strength and ductility of specimens with significant crevice corrosion and after exhausting all their calculated fatigue life.

Fatigue Specimens 2 and 4 were chosen for the strength testing protocol. Prior to testing, Specimen 2 had 4-inches of its cover plate removed near midspan to facilitate additional strain gauge instrumentation on the faying surface of the underlying member. Specimen 4 was initially tested as-is (Tests 1-3), then in a faulted state for the final load cycle (Test 4). Again, Specimen 4's cover plate was severed near midspan, in the constant moment region.

Results from this series of tests supported a number of observations:

- Specimens retained significant ductility. No fast fractures occurred, despite the existence of a known fatigue crack in Specimen 2.
- Plasticity was concentrated near the severed component, resulting only in a minor reduction in stiffness (~10%).
- The faulted specimens exhibited nearly linear behavior up to the original as-constructed yield design capacity, $M_y$.
- One of the faulted test specimens attained its original as-constructed plastic capacity, $M_p$. The remaining specimen appeared poised to achieve a similar capacity, but due to an instability caused by insufficient out-of-plane bracing at the reactions, this test was terminated early.

Large-scale strength testing demonstrated the remaining capacity of these specimens as illustrated in Figure 2. The ductile response coupled with an ability to attain the full member's plastic moment capacity was demonstrated in the specimen's faulted state. A desirable outcome, despite the member's prior ~75 years of service, advanced crevice corrosion, localized corrosion notching, and exhaustion of the member's calculated fatigue life.

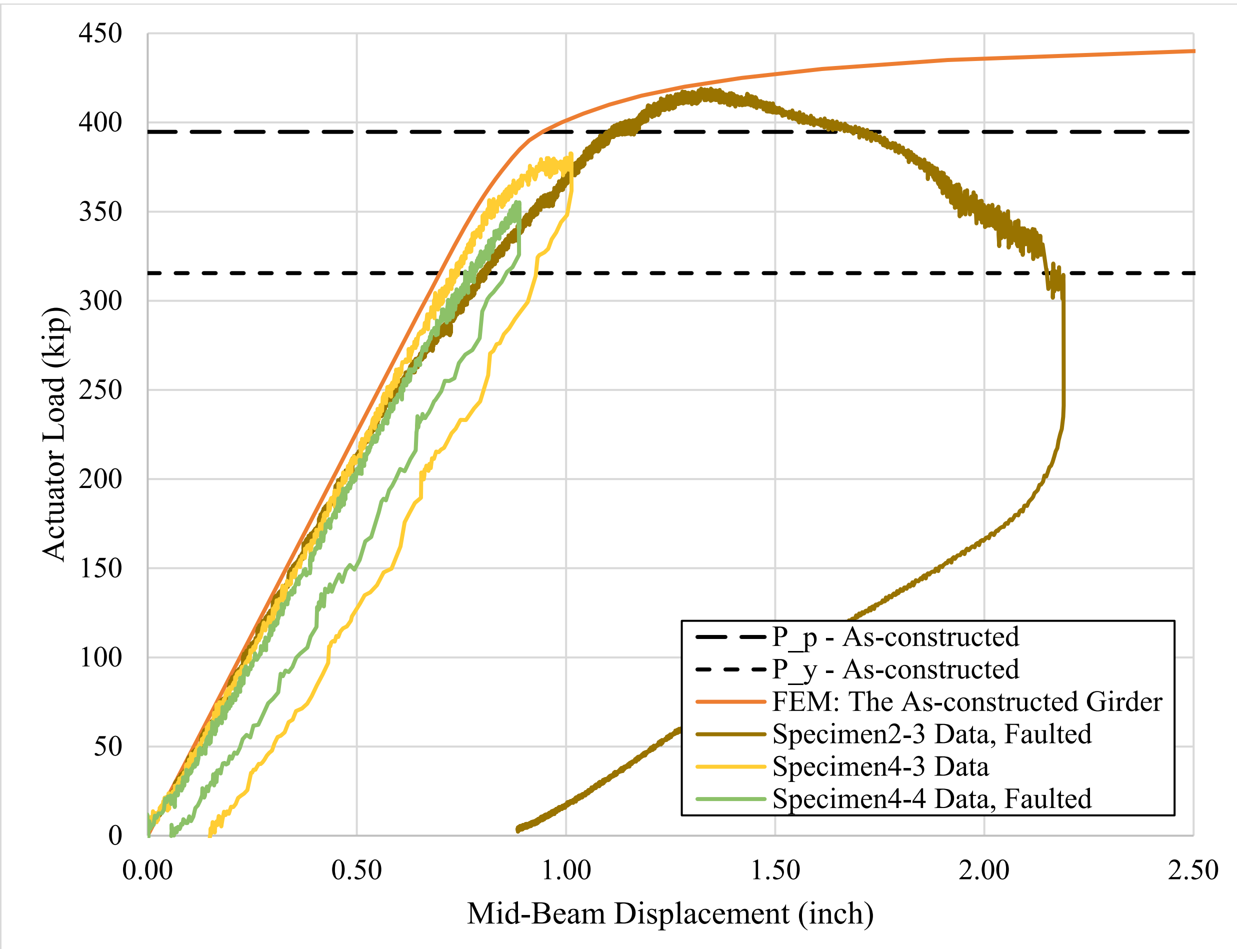


*Figure 2:Full-Scale Testing Load-Displacement Plots*

## Small-scale Tension Tests

Four (4) small-scale tension tests were prepared to evaluate the remaining strength, ductility and modes of failure of the cover plate independent of its companion channel element. Following the completion of both full-scale fatigue and strength tests, the cover plate from Specimen 2 was separated from its mating channel element by removal of the connecting rivets.

The specimens were 72-inch in length, 15-inch wide, with a 24-inch gauge region created by water-jet cutting of a 3x24-inch "keyhole" along the centerline of the specimen as illustrated in Figure 3. Additionally, "fixturing" was required to adapt the deformed and nonuniform specimen ends to the testing machine. Two groups of two specimens each were characterized, loosely referred to as the "worse-case" and "best-case" example sets. The first group focused on the most severely damaged corrosion sections and the latter on the least damage section within the 24-inch gauge region.

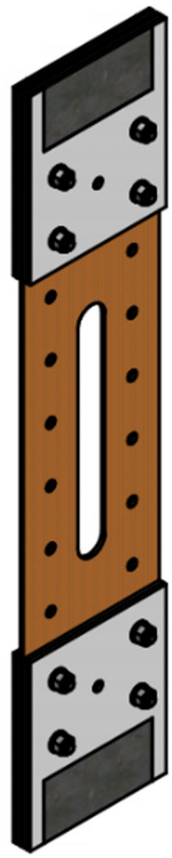

*Figure 3:Small Scale Tension Specimen*

The test objectives allowed minimal instrumentation, limited to recording the applied load, total displacement, and gauge region deformation. Displacement measurements were taken on both sides of the specimen, where the average value was defined as the gauge region deformation as the specimens were slightly out-of-straightness. The resulting force-displacement plots, also including fracture on the net ($F_u A_n$) and yielding on the gross ($F_y A_g$) lines are shown in Figure 4. It should be noted the gross area calculation was based upon the gauge area geometry being the entire section. Therefore, the 3-inch centerline slot was not included in the gross area calculation. Evident in the plot and similarly requiring explanation, the reloading branches at nearly half of the prior peak force was simply a result of how the specimen was configured and the loading protocol. A result of one of the two legs in the gauge region failing first, then the testing machine needing to travel some distance, prior to being able to load the remaining leg.

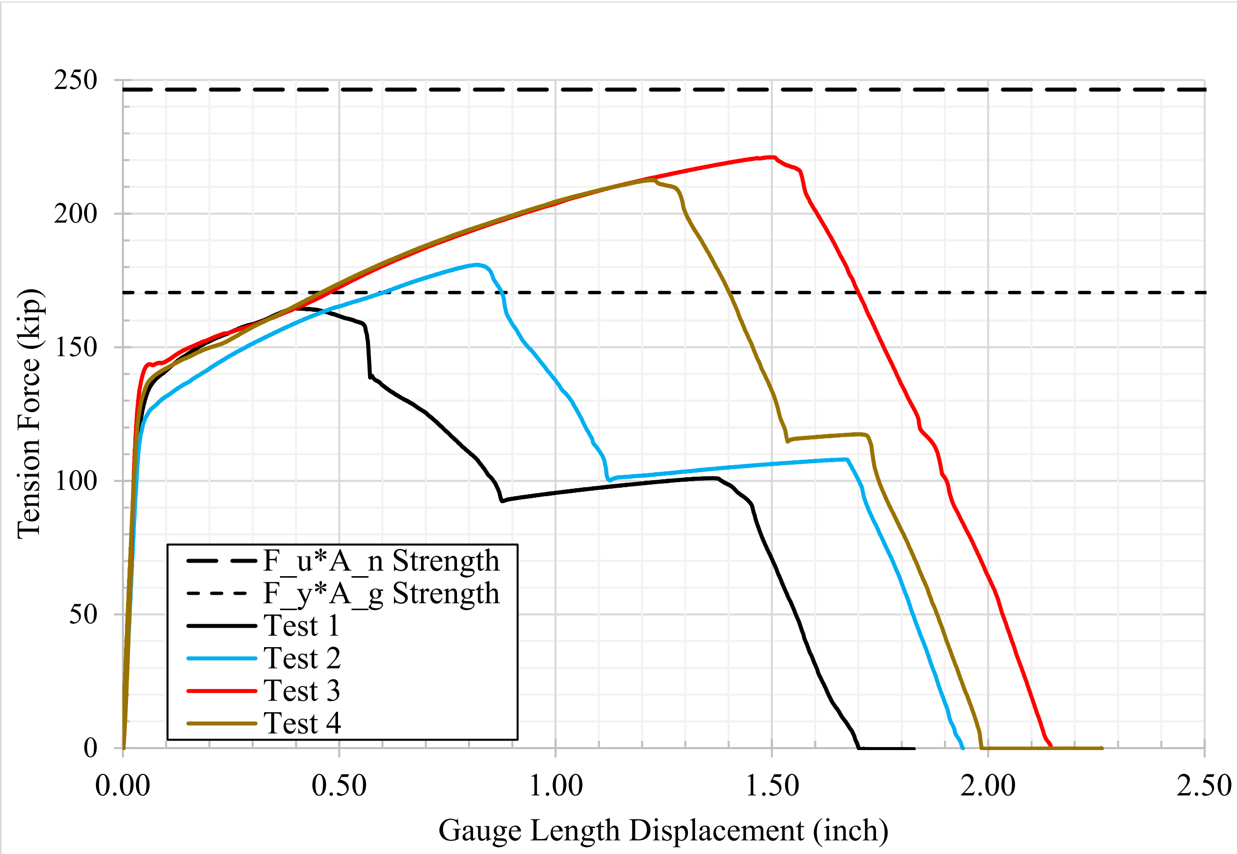


*Figure 4: Small-scale Tension Test Load-Displacement Plots*

None of the tests attained the full pristine specimen tension rupture capacity ($F_u A_n$ strength), while three of four tests reached similarly calculated yield capacity $\left(F_y A_g \text{ strength}\right)$. Intuitively, Tests 1 and 2 were in the worse-case subset exhibited the lower maximum capacity relative to Tests 3 and 4. Two of the four tests initially failed from fastener hole tear out. The exceptions, Test 1 initiated from a localized edge notch and Test 2 propagated through an isthmus of material between a full thickness inboard corrosion pit and outside edge. However, it should be noted this crack and the inboard pit was located just outside of the gauge region.

## Complete Bridge Test

Another opportunity to gain useful insight into the residual strength and ductility of an aging bridge structure presented itself in the form of a complete 33-feet railroad bridge span secured by Purdue's S-BRITE center. Originally constructed in 1904 near Fernie, British Columbia, the bridge was later donated to the Association of American Railroads' (AAR) Transportation Technology Center, Inc. (TTCI) by Canadian Pacific Railway. After being removed from revenue service, the bridge served on the Facility for Accelerated Service Testing (FAST) test track loop in Pueblo, Colorado prior to its acquisition by S-BRITE.

A benefit of acquiring and testing this bridge was it had been purposefully damaged in the form of crack-like features created in the bottom cover plate. Subsequently, two million real railroad loading cycles were applied via FAST. The ambition behind damaging the cover plate was the hope of propagating fatigue cracks in an element of the built-up plate girder and the resulting possibilities of fast fracture and/or a case study of internal or system redundancy for the railroad industry.

### *Fast Fracture Test*

A Fast Fracture Test was conceived and setup requiring simultaneous super cooling and loading of the cover plate to $0.6F_y$. Three such loading attempts were conducted on the damaged cover plate cold soaked to an average temperature of -55°F at midspan without the initiation of a fast fracture failure mechanism.

### *Faulted Strength Test*

The last applicable experimental assessment for the bridge was a Faulted Strength Test. A reference to the severing of the west cover plate at midspan and application of loads commensurate to the un-faulted bridge's yield moment, $P_y = 720$-k. The two final cycles were the attempts to attain the yield moment magnitude. However, those loadings were curtailed out of an abundance of caution when, at a constant 700-k load, both girders were continuing to deflect as illustrated in Figure 5. Also notable and evident in the plot, prior cycle residual deformations were zeroed out at the beginning of each new loading cycle.

Upon completion of the testing protocols, the bridge was destructively inspected for damage. Cover plate sections and cores were cut and removed from areas of interest. Examinations of the removed bridge parts indicated substantial damage at a number of rivet holes and fatigue cracks in the cover plate near midspan. Figure 6 illustrates two representative examples of the defects discovered upon destructive evaluation of the west girder. The left photograph provides indications of a fatigue crack which had opened up during the nonlinear loading cycles. The right photograph illustrates the result of magnetic particle testing indicating two cracks emanating outwardly from rivet holes.

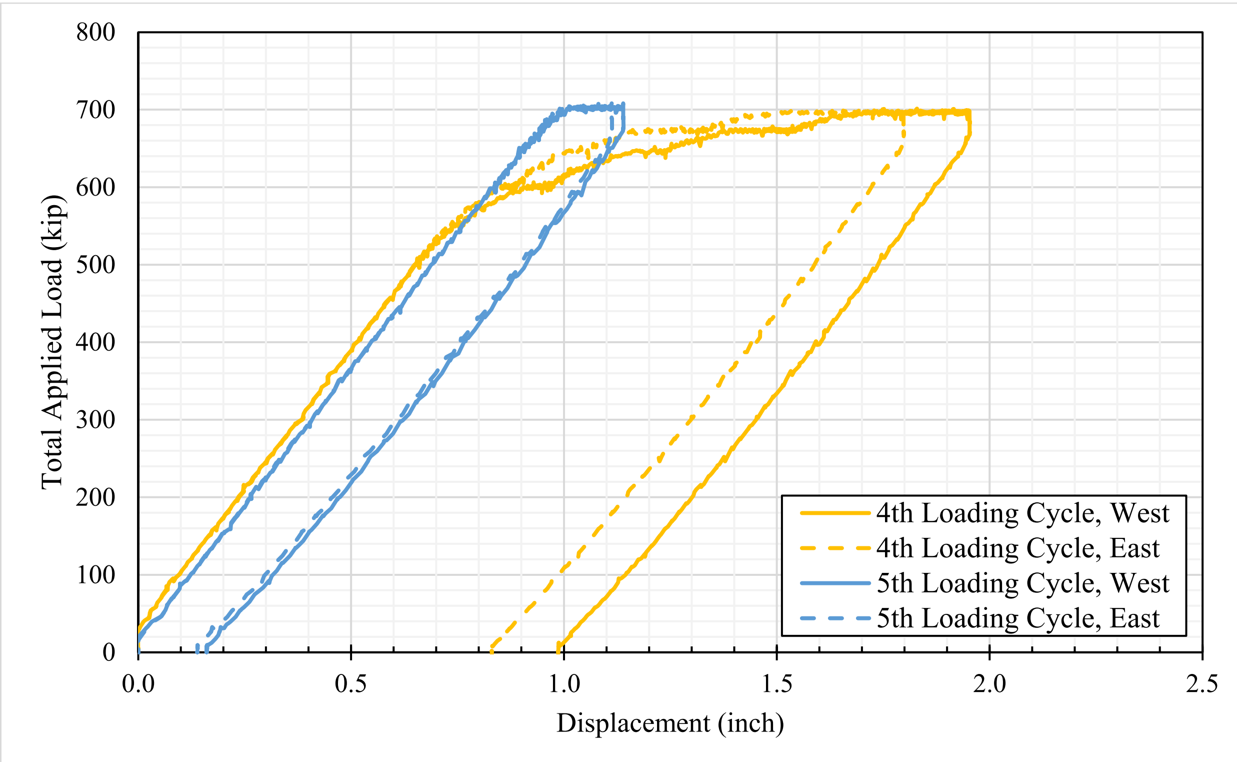


*Figure 5: Complete Bridge Test Force-Displacement Plot*

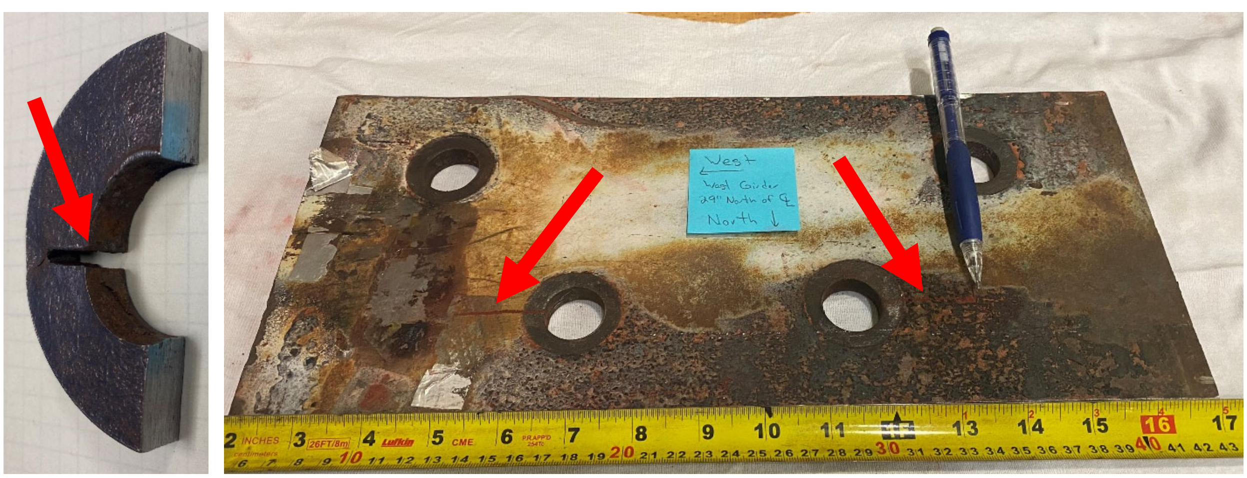

*Figure 6: Examples of Observed Damage from Destructive Investigation*

The initial conclusions drawn from this series of tests included that numerous undiscovered fatigue cracks were likely preexisting in the structure. Despite efforts to lower the material's fracture toughness, no fast fractures occurred in the bridge at midspan with repeated loads approaching $0.6F_y$. Additionally, the design yield moment of the bridge was nearly attained with the faulted west girder's fully fractured cover plate.

## Analytical Research

Initial efforts in Finite Element (FE) modeling have largely been conducted on a variety of local conditions/details, which due to their simplicity can be validated prior to incorporation into the larger, more complex models of actual bridge members. Generally it has been an iterative approach beginning with a certain condition/detail in isolation, thereby minimizing the possibility of other influencing factors. Modeling methodology validation was primarily determined either by or in combination with engineering first principles, review of applicable published research, this project's experimental work, and the contrasting of differing modeling methods. Some of the local conditions/details explored are extrapolated upon in the following subsection.

### Material Stress-Strain

Results from a third-party testing laboratory were post-processed into a format compatible with the project's FE software, i.e. converted from engineering to true stress-strain. FE models were created of the ASTM E8 (2022) Standard Sheet-Type 0.5-in wide specimen to replicate the laboratory's test results. Both shell and solid quadratic elements were modeled over a range of mesh densities, with and without imperfections. Over the entire range of parameters modeled, the FE results tracked well with the true stress-strain values calculated from the laboratory's results, but generally only up to the point of ultimate stress. Because damage parameters were not explicitly included in the material definition, the aforementioned observations were not unexpected. Acknowledging the material definition's inability to predict failure behavior beyond ultimate stress, none-the-less coincides with the project's current analytical objectives which primarily reside in the elastic regime.

## Small-scale Tension Tests

A FE modeling side project was undertaken in an attempt to estimate the ultimate strength resulting from the small-scale tension test's experimental results. The methodology employed a calibrated maximum longitudinal plastic strain taken from a representative FE model of the best-case tension tests average ultimate load. This was able to reasonably estimate the ultimate strength of the two worse-case specimens with caveats.

- Including near zero thickness regions in the model under predicted specimen strength by 25%. Using shell elements with near zero thicknesses were used to emulate full depth pitting and edge notches to avoid explicitly modeling the geometry. A minimum element thickness study was performed and indicated when a minimum shell thickness of between 1/16 and 3/16-inch was imposed on the model, the results markedly improved. In the case of these two examples, from a ~25% under-estimate to a ~3% over-estimate of ultimate strength.
- As opposed to the prior methodology, another study strictly modeled the geometric notches while holding the shell at a constant nominal thickness. This method resulted in a ~3% over-estimation of ultimate strength.

These studies showed in these two examples, modeling the reduced cross-section with a minimum thickness or the geometric notch provided a reasonable estimate of ultimate strength. The preferred modeling method may be contingent on the member under evaluation. Perhaps implying use of the reduced cross-section analysis only when section-loss is present in the absence of notching.
One drawback to this simplified approach is, at least one representative sample needs to be secured and experimentally tested to determine the calibrated plastic strain. A difficult, if not impossible, request of any structure intended to remain in-service.

## Fastener Modeling

A major goal of the project's analytical research is to determine if the effects of crevice corrosion, i.e. section-loss and deformation have a more detrimental effect on fatigue life compared to the member's original, as-constructed controlling fatigue category. An equitable comparison necessarily relies upon contrasting the effective Stress Concentration Factor (SCF) values of each condition. To compare, both the as-constructed and crevice corrosion condition must be analyzed in terms of SCF.

To model the rivets, a line/wire element solution was elected. Rivets were represented as wire features of a given stiffness, including both displacement and rotational degrees of freedom. Each rivet head was separately assigned a coupling constraint where surface nodes were constrained to follow the control point's transitional and rotational behavior. The surface nodes were defined on the face of the part which would be in direct contact with the underside of the rivet head. The constraint between the surface nodes and control points are enforced in an average sense (continuum distributed) so the SCF may develop during the analysis. The reference nodes are assigned to each end of the wire element representing the rivet. One wire and two continuum coupling constraints make up one rivet. The assembly is then simply recreated throughout the model for each occurrence of a rivet.

## Crevice Corrosion

Modeling of crevice corrosion is the integration of separate modeling processes into a single complete working model. Those components include; variable element thicknesses emulating section loss (shell thickness, `STH`), nonlinear couplers simulating rivets and the corrosion product (compression only resisting wire elements) forming between faying surfaces, and pressure loads simulating the distinctive separation (displacement in y-direction, `U2`) characteristically representative of this type of corrosion. All these processes must work in concert and under the conditions of nonlinear behavior associated with crevice corrosion deformation as illustrated in Figure 7.

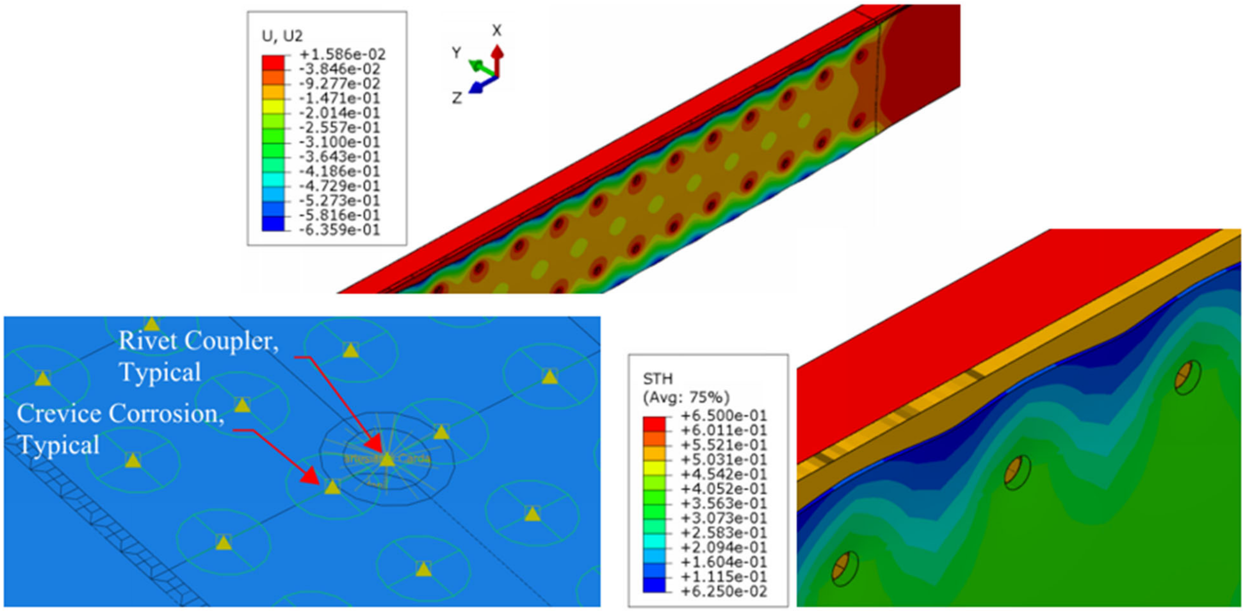


*Figure 7: FE Examples of Couplers, Deformation, and Shell Thickness Integrations*

## Initial Analytical Conclusions

Initial modeling appears to indicate uniform crevice corrosion in the absence of notches does not materially affect the fatigue life of a member with a controlling design fatigue category D or E detail. Single cover plate models in simple uniaxial tension do not indicate SCF magnitudes in excess of the values indicated at the fastener holes in nearly all cases. In the case of a near zero edge thickness, the edge condition has a SCF exceeding the fastener hole but may be a result of issues with accurately modeling near zero shell element thicknesses and not the actual conditions.

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