TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): Kansas 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 #	**Transportation Pooled Fund Program - Report Period:**
TPF-5(189)	X Quarter 1 (January 1 – March 31) ☐ Quarter 2 (April 1 – June 30) ☐ Quarter 3 (July 1 – September 30) ☐ Quarter 4 (October 4 – December 31)

Project Title:
"***Enhancement of Welded Steel Bridge Girders Susceptible to Distortion-Induced Fatigue***"

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Lead Agency Project ID:	**Other Project ID (i.e., contract #):**	**Project Start Date:**
	KAN00063732	08/31/2008
Original Project End Date:	**Current Project End Date:**	**Number of Extensions:**
08/31/2011	**08/31/2013**	**1**

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	Total Percentage of Work Completed
$1,045,000.00	$899,126.77	78%

Quarterly Project Statistics:

Total Project Expenses	Total Amount of Funds	Percentage of Work Completed

This Quarter	Expended This Quarter	This Quarter
$31,017.69	$31,017.69	5%

Project Description:

A large number of steel bridges within the national inventory are affected by distortion-induced fatigue cracks. Repairs for this type of failure can be very costly, both in terms of direct construction costs and indirect costs due to disruption of traffic. Furthermore, physical constraints inherent to connection repairs conducted in the field sometimes limit the type of technique that may be employed. The goal of the proposed research is to investigate the relative merit of novel repair techniques for distortion-induced fatigue cracks.

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

Project Meetings

A TPF-5(189) participants meeting was held on March 16, 2012. In attendance were representatives from OR, TN, CA, KS, and WI. A FHWA representative also visited KU for a site visit on March 5, 2012. An update was provided to all in attendance, and a tour of the laboratory testing was provided. Much of the meeting agenda was devoted to discussion of the current testing and results. Discussion also took place concerning the remaining testing for the Minutes of the discussion are provided at the end of this progress report.

Contract Status

As reported in September, 2011 and December, 2011, the contract for TPF-5(189) has been extended to August 31, 2013. Kansas, Tennessee, Illinois, New York, Pennsylvania, and Louisiana have each committed to contributing additional funds through the project extension. The KU Transportation Research Institute (KU TRI) will provide a 50% match to these contributions. As described in the June 21, 2011 letter sent to participating State DOTs and in the June 30, 2011 progress report, the request for one additional $35K commitment was made: to close the original funding shortfall, to fund student personnel while testing is completed, and to allow for an expansion in project scope.

Technical Updates

1. 30 ft. Three-Girder Specimens

The first full bridge set-up is complete, and static testing has been completed. All data is being recorded using National Instruments data acquisition modules. Strain gages (Fig. 1) , Bridge Diagnostics Inc. (BDI) strain transducers (Fig. 2), LVDTs, and load cells are collecting data from several locations within the bridge. The 26 strain gages were strategically placed throughout the mid-span (test) region of the bridge to capture strains around each web gap region. These include gages near the flange-to-stiffener weld and near the flange-to-web weld. Using this gage placement, changes in stress fields will be captured as a crack initiates and propagates through the material.

Fig. 1: Strain gages and LVDT in top web gap

Fig. 2: View of BDI strain transducers and LVDTs placed along the girder height

Another expected change signifying crack initiation is force distribution between girders. Once one girder is cracked, it is expected that load will be slightly redistributed to the other girders. This change will be captured by the BDI strain transducers and load cells. Two strain transducers are installed on each girder, intended to measure bending stresses within the section. One is placed near the top of the web and one is placed near the bottom of the web to develop the strain profile. Additionally, each end of all three girders rests on a load cell intended to collect reaction forces from the girders and establish force distribution.

In addition to the instrumentation already described, 9 LVDTs have been placed on the bridge to record displacements. Each exterior girder contains similar LVDT placement as seen in the 9 ft. girder set-up to establish a displacement profile. As the bridge deflects, it is expected that the bottom of the girder will also displace laterally. This displacement will be captured using the three LVDTs placed on the exterior girders, spaced along the depth of the girders. Additionally, vertical girder displacements are of interest; many attempts to quantify distortion-induced fatigue have been correlated to differential displacements between girders. Due to this, vertical girder displacements of the bottom flanges at midspan will be measured and recorded with 3 LVDTs (one for each girder), as shown in Fig. 3.

Fig. 3: View of LVDTs intended to record vertical displacements at mid-span

Static testing was performed by loading the bridge incrementally up to a value of 60-kips, as presented in Fig. 4. The purpose of this was to develop baseline curves for strain gages, LVDTs, and load cells to reflect their readings at various loads before cracking is present in the bridge system. Additionally, static tests are intended to aid in selection of an appropriate load range for the bridge system to undergo fatigue testing.

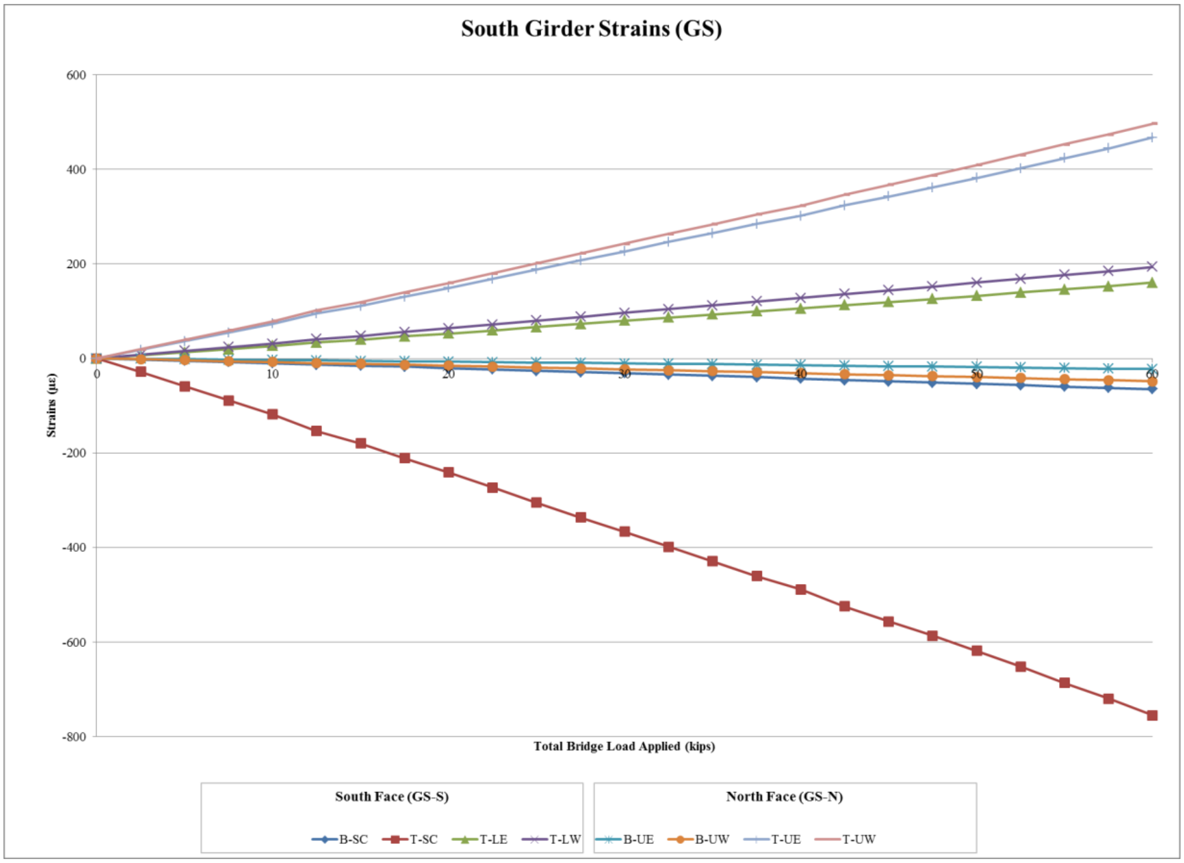

Figure 4: Static calibration of strain gages in the south exterior girder up to a load of 60 kips.

2. 9 ft. Girder Specimens

Fatigue testing Specimen 3 has continued this quarter, and testing of Specimen 4 has commenced. The total number of cycles on the Specimen 3 is just over 4.5 million with 3.6 million of those in the retrofitted configuration. Since the last retrofit was removed, approximately 230,000 load cycles have been placed on the specimen; this has caused the horizontal web-flange crack to extend to 7.75 inches on the fascia side of the girder. This crack has additionally propagated through-thickness and its opening has been growing quite quickly (1.5 inches in 65,000 cycles). It is for this reason that the growth of the horizontal web-flange crack has slowed, most likely—the softening of the web gap region has altered the stress field to curtail crack growth.

The vertical cracks on either side of the stiffener plate-to-web weld are 2.875 and 2.125 inches respectively. Coming off of both vertical cracks are horizontal “spider” cracks which are 1.25 and 0.875 inches long. On the opposite side of the web (the fascia side of the girder) from where these cracks started, the cracking has propagated through the thickness of the web and is 2 inches in length. There is a small crack (0.375 in.) at the stiffener weld in the top web gap but this crack has not grown in over 1.5 million cycles. There are no other detectable cracks in the top web gap region.

Once the horizontal web-flange crack does reach 8 inches, the double angle & plate retrofit will be reapplied and the specimen will be cycled for 1.2 million cycles. Based on the observed trends, it is likely that little to no crack growth will occur while the retrofit is in place, as was the case when the retrofit was applied to the 2, 4, and 6 inch crack length cases. The two included graphs (Figs 5 and 6) show clearly that when the retrofit was applied, all crack growth ceased, which is particularly promising considering the exponential trend in some of the cracks (the horizontal web-flange crack especially).

Static testing of Specimen 4 has been completed, and fatigue testing has been started. A crack approximately 0.375" long has occurred at the web-to-stiffener weld. The crack is currently being propagated to prepare the specimen for a retrofit.

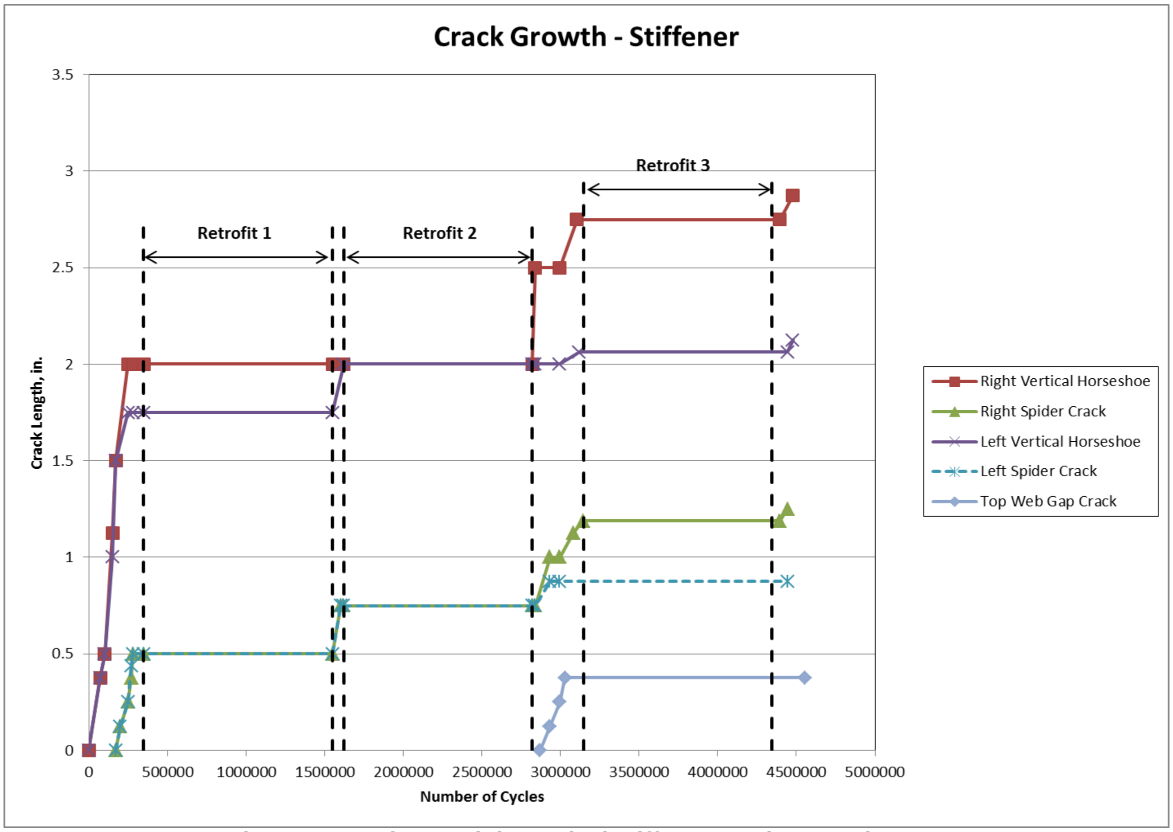

Figure 5: Crack growth in vertical stiffener cracks; Specimen 3

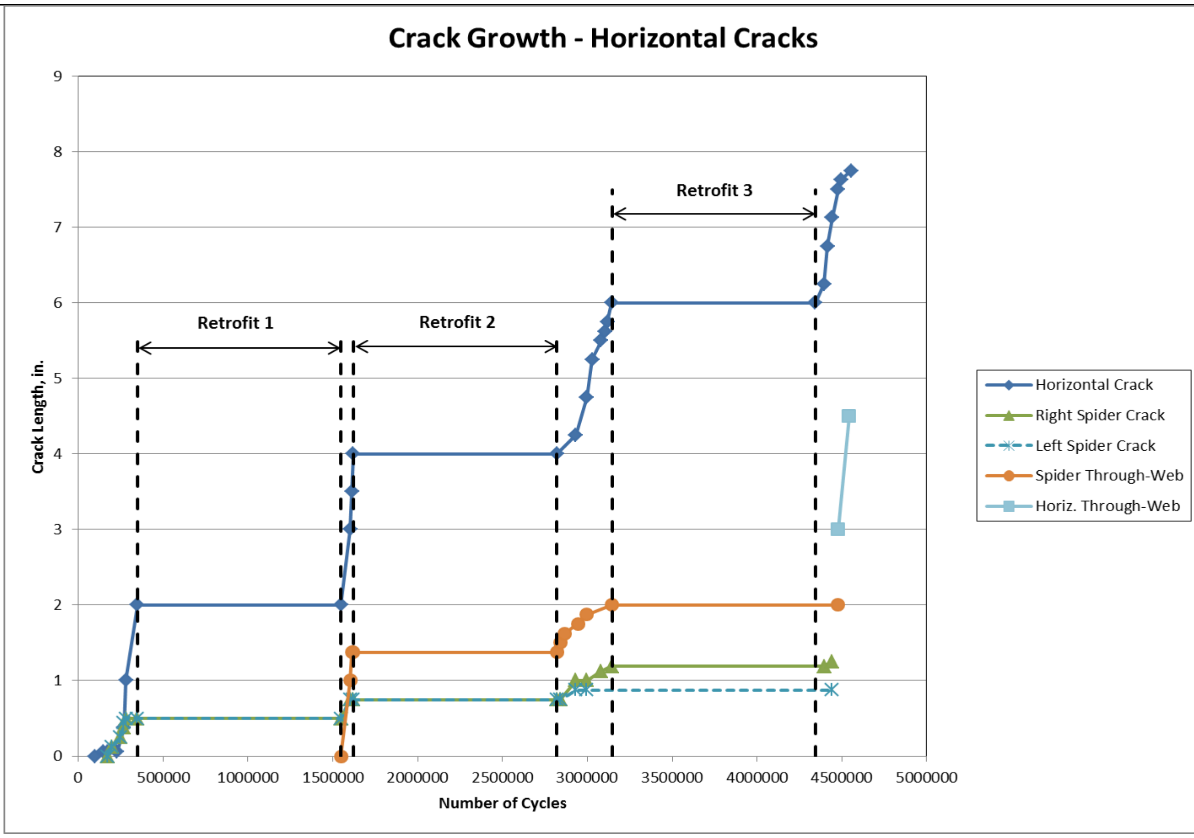

Figure 6: Crack growth in horizontal cracks; Specimen 3

3. Transfer of Retrofit Technology to the Field

The investigators have been working with the Kansas DOT to examine the double-angle retrofit with backing plate as a field retrofit for a bridge slated for repair. The bridge has numerous locations of cracking caused by distortion-induced fatigue. To determine the effectiveness of the double-angle with backing plate repair, a full 3D finite element model of the bridge has been built, and variations of the repair have been included in the model (Figs. 7 and 8). The repair is showing promise in the models, and a series of truck-load tests are planned at the bridge. The first truck-load test will be performed to determine the current state of stress in the bridge, while the second truck-load test will be performed after retrofits are installed to gage the effectiveness.

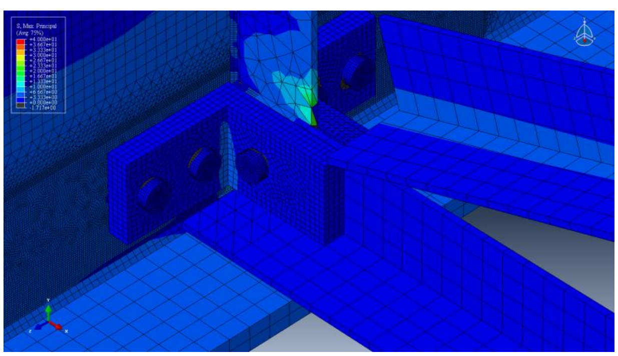

Fig. 7: View of the double-angle with backing plate retrofit included in the finite element model

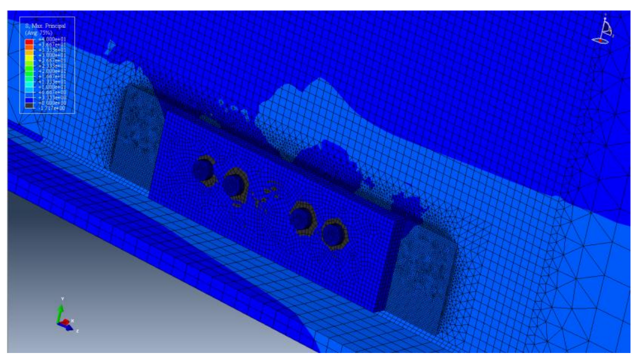

Fig. 8: View of the double-angle with backing plate retrofit included in the finite element model (fascia side of girder)

4. Crack-Stop Hole Investigation

As crack-stop holes are often the first mitigation measure implemented when fatigue cracking is noted, this well-established technique is often of interest to bridge engineers. However, the performance of crack-stop holes under distortion-induced fatigue is generally poor, and compounding this is the fact that no equations or clear guidance currently exist to place and size crack-stop holes for distortion-induced fatigue. The investigators have created a series of finite element models to study the size and configuration of crack stop holes in steel bridge girders susceptible to distortion-induced fatigue. Crack placements have included cracks at the flange-to-web weld (Fig. 9) and at the stiffener-to-web weld (Fig. 10). Crack-stop holes have been modeled with various diameters, and have been placed at the tips of the cracks in two manners: just outside the weld, and directly through the weld. In regions where crack-stop holes lie in overlapping stress zones from multiple welds (such as the web gap), complex interactions are being noted. For example, as crack-stop hole diameter is increased for a crack-stop hole at the end of a flange-to-web weld, the stress demand at that weld location is reduced; however, stress demand at the nearby stiffener-to-web weld is amplified. In regions where little stress overlap is present, increasing crack-stop hole diameter does tend to correspond with decreasing stress demand (Fig. 11).

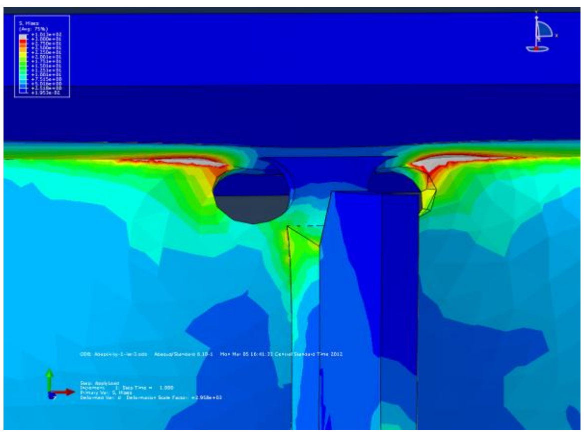

Fig. 9: View of crack-stop holes placed at tips of flange-to-web weld

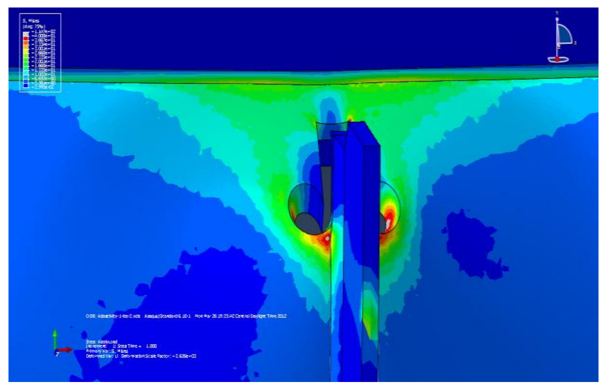

Fig. 10: View of crack-stop holes placed at tips of horseshoe-shaped crack at stiffener-to-web weld

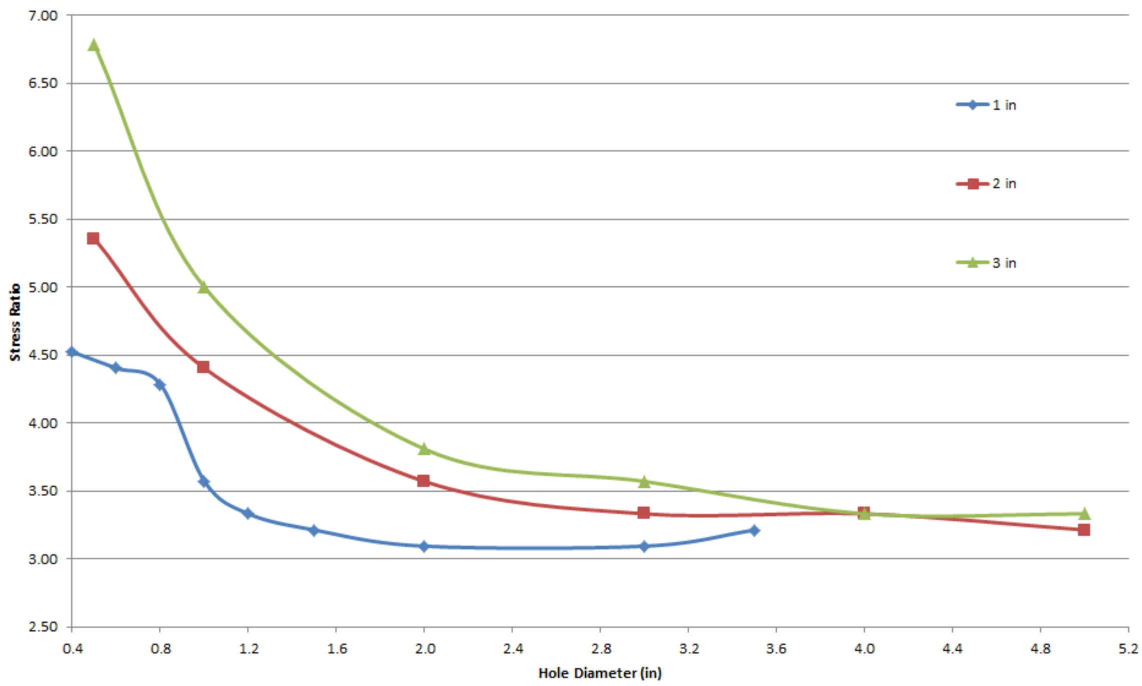

Fig. 11: Crack-stop hole diameter vs. peak stresses for various crack lengths (for stiffener-to-web weld)

Anticipated work next quarter:

- Fatigue testing the 30-ft. bridge test set-up.
- Fatigue testing Specimen 3, Specimen 4, and Specimen 5 in the 9-ft. girder test set-ups.

Significant Results:

The angle retrofit described in the June 2011, September 2011, and December 2011 reports has continued to perform excellently under fatigue testing. This retrofit technique has a great deal of promise for practical field application, as it avoids complications that arise with connecting to a top flange.

A list of in-print publications produced by the project team in direct relation to TPF-5(189) is presented here, for the reader interested in further analysis of results to-date.

Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., and Rolfe, S. (2011). "Use of CFRP Overlays to Strengthen Welded Connections under Fatigue Loading," Accepted for publication in the *Journal of Bridge Engineering*, ASCE.

Kaan, B‡, Alemdar, F.‡, Bennett, C., Matamoros, A., Barrett-Gonzalez, R., and Rolfe, S. (2011). "Fatigue Enhancement of Welded Details in Steel Bridges Using CFRP Overlay Elements," Accepted for publication in the *Journal of Composites for Construction*, ASCE

Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., and Rolfe, S. (2011). "Improved Method for Bonding CFRP Overlays to Steel for Fatigue Repair," Proceedings of the ASCE/SEI Structures Congress, Las Vegas, NV, April 14-16, 2011.

Hartman, A., Hassel, H., Adams, C., Bennett, C., Matamoros, A., and Rolfe, S. "Effects of lateral bracing placement and skew on distortion-induced fatigue in steel bridges," *Transportation Research Record: The Journal of the*

Transportation Research Board, No. 2200, 62-68.

Crain, J., Simmons, G., Bennett, C., Barrett-Gonzalez, R., Matamoros, A., and Rolfe, S. (2010). “Development of a technique to improve fatigue lives of crack-stop holes in steel bridges,” *Transportation Research Record: The Journal of the Transportation Research Board,* No. 2200, 69-77.

Hassel, H., Hartman, A., Bennett, C., Matamoros, A., and Rolfe, S. "Distortion-induced fatigue in steel bridges: causes, parameters, and fixes," Proceedings of the ASCE/SEI Structures Congress, Orlando, FL, May 12-15, 2010.

Alemdar, F., Kaan., B., Bennett, C., Matamoros, A., Barrett-Gonzalez, R., and Rolfe, S. "Parameters Affecting Behavior of CFRP Overlay Elements as Retrofit Measures for Fatigue Vulnerable Steel Bridge Girders," Proceedings of the Fatigue and Fracture in the Infrastructure Conference, Philadelphia, PA, July 26-29, 2009.

Kaan, B., Barrett, R., Bennett, C., Matamoros, A., and Rolfe, S. “Fatigue enhancement of welded coverplates using carbon-fiber composites,” Proceedings of the ASCE / SEI Structures Congress, Vancouver, BC, April 24-26, 2008.

Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).

TPF-5(189) PARTICIPANT'S MEETING – MARCH 16, 2012
1 EATON HALL
MEETING MINUTES

ATTENDING

- Lian Duan (CA)
- Craig Wehrle (WI)
- Tom Quinn (TN)
- Bruce Johnson (OR)
- Loren Risch (KS)
- John Jones (KS)
- Paul Kulseth (KS)
- Caroline Bennett
- Adolfo Matamoros
- Stan Rolfe
- Amanda Hartman
- Temple Richardson
- Gary Simmons
- Daniel Nagati
- Jeff Wheeler
- James Zhou
- Alisha Elmore
- Say Hak Bun
- Jack Przywara

PRESENTATION QUESTIONS/COMMENTS (MORNING SESSION)

Overview of Problem (Slides 5 & 6)

- Craig: Is the stiffener welded to the flange in this model? (A.M. – No, this is an un-retrofitted model.)
- Bruce: So far are you only looking at finite element models (concerning crack stop holes)? (C.B – No, we have performed physical tests with crack stop holes but all with same size holes.)

Evaluation of Commonly-Used Mitigation Measures
Crack-Arrest Holes (Slides 18 & 19)

- Bruce: Do you use an offset drill in the lab? (C.B. & A.M. – No.; S.R. – You can model anything analytically. The hole can be placed anywhere.)

Evaluation of Commonly-Used Mitigation Measures
Transverse Back-Up Stiffener (Slide 26)

- Craig: Why does the back-up stiffener do that? Does the back-up stiffener spread the load? (A.M. – Yes, the plates may take some of the load through bearing on the flange.)
- Tom: Is the back-up stiffener in contact with the bolt? (A.M. – Yes.)
- John: Are these models for skewed or non-skewed bridges? (A.M. – The models are for non-skewed but we have modeled full skewed bridges with different cross-frame layouts.)
- Bruce: Did you take into consideration the prying action? Is it allowed to flex? (A.M. – Yes.)
- Bruce: Do you have a way to modify the bolt spacing and plate thickness to minimize this? (C.B. – We have done a series of parametric studies, but not looking explicitly at the bolt spacing. Plate thickness has not been found to be a significant driver.)
- John: The practical limitations of applications of these experiments are paramount.

Evaluation of Commonly-Used Mitigation Measures
Back-Up Stiffener (Slide 34)

- John: For 2-girder bridges this retrofit helps prevent flange tilt.

- When there are obstacles on the other side, like longitudinal stiffeners, what happens? (A.M – Can use back-to-back angles.)
- Bruce: Did you investigate the bottom of the web? (C.B. – Yes.)

Evaluation of Commonly-Used Mitigation Measures
Local Retrofit Application (Slide 39)

- Bruce: Results should have shown some reduction in stress even though the susceptible detail was just moved to the next cross-frame location in the bridge. (C.B. – Yes it did, but the stress reduction was not significant.)

Mitigation Methods Under Development
Web-to-Stiffener Angles with Backing Plate (Slides 47-50)

- Craig: In real world applications would you weld the backing plate? (A.M. – No, bolt.)
- Bruce: Are you just spreading out the stress with the backing plate? (A.M. – Yes, the backing plate helps distribute the stress.)
- Craig: Do you think spreading the stress out, just delays the problem? (A.M. – Not according to the analytical models or the experimental tests performed so far.)
- Craig: Suggested bolting the angle to the web first, then the stiffener.
- Tom: Does this model take into consideration the tension and compression flange? (C.B. – Not in these models, but the full bridge models do.)
- Craig: What do you think about usage in floor beams? (C.B. – Yes, Paul K – Using it where the stringer terminates at a hinge.)
- Paul: Size doesn't really matter on local retrofit, but cost is an issue on global installation.

Q&A/ DISCUSSION (MORNING SESSION)

Stan R.

- Since analytical studies have been done on the composite sandwich retrofit, the next step would be to apply the retrofit to an experimental specimen. If it is found that the retrofit does not work on the experimental specimen, then it will not be applied in the field.

Craig W.

- Would like the research time to look at the angle with backing plate retrofit on a stringer and floor beam configuration. (With more than just one floor beam – unlike KDOT configuration that was studied briefly analytically)
- Suggested using four angles to connect the connection plate to the flange when applying the full depth splice.
- When applying the composite material, do you roughen the surface with a needle scaler? (John J.- It is a very safe method to remove corrosion. Looks like a giant UIT with air driven needles. Must be used with an air compressor. Very safe, and you can't damage the girder. A.M. Do not want a smooth surface, must be roughened.)
- Is the plug diameter slightly larger than the crack stop-hole diameter? (C.B. Yes, the plug is press-fitted in the crack-stop hole and then expanded, which produces compressive stresses.)

Tom Q.

- Need to look at angle with backing plate retrofit on a configuration that has bending.

Bruce J.

- On the angles with backing plate retrofit, try varying the distance of the bolt to the angle edge, and also vary the length of the angle.

Loren R.

- How difficult is it to put fabric on the sandwich composite retrofit? (A.M. Use a pre-fabricated material and take to the field. While in the field, just glue to steel.) Does the area need to be cleaned? (A.M. Create a rough steel surface by using a grinder and clean with acetone.)

John J.

- To avoid intersection of back-up stiffener to longitudinal stiffeners, try looking at stiffeners that are ¾ of the web's depth.
- On an interior girder a full depth splice cannot be used.
- Had concerns with low modulus in conjunction with high modulus in the sandwich composite. Would creep occur? Pre-load fastener to 70% and rely on that to pre-load on a fastener to resist fatigue, so that cyclic load is never what the pre-load sees. As composite creeps, pre-load goes away. (S.R. - Similar to Kemper Arena) (A. M. - Thermal plastic could remedy this.)
- A fastener would be tightened too much in the sandwich composite, and composite would be over squished. Is intent a slip-critical connection, or is the intent just to provide some uniform clamping to facilitate a bond? (Different situations) (C.B. – use washer inside resin layer so bolts would bear on a washer and not squeeze resin out.) Similar to head gasket on a car, also, cars have bushings. They are calibrated to fasten to a certain amount.
- Sandwich retrofit - Grind the surface of a bridge to roughen an area? Do you mean a flat disk so as to not damage the bridge? Must be specific as to what you want an ironworker to do. (A.M. - Just roughen. Accomplish with a sand blaster in the lab.)
- Simpler retrofits have less chance for error. A great design can be constructed poorly.

Paul K.

- On the bridge south of Park City, the stiffener was removed, and then the full depth splice was installed. Finally, the stiffener was welded back in place. This retrofit might be better than local repairs, but this retrofit was extremely expensive. It requires grinding after the stiffener is removed, and all bolts must be drilled. It is very work intensive. Angles are connected to the flange.
- Use clamping force in sandwich composite to stop creep.
- In a steel plate and neoprene trough, what is stopping the neoprene from squeezing out?
- Complex details can be very expensive to implement in the field.

PROJECT DIRECTION / FUTURE TESTING (AFTERNOON SESSION)

- Tom: Optimum backing plate size or method to determine appropriate plate size. (C.B. – Seems not to be sensitive to length of back plate or thickness. Will definitely examine where bolts should be placed, Justin Ocel recommended. Will be explored in 30 ft. setup)
- Tom: What about size of angles? (C.B. – Angles appeared not to be a driving factor.)
- Bruce: There was an old railroad criteria for thickness verses gage length for bolts (may be worth exploring). It discussed gage length from center to reduce prying action. Paper establishes method to determine number and size of bolts. (Journal Paper in 1930's, prying action in title.) Maybe update or confirm paper. (Craig – There is another railroad paper for designing for moment.)
- Bruce: U-shaped crack is most prevalent for Oregon DOT. Keep working to find how to recreate this type of crack. (C.B. – Stiffener crack develops first…then horizontal. S.R. – Longitudinal force might pull the stiffener crack out into the horseshoe shape consider in full bridge…we will try to model analytically and then push to bridge.)
- John: U-shaped cracks dominate in Kansas. Seen in positive and negative moment region regardless of whether the longitudinal stress is in tension or compression. Having the 9 ft. specimen is isolating the problem we are concerned about. Remove fasteners except at the end allowing the flange to rotate—may allow girder to twist inducing an additional stress state even if it still doesn't quite match the real world. (Bruce agrees with John.) Maybe the reason why the flange weld is dominating is because the weld is now loaded in tension…not shear. In compression region, horseshoe is pushed back in. In tension, the horseshoe is being pulled out. In the 30 ft. specimen the flange conditions may be more realistic. Maybe remove some restraint to induce horseshoe shape crack (in model and in experiments). In positive moment, the bottom flange is not restrained and is really flexible. (A.M. – Regan Gangel looked at adding longitudinal stresses with normal bending loading and considered many configurations. Live load is the only thing that matters because live load induces stress range. We have not spent a significant amount of time examining the effects of slab flexibility. Probably needs to be considered in the future.)
- Tom: Don't see just the horseshoe-shaped crack in TN. Has seen many along the toe of the weld similar to what we have seen in lab. Has seen cracking even when stiffeners are back to back. (John – KS usually only sees cracking when there is a cross frame on one side of the web. Bruce – for skewed bridge whether straight (cross frames unstaggered on the skew) or staggered, we see cracking in interior girders. Bottom flange cracking for only skewed bridges. A.M. – Every time we simplify to make testing cheaper…we are giving something up. We are trying to make sure we capture the state in the full bridge. Bruce – The overall state of the bridge influences the way the crack grows including dead and residual stresses impacting crack growth and pattern.)
- Lian: No flange weld crack…mostly just web cracking noted in CA. CA using bolted angle to attach connection stiffener to flange. From your study, you are evaluating using HSS. Do you intend to recommend HSS paths? AASHTO no longer checks fatigue for flange weld. Now just requires design for shear (category E???) (C.B. – A TRB research needs statement was just put in about this very issue concerning HSS. Lian – Need simplified procedure to cover modeling information. Bruce –Check for category C, not E. John – Check location for C (stud and transverse stiffener).)
- S.R.: In the next 16 months, PFS will be closed off…focus on:
  (1) ongoing studies of 9-ft. specimens,
  (2) run two to three 30 ft. bridges to crack and retrofit and establish performance (expect to obtain multiple tests from each bridge setup),
  (3) optimize geometry for the 'best' retrofits for application in the field to establish field guidelines and application…specific procedural details, and
  (4) new 9 ft. series to unlock the top flange to allow rotation (exploring analytically first).

- John – Develop procedure very specific and it must be practical ('Bubba' must be able to complete this). This guideline must also be reproducible…no freehand drilling and cutting. Templates for hardware! Paul – Full procedure needs to be specifiable step-by-step in plans.
- John – On round two…use the procedure to check for accuracy. Must follow exactly what is specified to find any potential confusion or errors.
- John – Look for flange rotation not just web rotation. Analytical first to see if it may change cracks before applying to experimental study.
- Craig – Will loosening the 9-ft. girder's flange add longitudinal stresses? (S.R. – No it will not.)
- Tom – Are the retrofit details going to be for stiffener on one face? (S.R. – Absolutely. We could always end up having issues in the center girder of the 30 ft. system to try to fix.)
- Bruce – Is there one answer for the size of the angle? (Paul – For 5/8" web what size do you use…for 1" web what size do you use? Or what about just using a 1" as an upper bound? Material thickness is not the driving cost, labor is. Can we find an upper limit that is applicable everywhere? C.B. – Every detail is different because of the geometry. A.M. – We have done parametric studies as far as length and stiffness, we can continue to explore. Bruce – Guidelines are going to be critical. Lifting or handling material is going to be important because it influences cost. Craig – Angle thickness may impact load transfer and spread.)
- John – Kansas has used UIT in combination with other repairs. We need to understand benefits of technology with respect to this retrofit. For example, at Tuttle Creek, UIT the face of the hole. We actually dressed the cope hole and UIT'ed. Oregon and Tennessee have not used UIT. Wisconsin has. Redundancy for repairs implemented.
- Bruce – Have different details in stringer floor beams. One in original connection in floor joist, and one where bottom flange sits on angle 'thing'.

- CRB what involvement would DOTs like over the next 16 months?
  - Bruce – conference call would engage DOTs more.
  - S.R. – In 6 to 9 months, send out an outline of the final report. Web meetings so that images can be presented.
- Bruce – Is the angle/plate retrofit intended to fix both cracks? (A.M. – Yes. Since a true horseshoe-shaped crack has not developed in tests, more research is required. Horizontal crack is a result of the web bending. Bending stress would project the stress out and possibly cause the horseshoe crack.)
- John –Angle repair, is it the intention for angle to be in bearing on the flange? (A.M. – Concerned it would be detrimental by pulling on the crack. Could warrant some investigation.)
- Bruce – What is the benefit of the composite in the sandwich retrofit? (A.M. – A compliant layer helps in fatigue. Orthotic analogy.)
- Paul – From a maintenance view, sandwich retrofit would still be far off from implementation. Bruce – If you do recommend it, you have to say why (vs. simpler retrofit). Paul – Because with specialty materials, the number of bids goes down.
- John – If you have no dead load capacity in a damaged member, you don't get load transfer until more failure occurs.
- Loren – In the future, new fatigue details will be needed for new designs.

Minutes respectfully submitted by AME, TIR, ASH, ADN 3.16.2012

TPF-5(189):
Enhancement of Welded Steel Bridge Girders Susceptible to Distortion-Induced Fatigue

March 16, 2012

Caroline Bennett, Assistant Professor
Adolfo Matamoros, Associate Professor
Stan Rolfe, A.P. Learned Distinguished Professor
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Students

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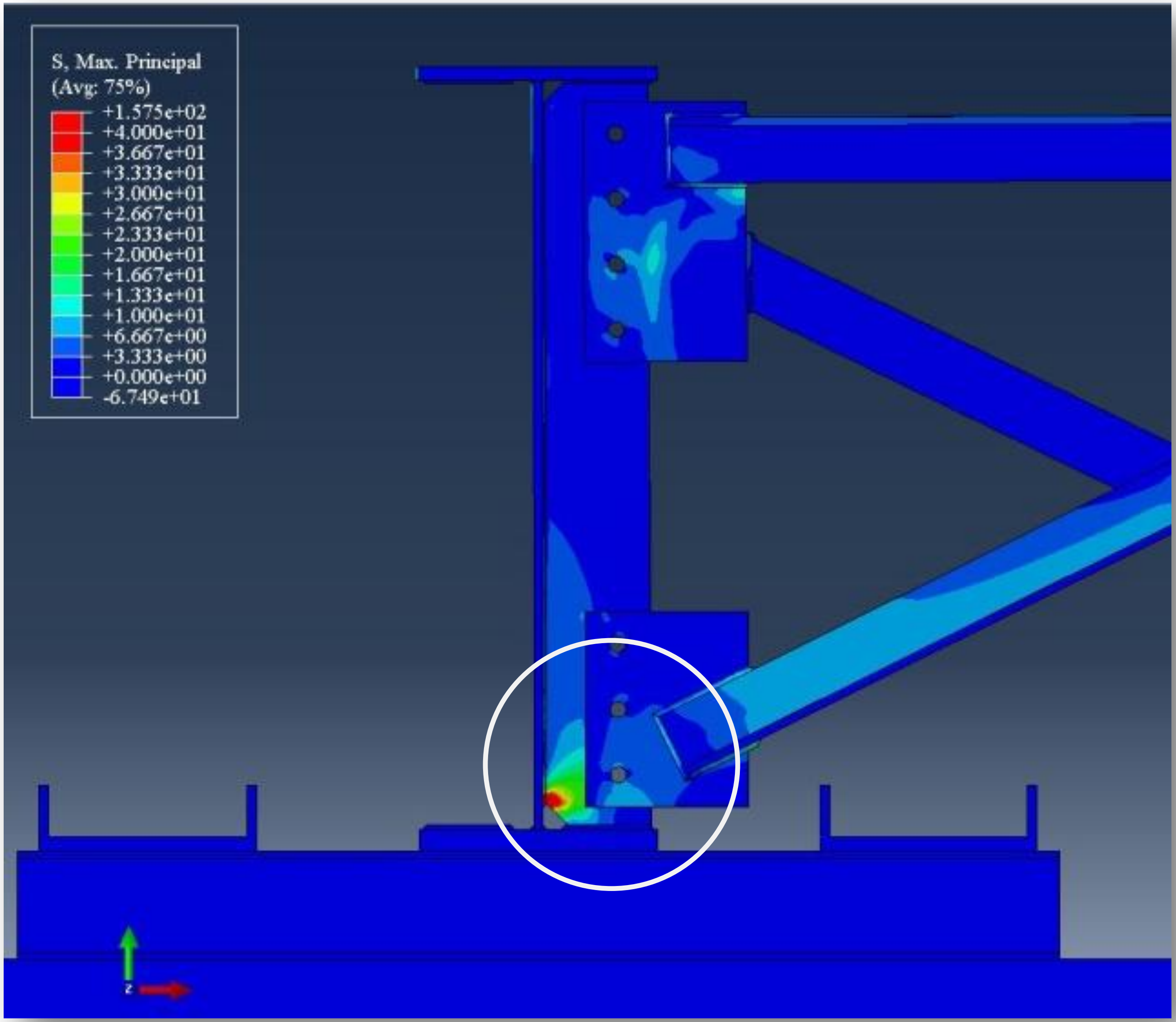
Outline of Presentation

- Overview of Problem
- Project Approach
- Mitigation Methods Under Development
    - Relatively short cracks
    - Deep web cracks
    - Crack-arrest hole improvements
- Conclusions & Summary

Overview of Problem

- Identify locations with high potential for stress
- Develop measures that will mitigate that distress

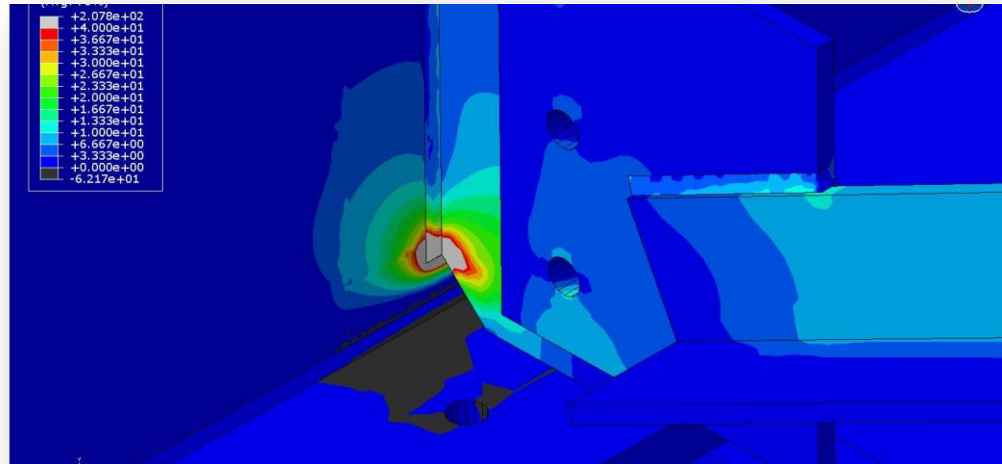
Overview of Problem



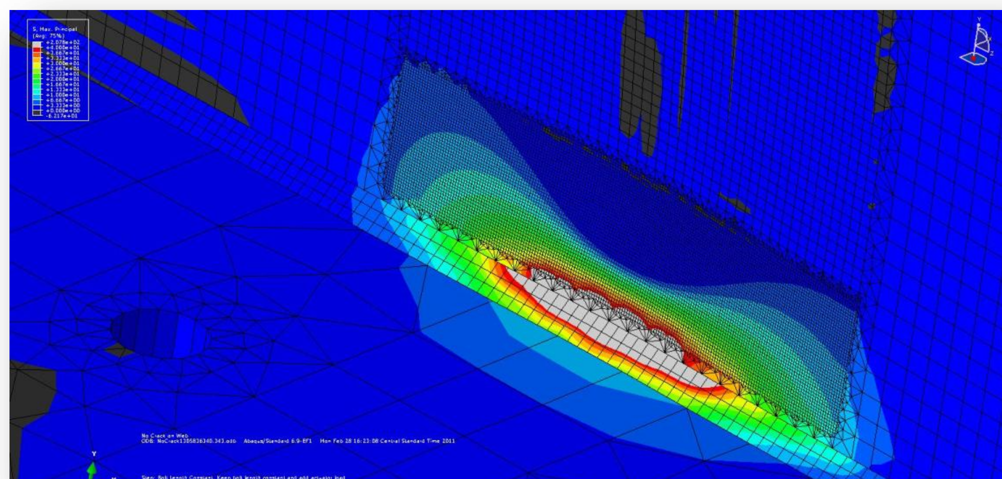
Overview of Problem

- Two locations of cracking to be concerned with:
  - Stiffener-to-web weld
  - Flange-to-web weld

Stiffener-to-Web Weld:



Flange-to-Web Weld:



Overview of Problem

Photo acknowledgement: (John Jones, KDOT)

Overview of Problem

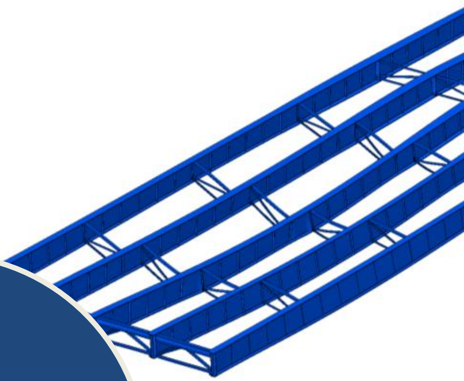
Photo acknowledgement: (John Jones, KDOT)

Project Approach

Laboratory Testing

TPF-5(189)

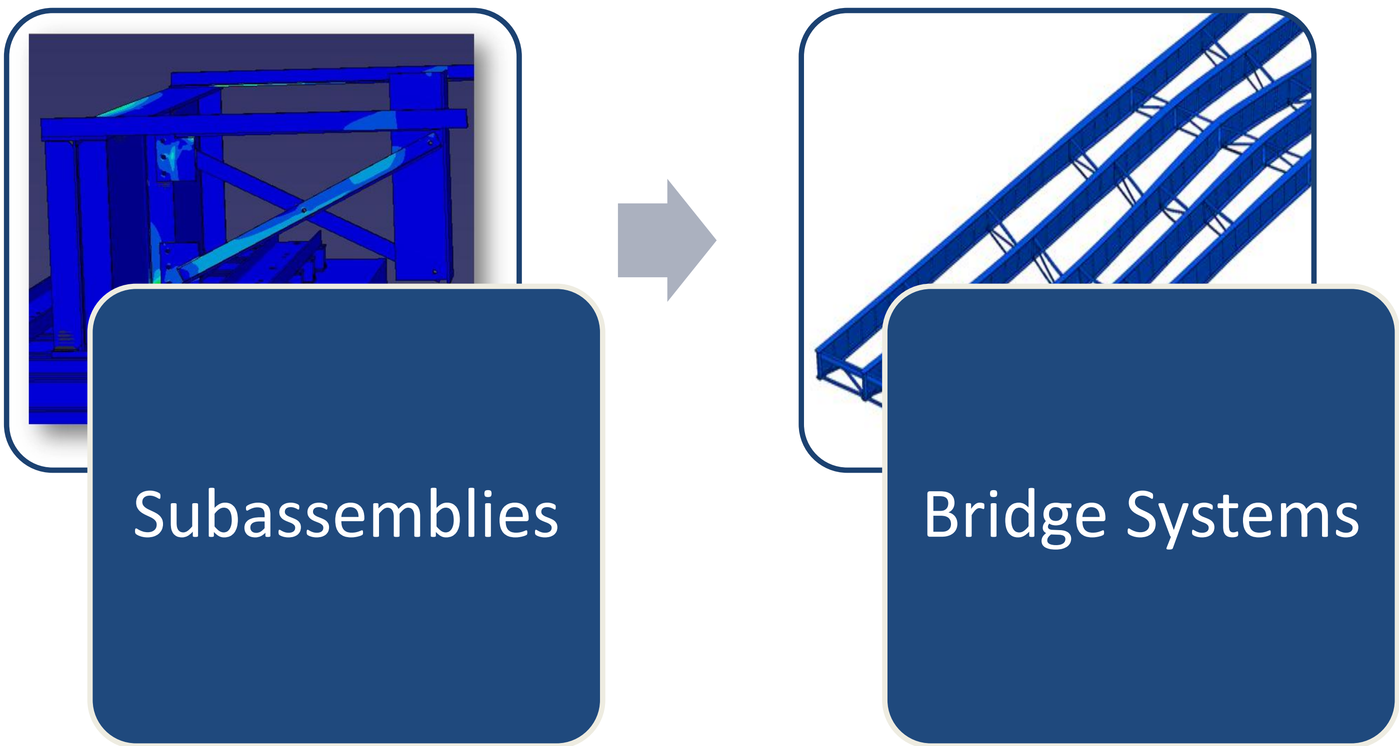
Field Reconnaissance and Testing



Computational Modeling

Project Approach

- **Simulation Thrust:**
  - Develop and evaluate various repair methodologies for distortion-induced fatigue that are ***Effective, Economical, and Practical.***



Project Approach

- **Experimental Thrust:**
  - Develop and evaluate various repair methodologies for distortion-induced fatigue that are ***Effective, Economical, and Practical.***

Component Level Testing

Girder Testing

Bridge System Testing

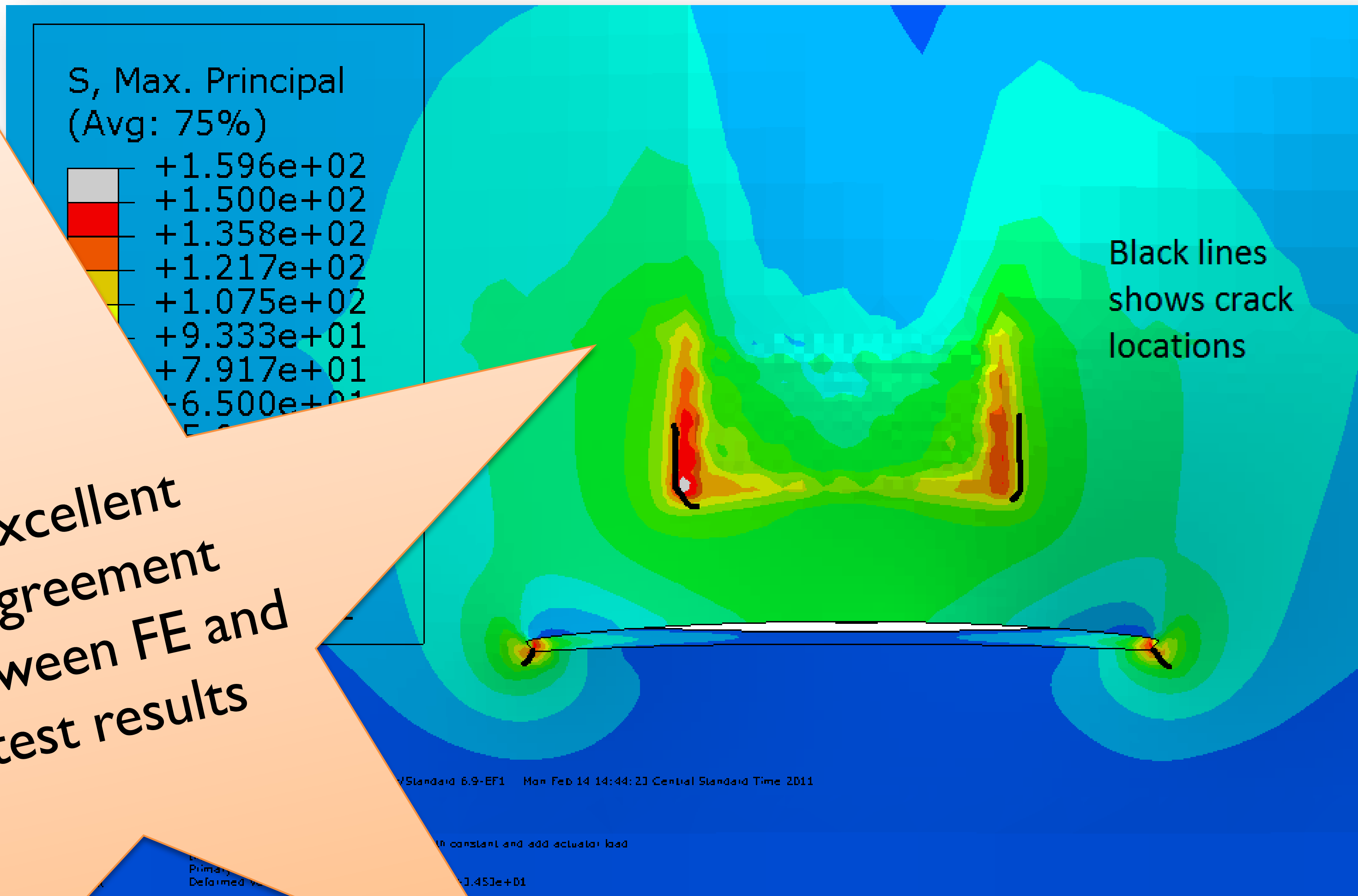
Project Approach

- **Field Evaluation and Repair Application:**
  - Develop and evaluate various repair methodologies for distortion-induced fatigue that are ***Effective, Economical, and Practical.***

Photo acknowledgement: (John Jones, KDOT)

Alignment between Project Thrusts

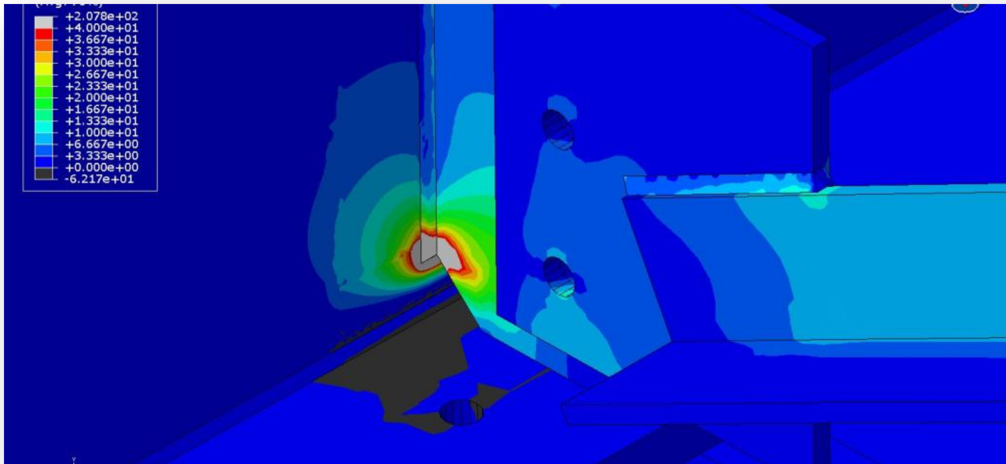
- FE model of Specimen No. 1 (with starter crack)



Excellent Agreement between FE and test results

Alignment between Project Thrusts

Stiffener-to-Web Weld:



Flange-to-Web Weld:

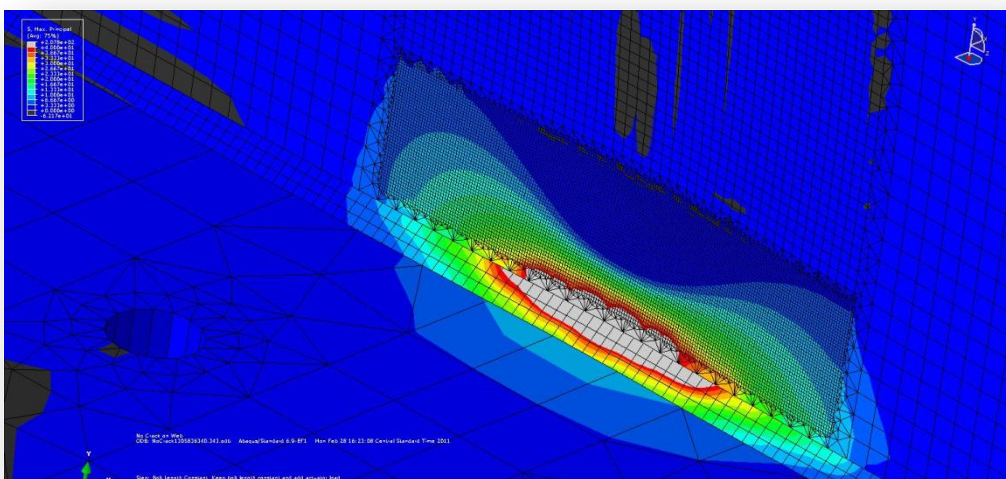


Photo acknowledgement: (John Jones, KDOT)

Evaluation of Commonly-Used Mitigation Measures

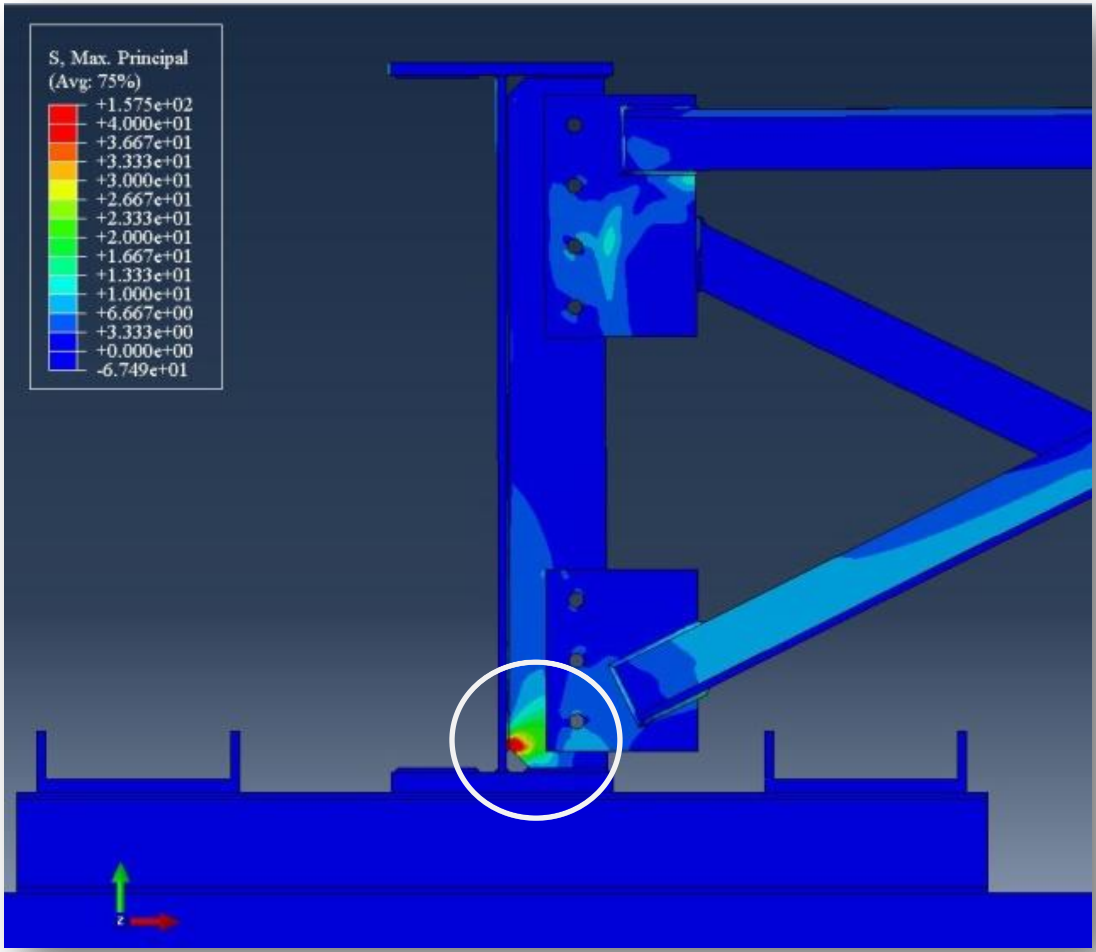
- **Commonly-Used Measures Examined:**
  - Crack-arrest holes
  - Transverse back-up stiffeners
  - Bolted stiffener-to-flange angles
  - Slotted connection stiffener

- **Sub-Assembly vs. System Simulations**

Bridge Subassembly Simulations

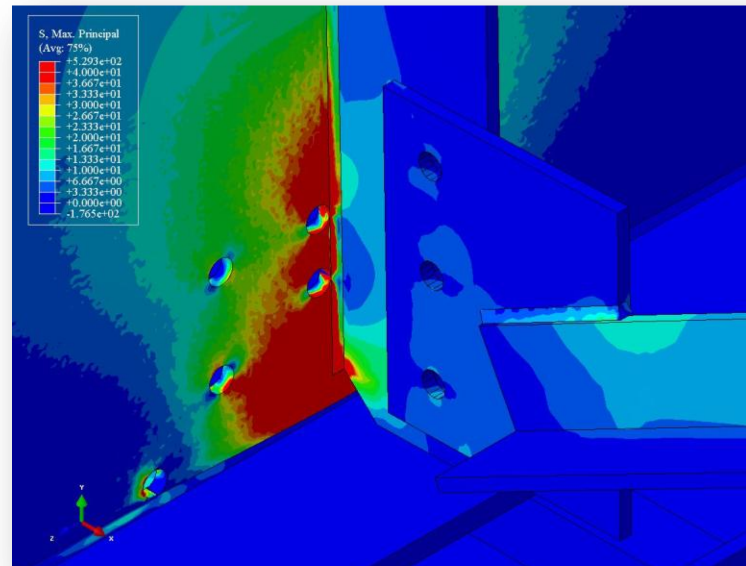
Evaluation of Commonly-Used Mitigation Measures

Bridge Subassembly Analyses



Evaluation of Commonly-Used Mitigation Measures

- **Crack-Arrest Holes**



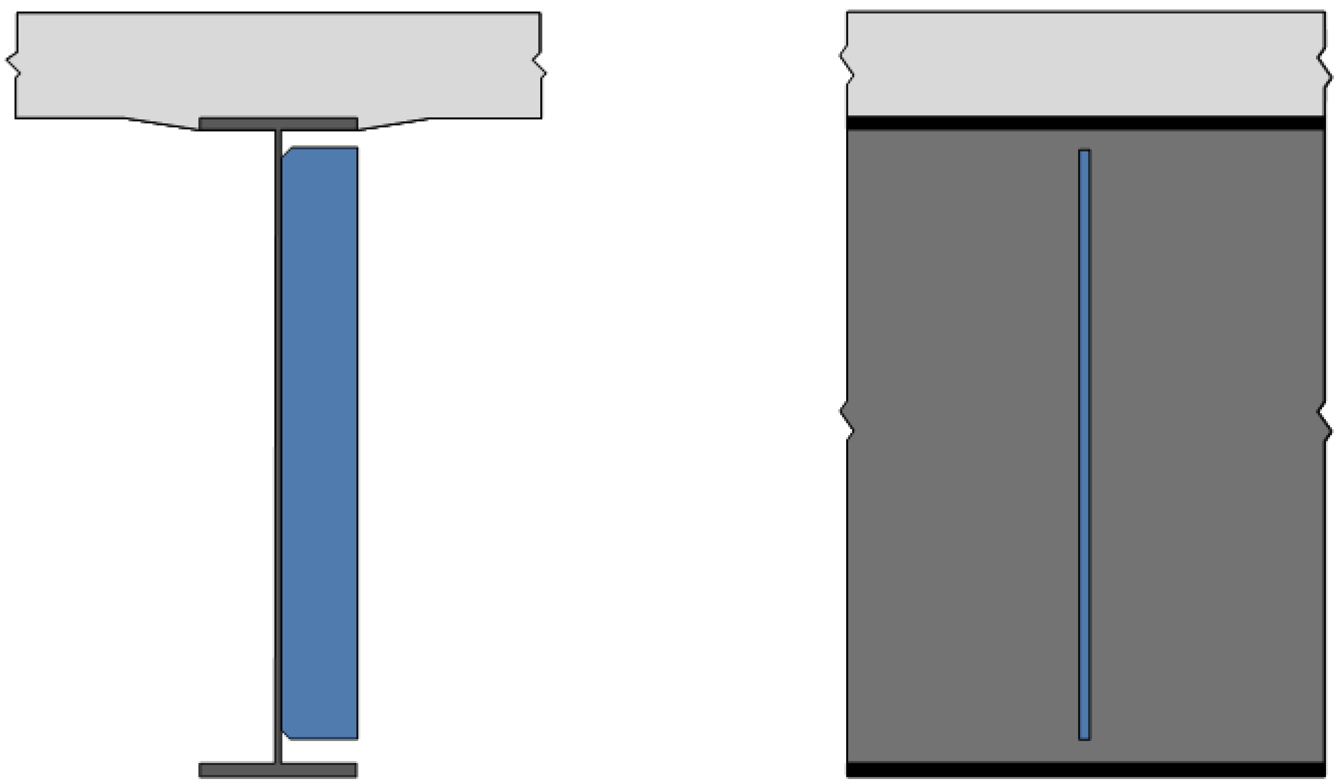
- ¾-in. dia. crack-arrest holes drilled at tips of cracks in bottom and top web gaps.
- 4-in. horseshoe-shaped crack grew 2.75 in. over 39,700 cycles after retrofit.

Evaluation of Commonly-Used Mitigation Measures

- **Crack-Arrest Holes**

Evaluation of Commonly-Used Mitigation Measures

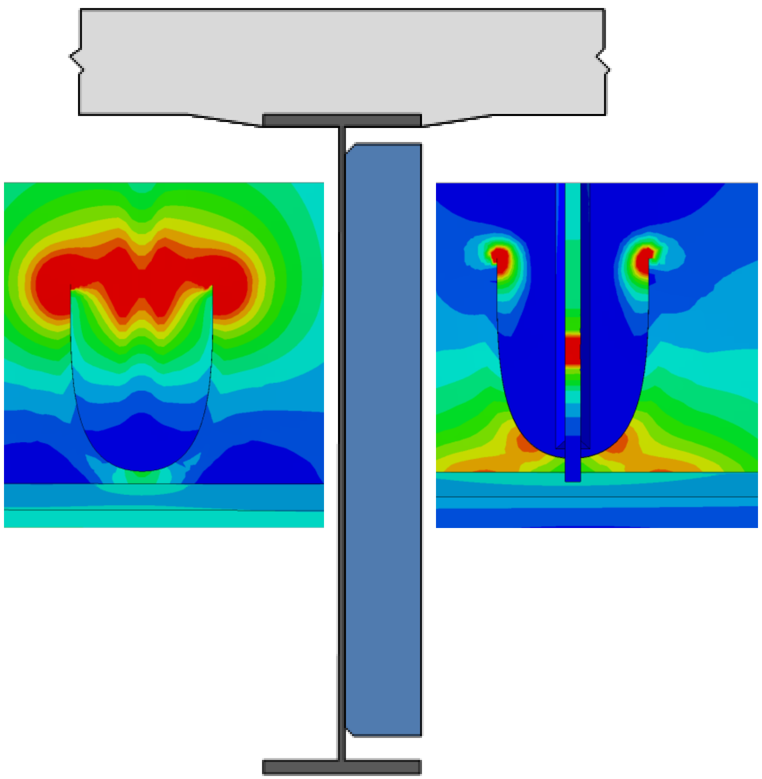
- **Crack-Arrest Holes**
  - Uncracked girder

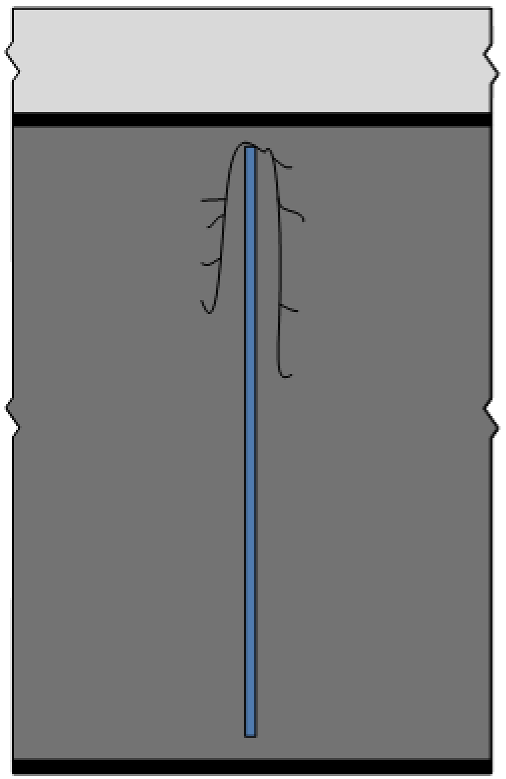


Evaluation of Commonly-Used Mitigation Measures

- **Crack-Arrest Holes**
  - Cracked girder

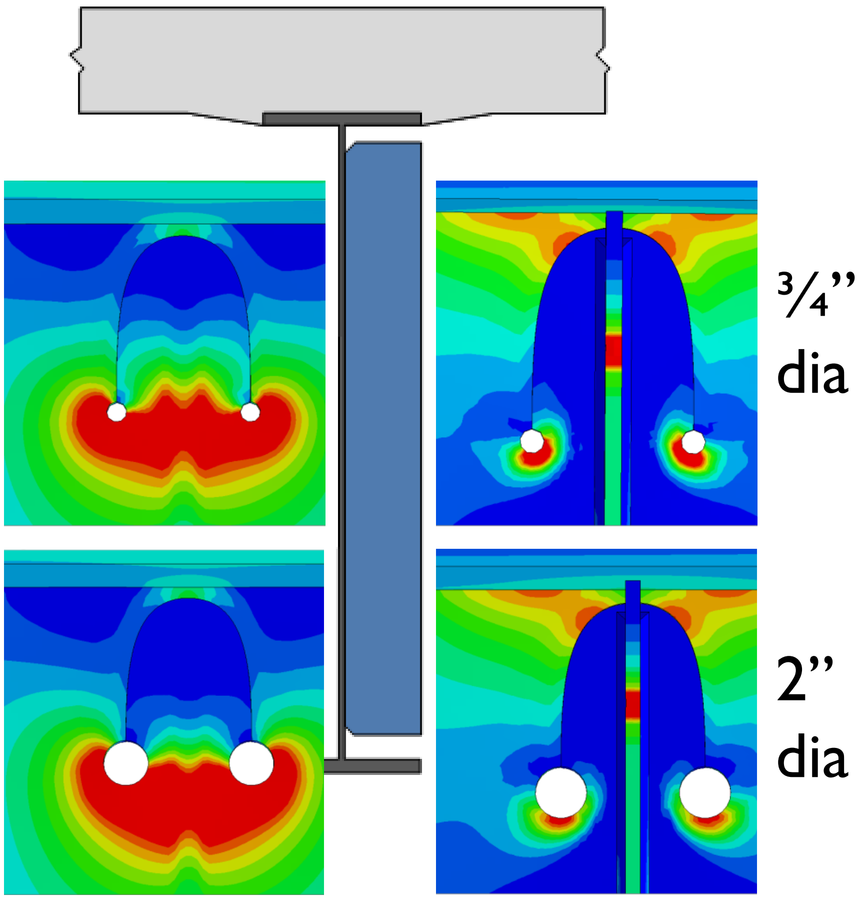
$$\left(\frac{\Delta K_{total}}{\sqrt{\rho}}\right)_{th} = 10\sqrt{\sigma_{ys}}$$

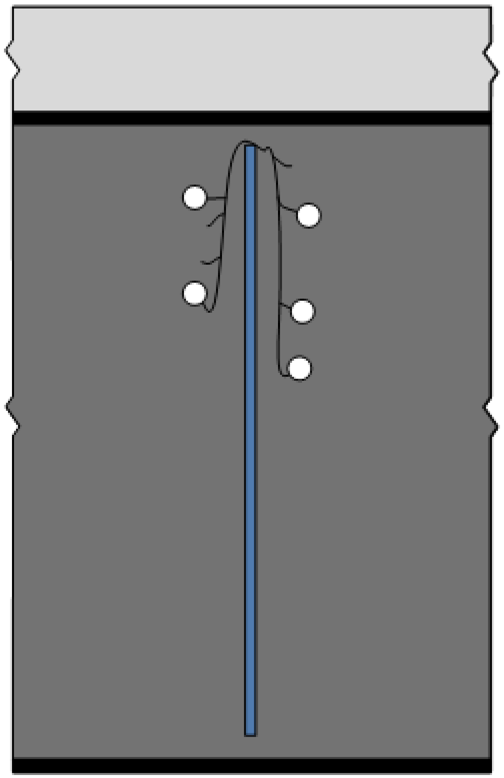




Evaluation of Commonly-Used Mitigation Measures

- **Crack-Arrest Holes**
  - Cracked girder with crack-stop holes

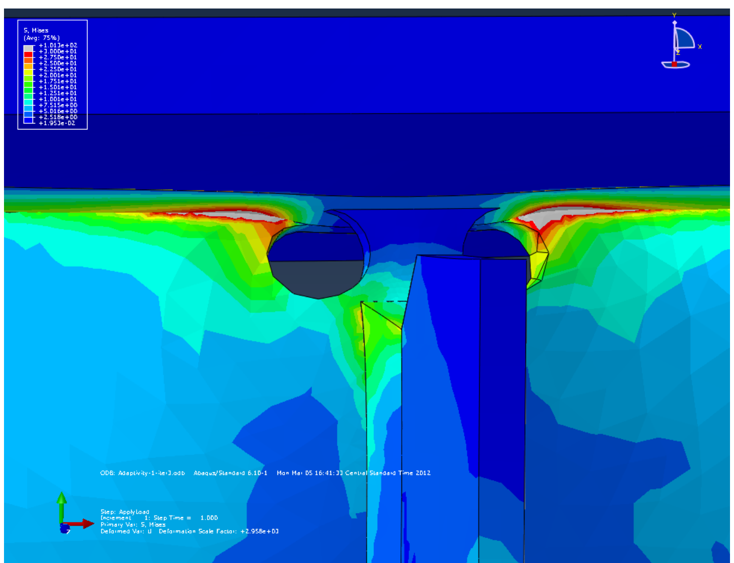


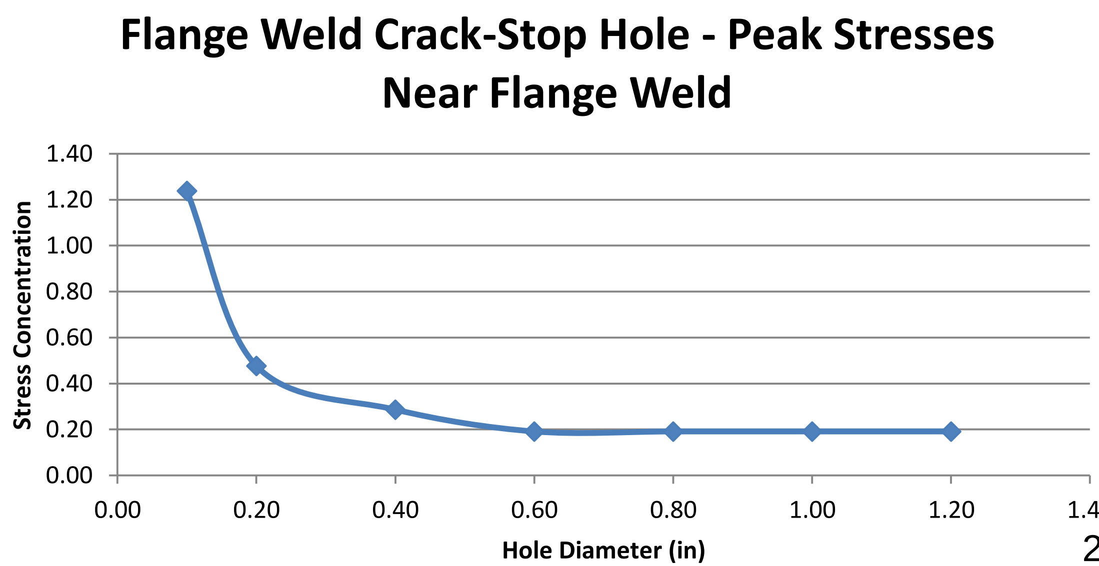


Evaluation of Commonly-Used Mitigation Measures

- **Crack-Arrest Holes**
  - Effect of placement and hole diameter

Crack-Arrest Holes at Flange-to-Web Weld

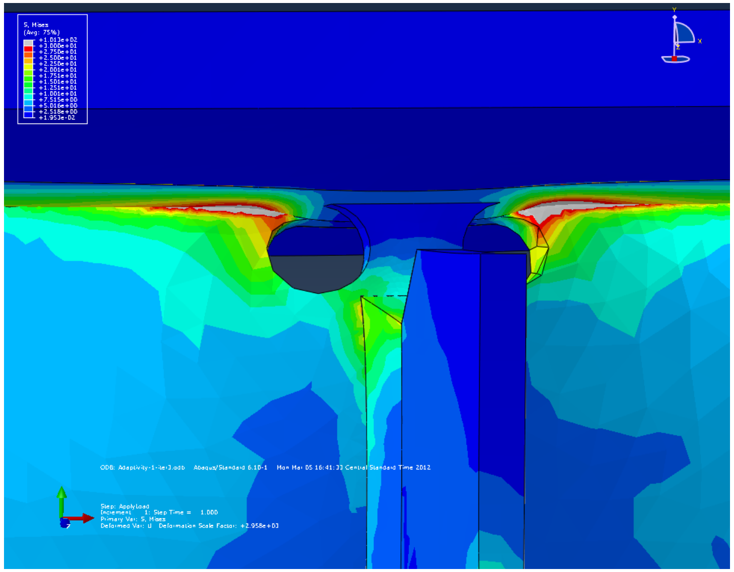


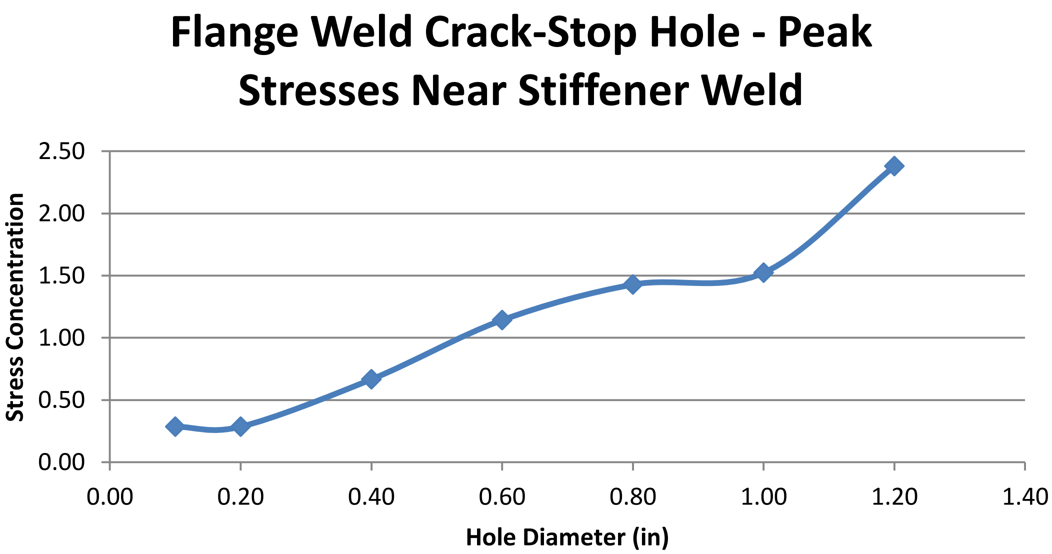


Evaluation of Commonly-Used Mitigation Measures

- **Crack-Arrest Holes**
  - Effect of placement and hole diameter

Crack-Arrest Holes at Flange-to-Web Weld

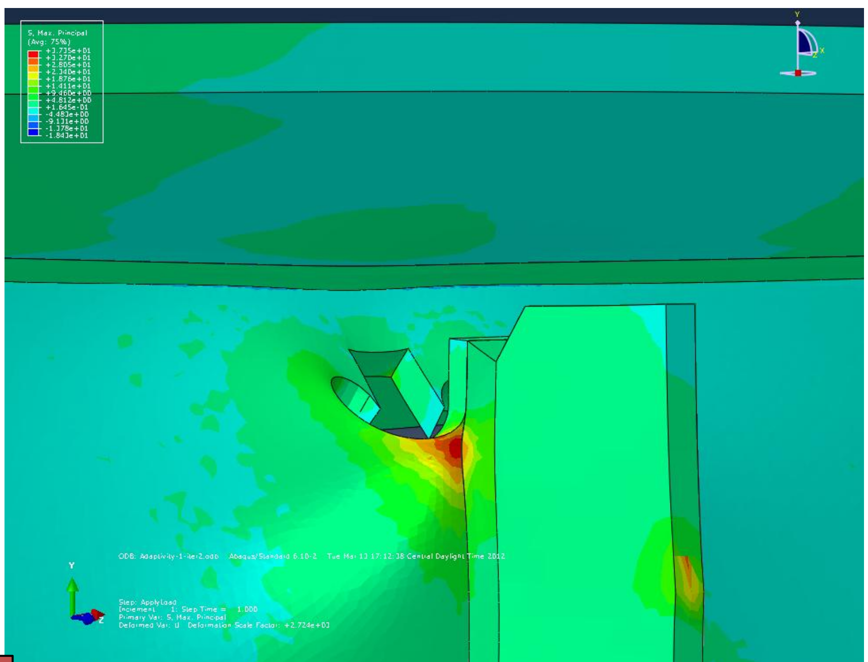


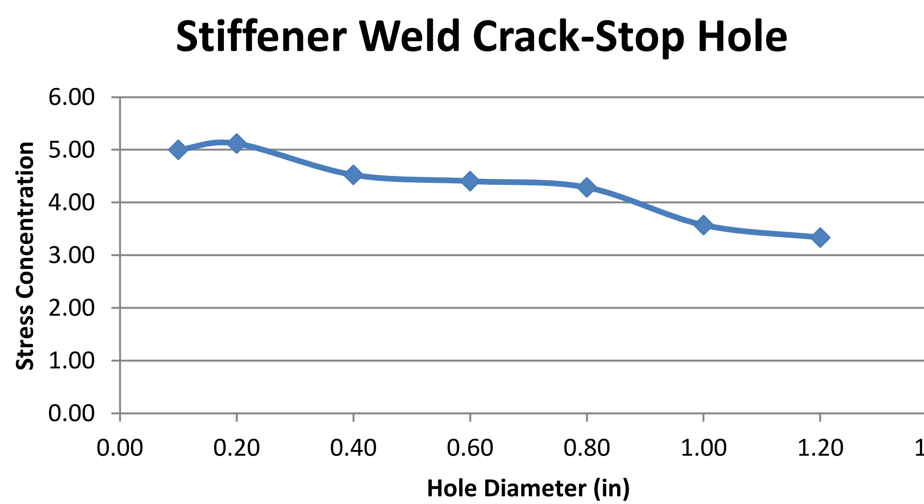


Evaluation of Commonly-Used Mitigation Measures

- **Crack-Arrest Holes**
  - Effect of placement and hole diameter

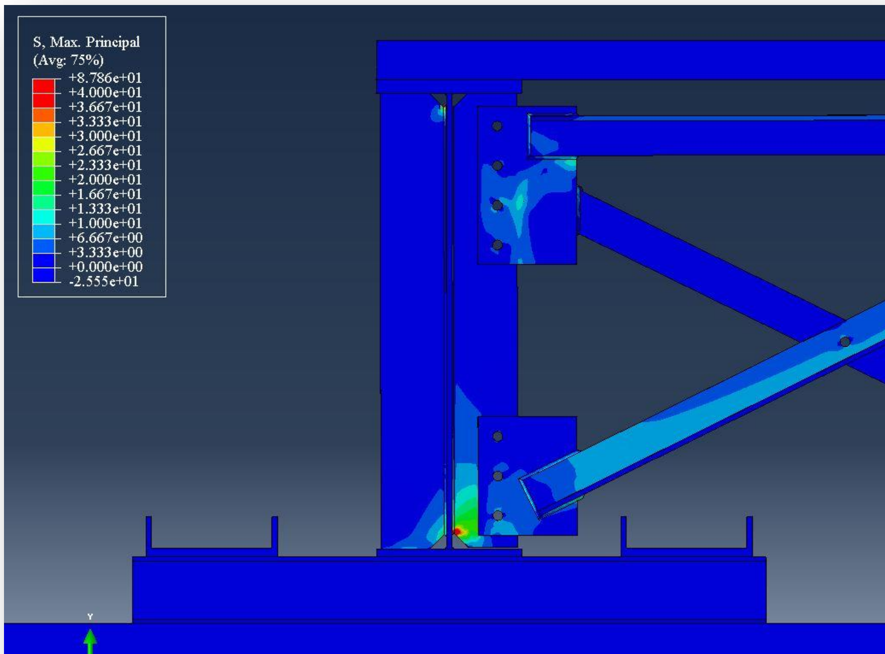
Crack-Arrest Holes at Stiffener-to-Web Weld



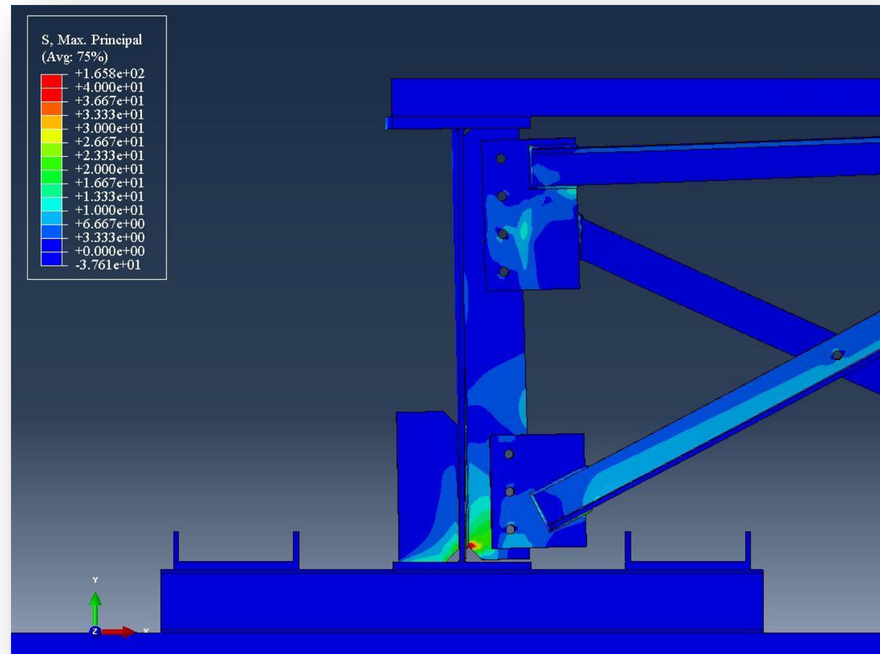


Evaluation of Commonly-Used Mitigation Measures

- **Transverse Back-Up Stiffeners**



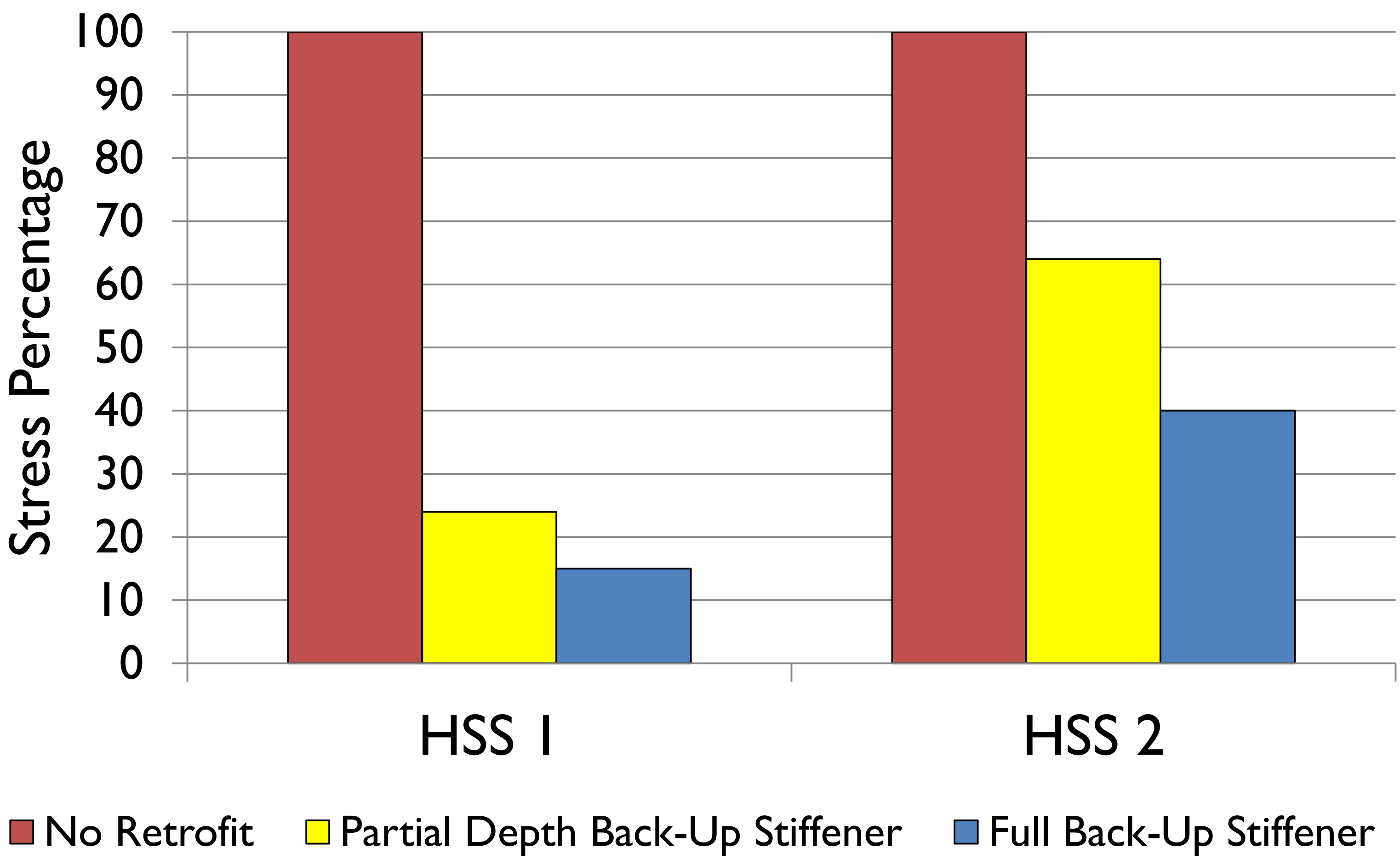
Full depth back-up stiffener



Partial Depth back-up stiffener (Length = 12 in.)

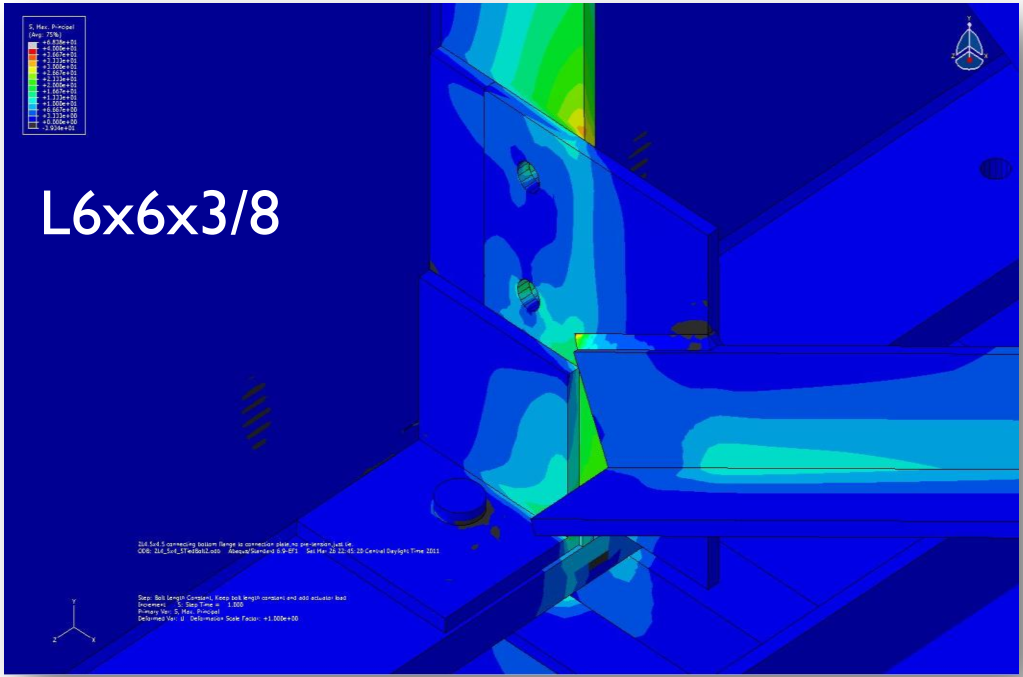
Evaluation of Commonly-Used Mitigation Measures

- **Transverse Back-Up Stiffeners**



Evaluation of Commonly-Used Mitigation Measures

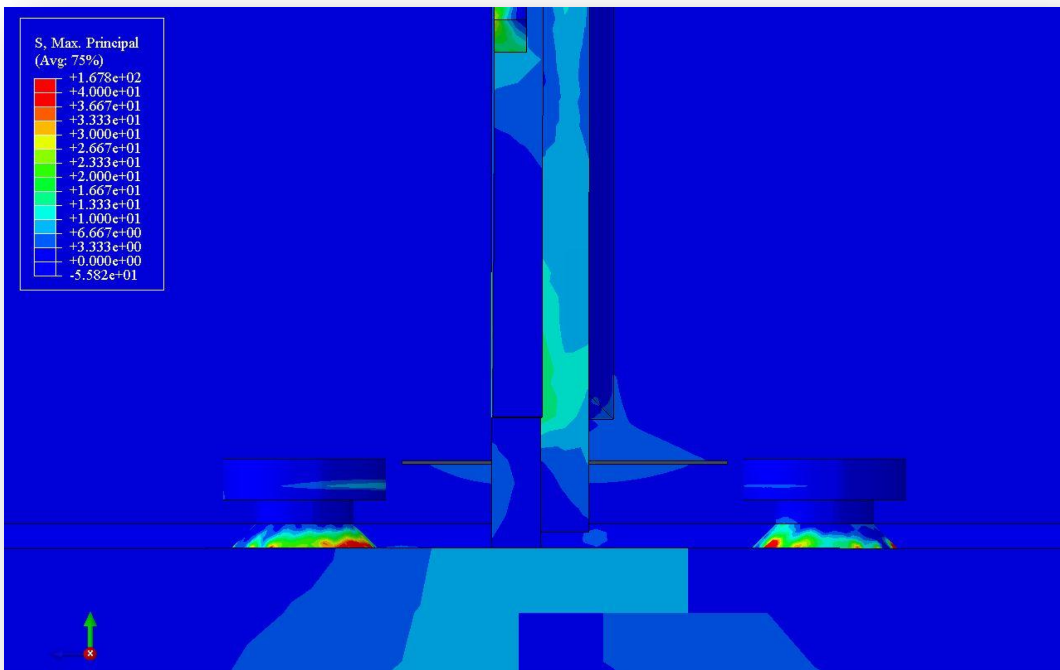
- **Bolted Stiffener-to-Flange Angles**



- Angle bolted to flange; bolted or welded to stiffener
- Constructability implications

Evaluation of Commonly-Used Mitigation Measures

- **Bolted Stiffener-to-Flange Angles**



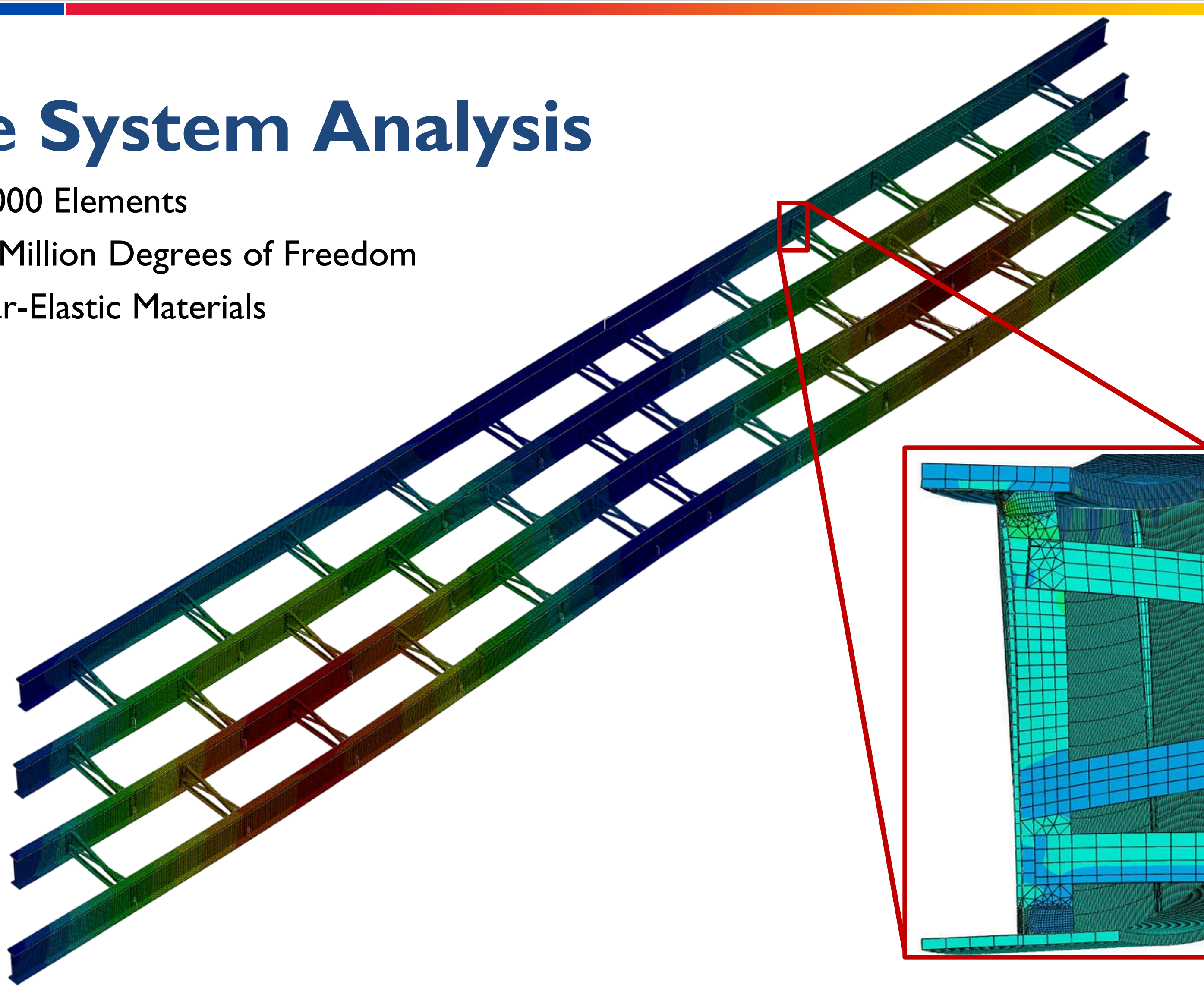
- Bolts welded to flange, angle welded to stiffener.
- Implications of welded studs

Bridge System Simulations

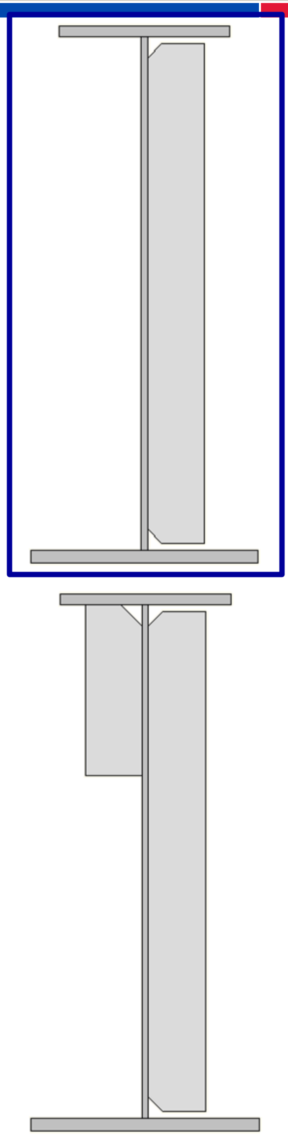
Evaluation of Commonly-Used Mitigation Measures

Bridge System Analysis

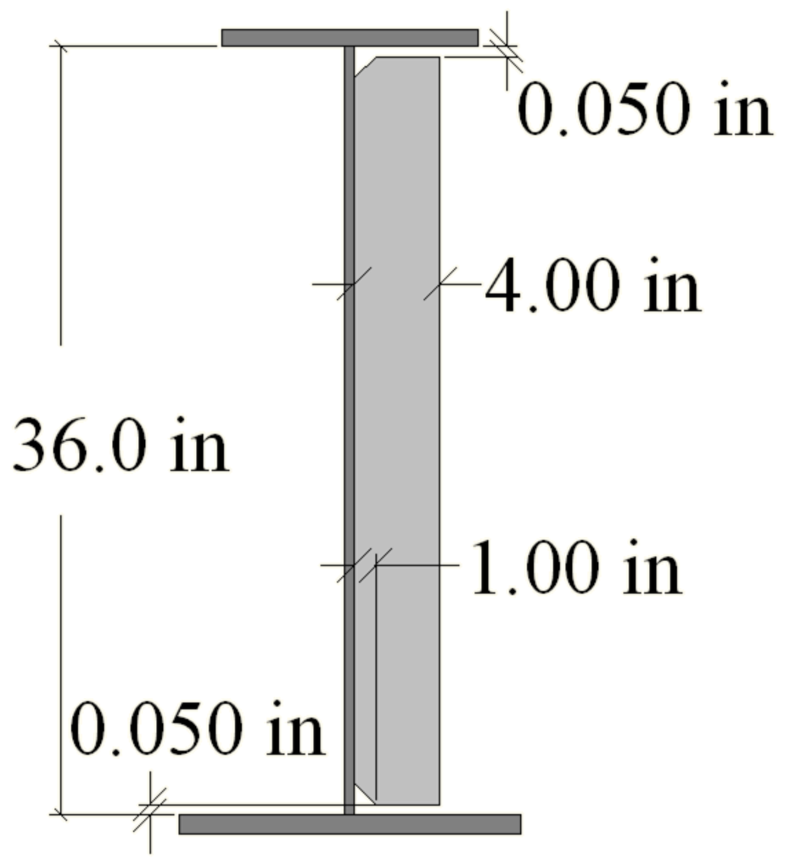
- 750,000 Elements
- 2.75 Million Degrees of Freedom
- Linear-Elastic Materials

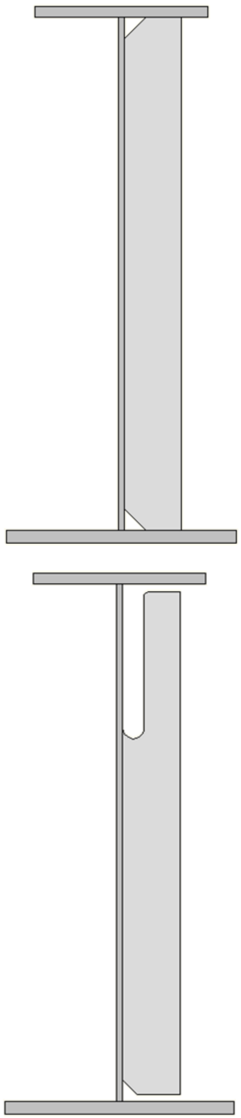


Evaluation of Commonly-Used Mitigation Measures

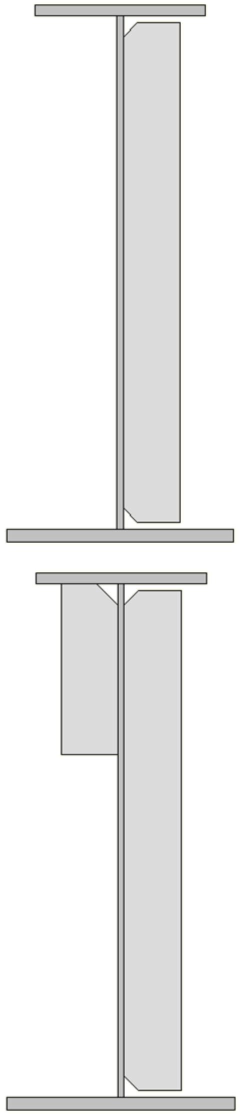


Original Connection Plate

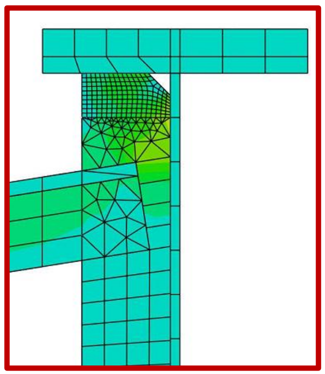


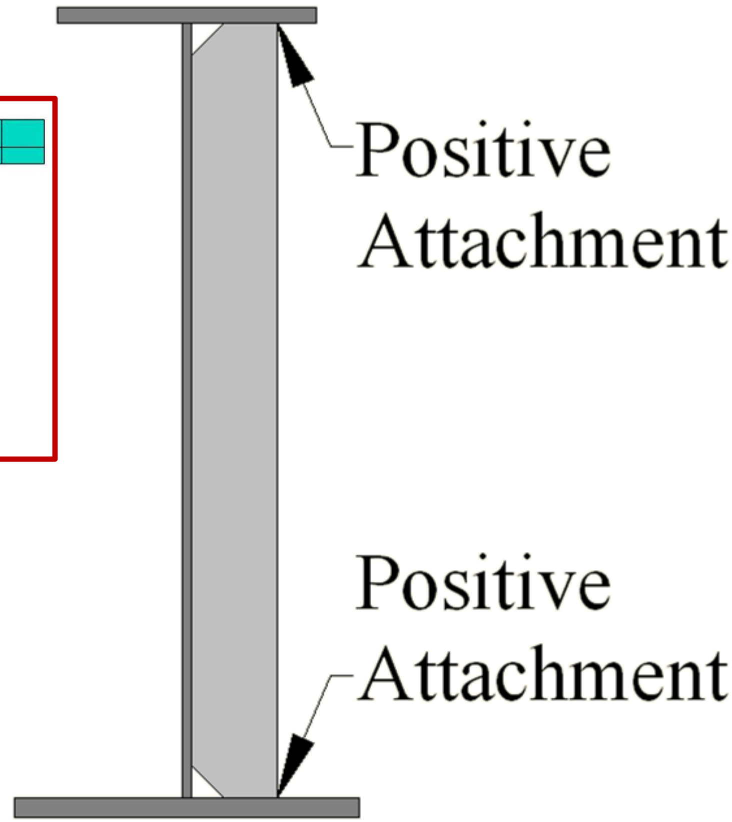


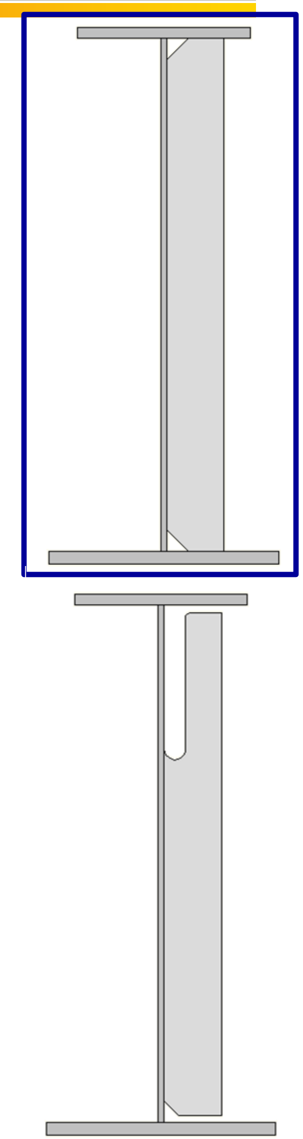
Evaluation of Commonly-Used Mitigation Measures



Positive Attachment

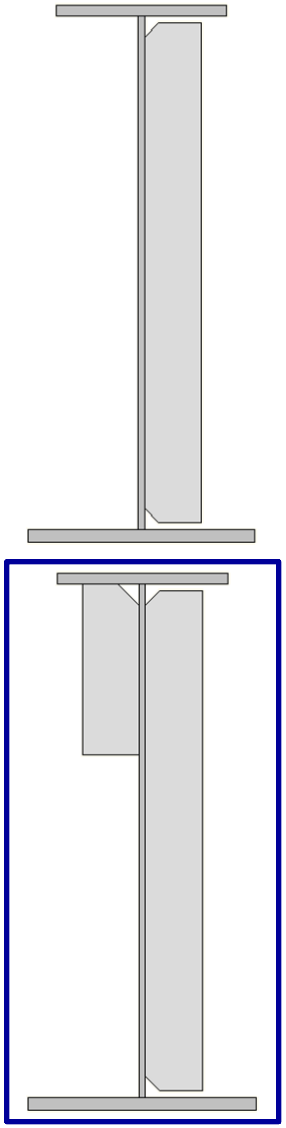


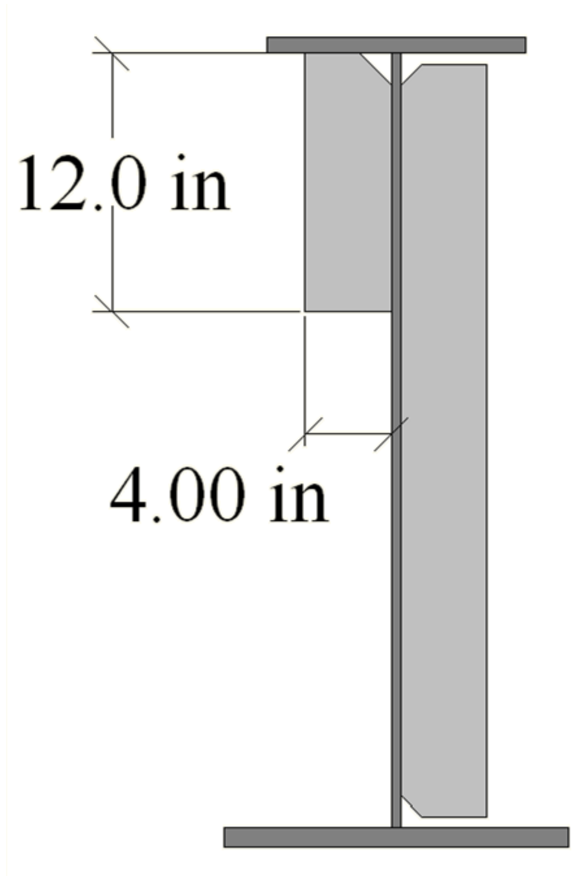


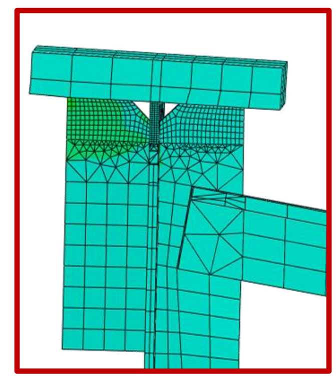


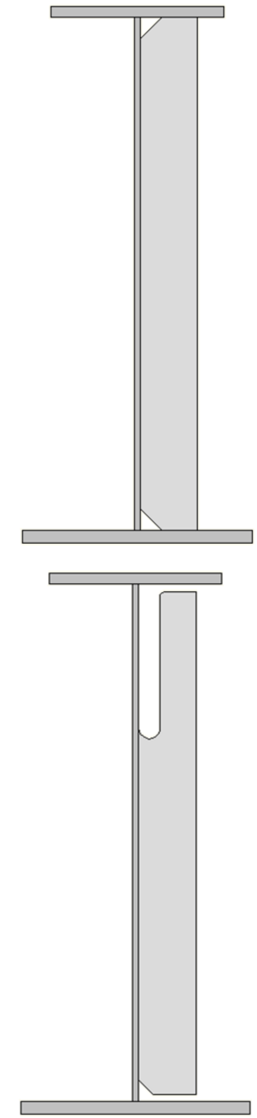
Evaluation of Commonly-Used Mitigation Measures

Back-Up Stiffener



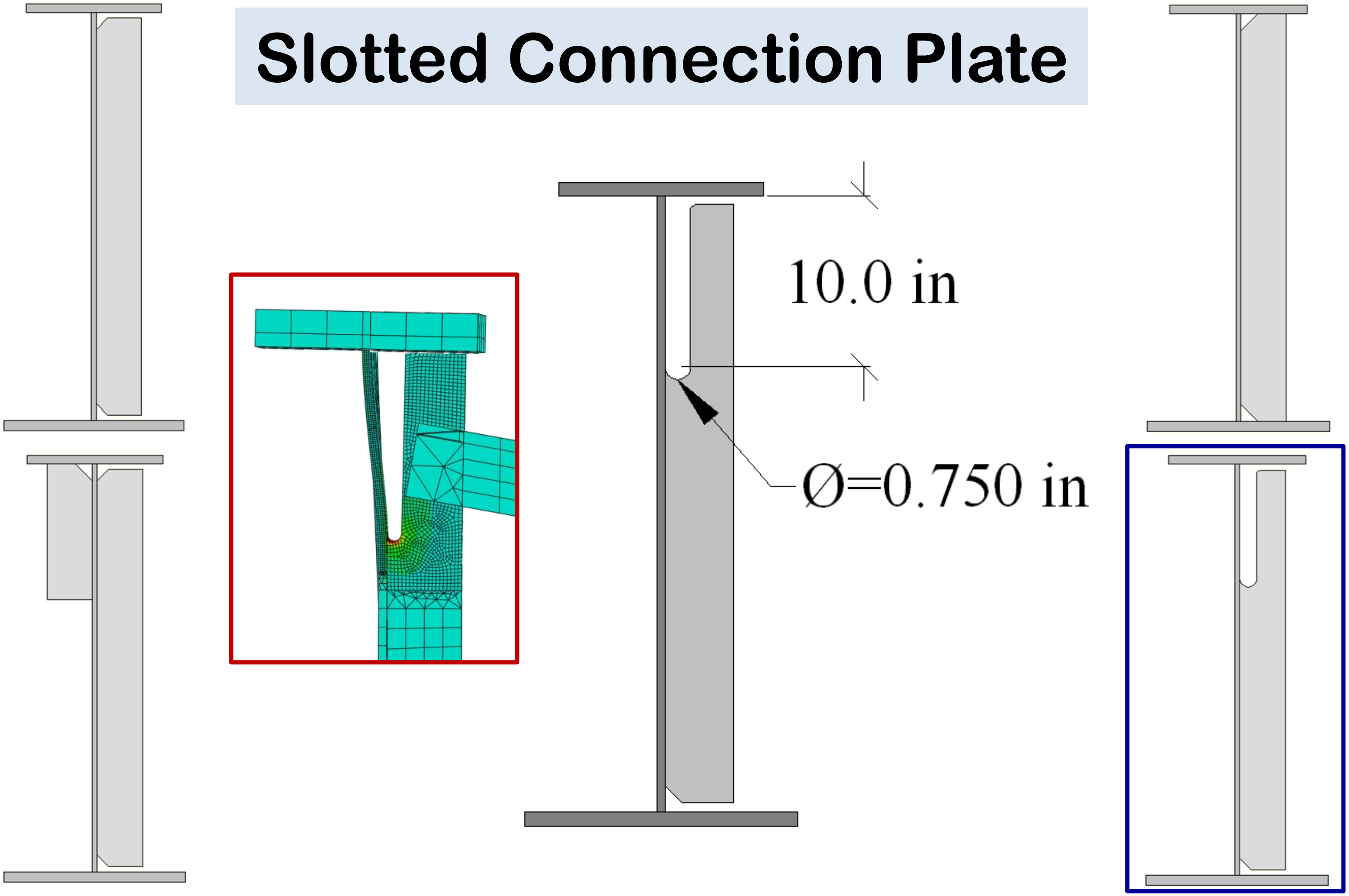






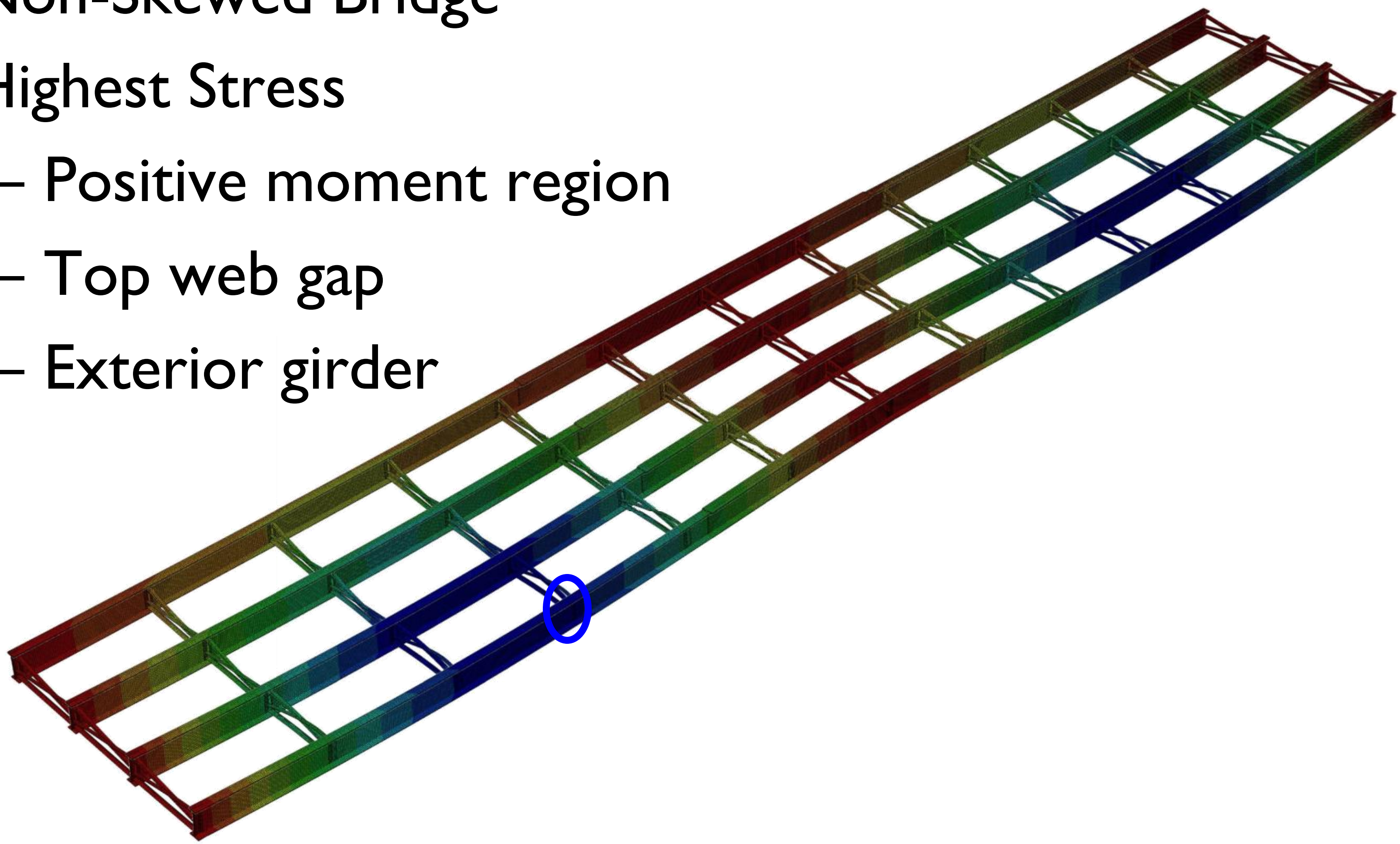
Evaluation of Commonly-Used Mitigation Measures

Slotted Connection Plate



Evaluation of Commonly-Used Mitigation Measures

- Non-Skewed Bridge
- Highest Stress
  - Positive moment region
  - Top web gap
  - Exterior girder



Evaluation of Commonly-Used Mitigation Measures

- Non-Skewed Bridge
- Highest Stress
  - Positive moment region
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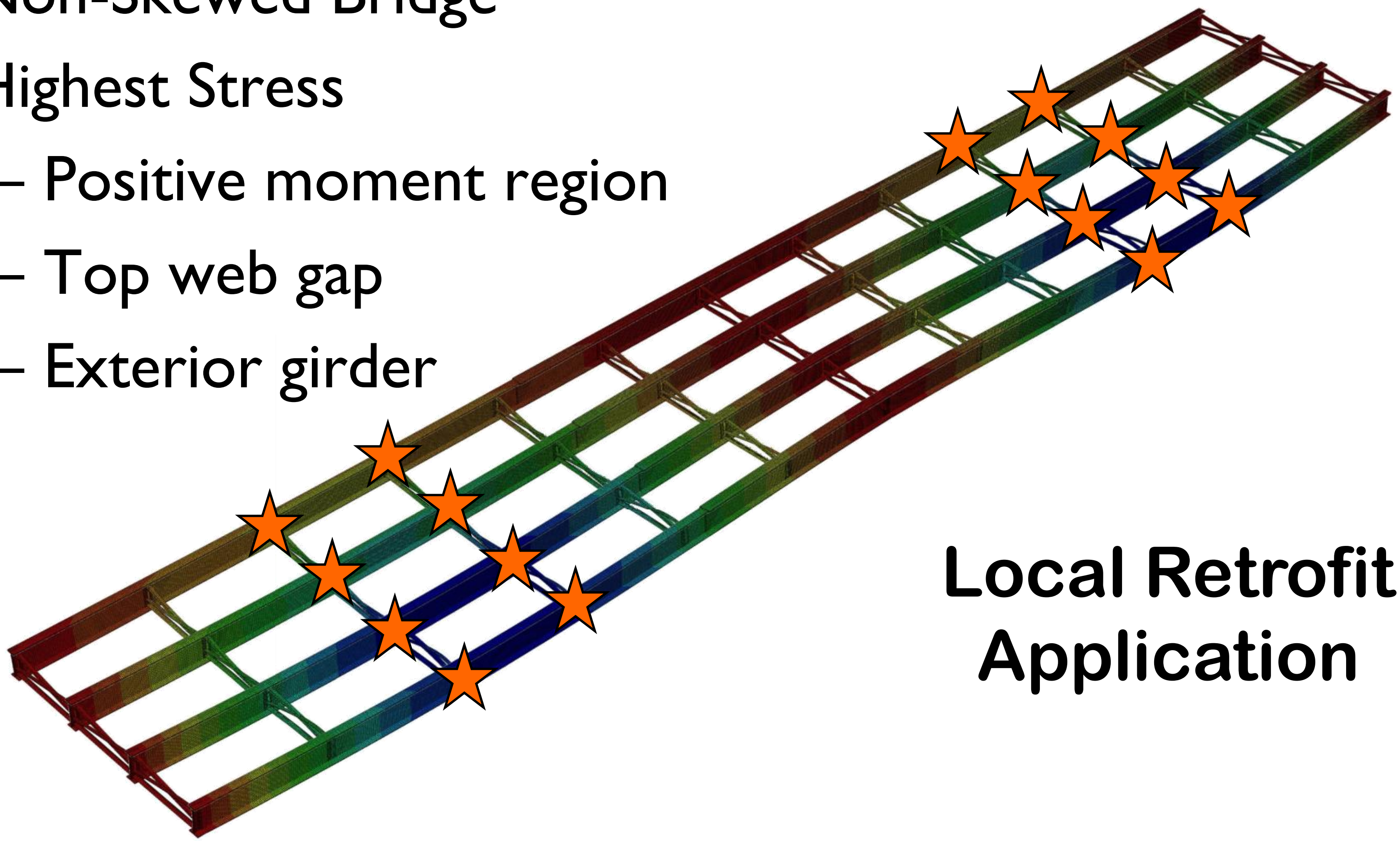
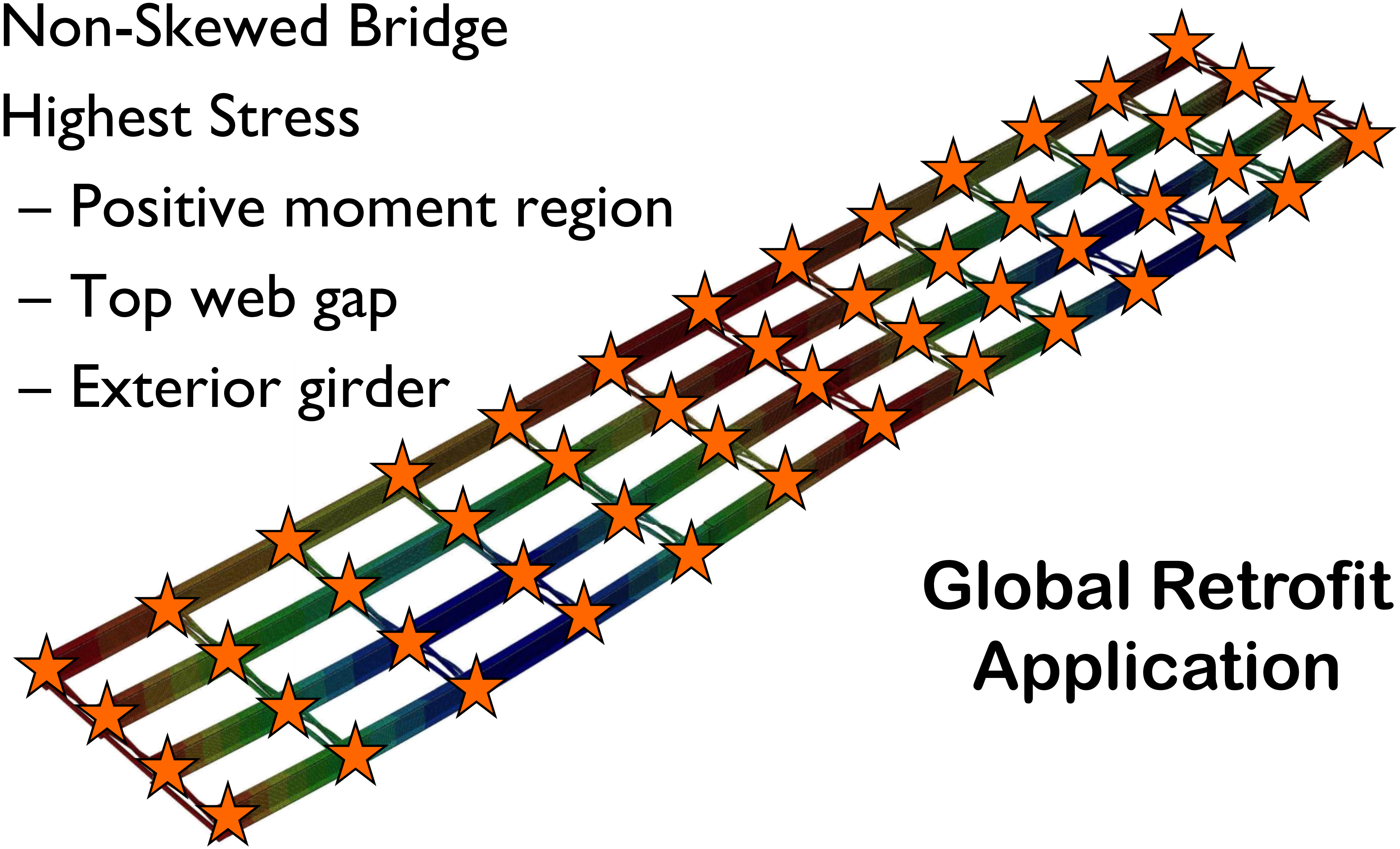


Local Retrofit Application

Evaluation of Commonly-Used Mitigation Measures

- Non-Skewed Bridge
- Highest Stress
  - Positive moment region
  - Top web gap
  - Exterior girder



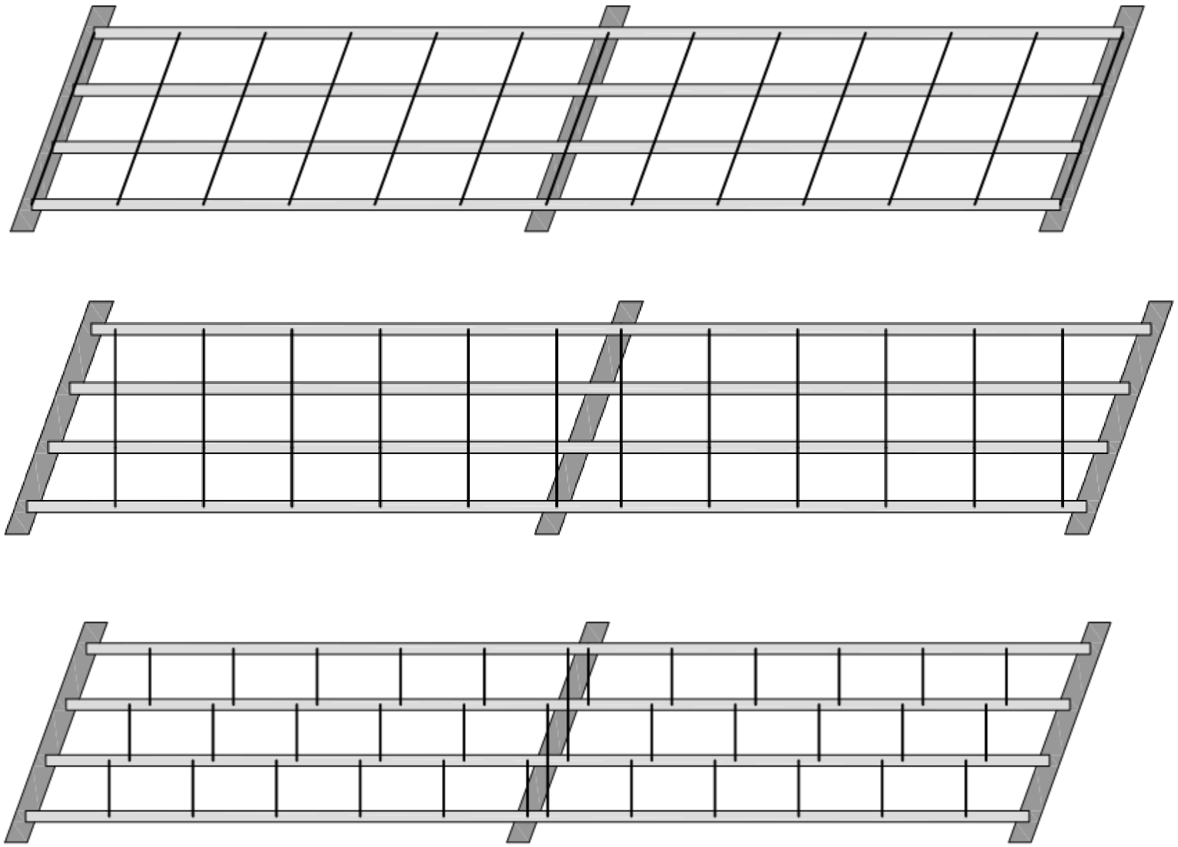
Global Retrofit Application

Evaluation of Commonly-Used Mitigation Measures

- **Local Retrofitting**
  - All four retrofit techniques reduced stress significantly where they were applied in the non-skewed bridge
  - In models where connections were softened, stress adjacent to retrofitted locations increased
  - Softening cross-frames or removing cross-frames put more stress demands elsewhere in the bridge
  - Local retrofitting not practical
- **Global Retrofitting**
  - Reduced differential deflection twice as much
  - Reduced maximum stress in bridge twice as much

Evaluation of Commonly-Used Mitigation Measures

- Skewed Bridge Layouts



Parallel to Support Skew

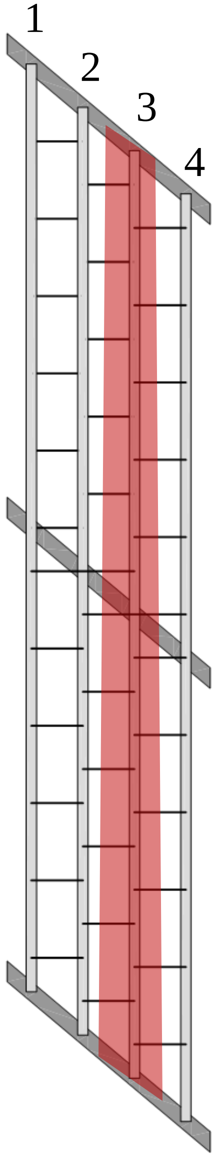
Non-staggered, Perpendicular to Girder Line

Staggered, Perpendicular to Girder Line

Evaluation of Commonly-Used Mitigation Measures

- Skewed-Staggered Bridge Layout

Retrofit Description	***HSS Stress [ksi]***	***% Change from no-retrofit model***
No Retrofit	14.6	
Bottom Partial Stiffener	7.43	-49%
Full Depth Stiffener	5.20	-64%



Mitigation Methods under Development

For:

- Relatively short cracks
- Deep web cracks
- Crack-arrest hole improvement

Mitigation Methods Under Development

The techniques studied were selected because they are relatively inexpensive, easy to implement, and can be carried out without significant disruptions to traffic.

Mitigation Methods Under Development

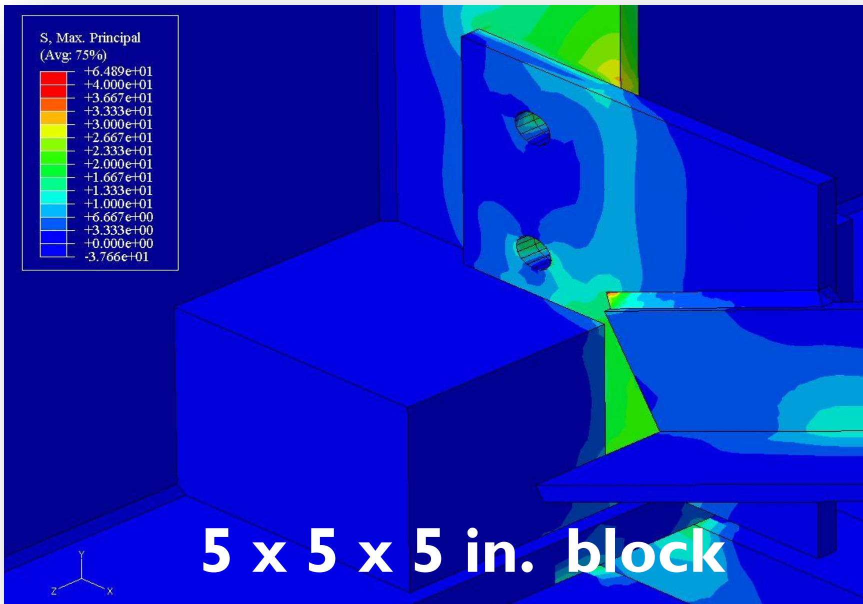
For Relatively Short Cracks

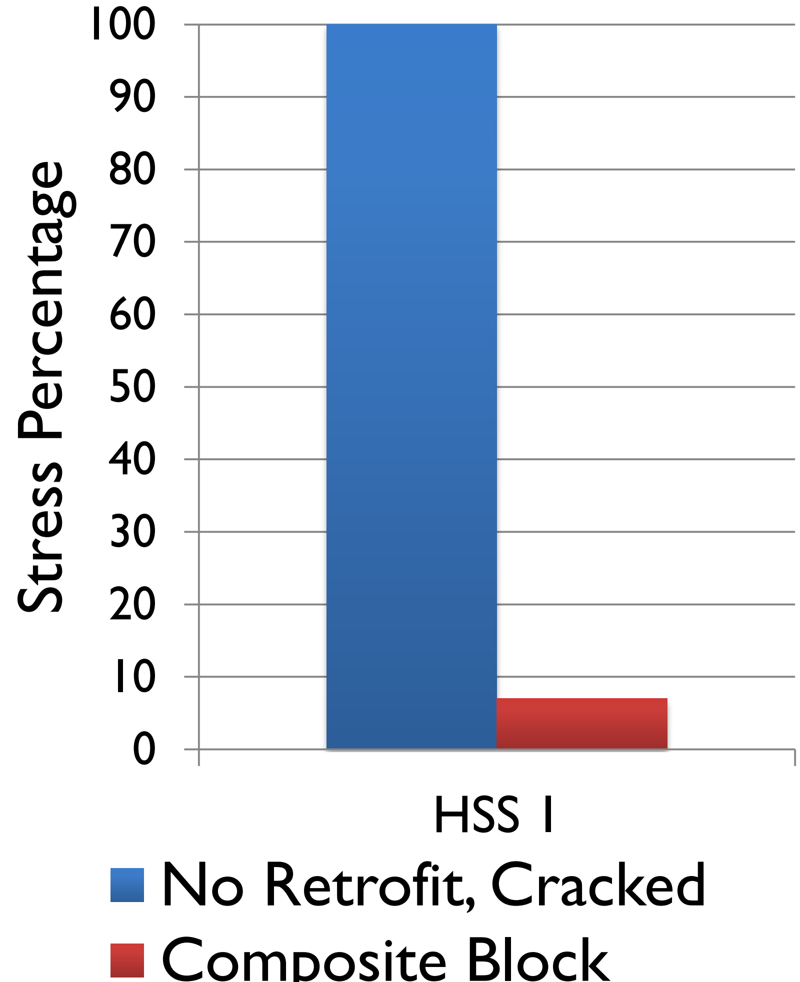
"Chewing Gum" Block

Web-to-Stiffener Angles and Backing Plate

Mitigation Methods Under Development

- **“Chewing Gum” Block**

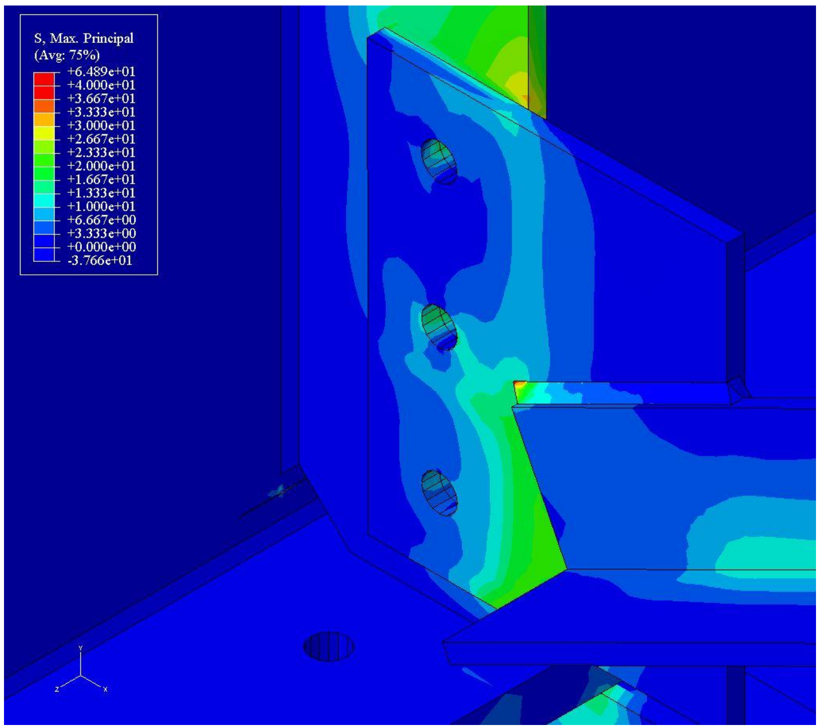


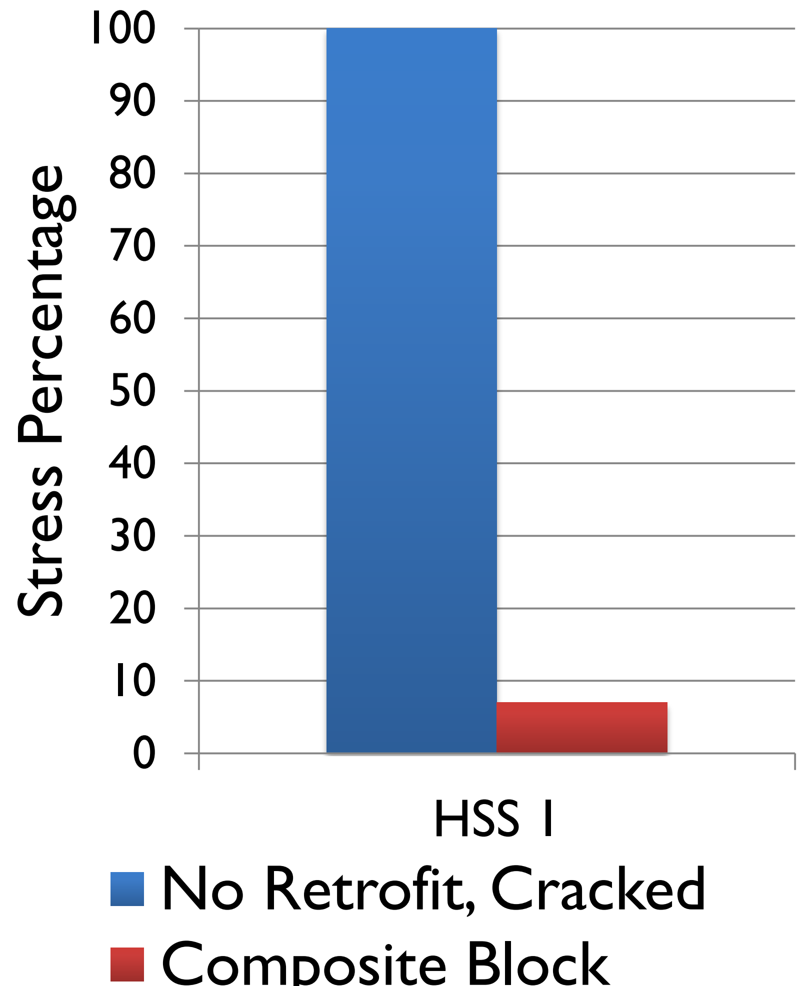


- E = 5,000 – 10,000 ksi
- $\nu = 0.1$

Mitigation Methods Under Development

- **"Chewing Gum" Block**

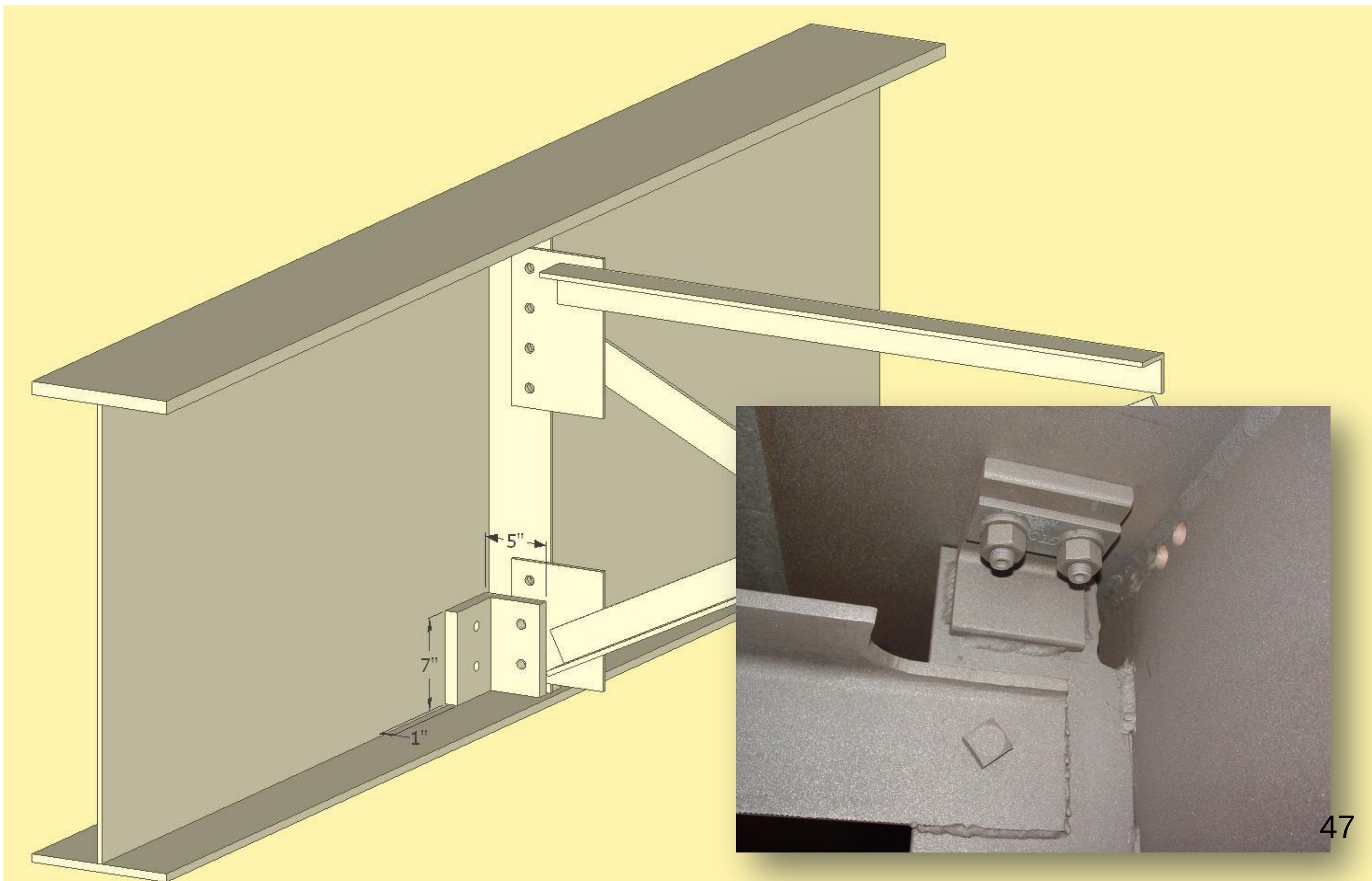




- E = 5,000 – 10,000 ksi
- ν = 0.1

Mitigation Methods Under Development

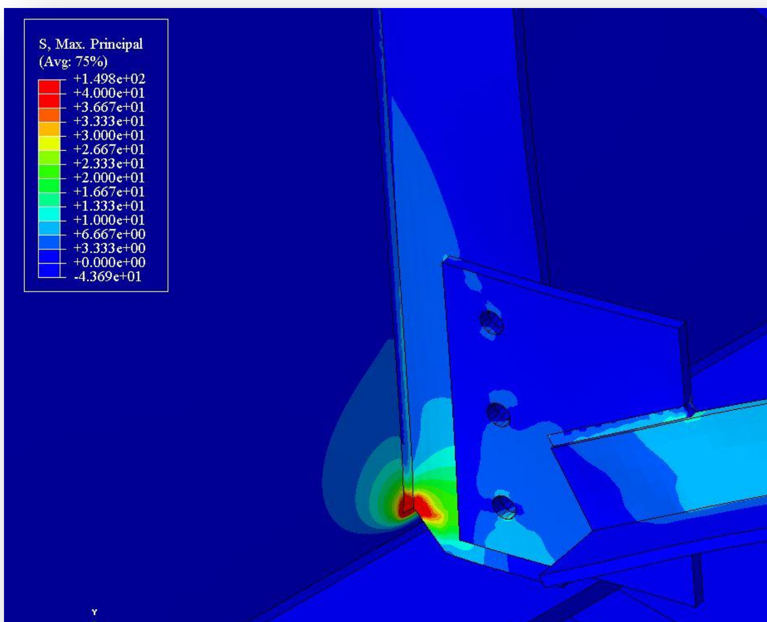
- **Web-to-Stiffener Angles with Backing Plate**



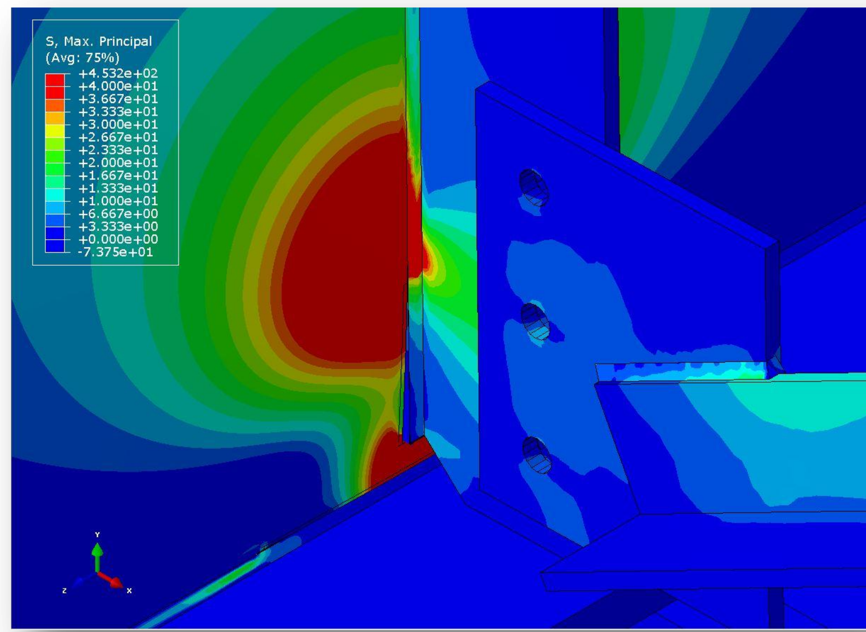
Mitigation Methods Under Development

- **Web-to-Stiffener Angles with Backing Plate**
  - Stress state before retrofit

<u>Uncracked</u>

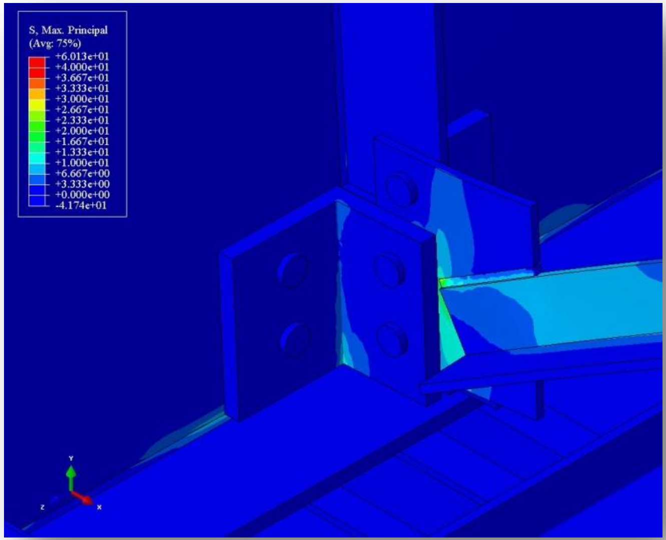


<u>Cracked</u>



Mitigation Methods Under Development

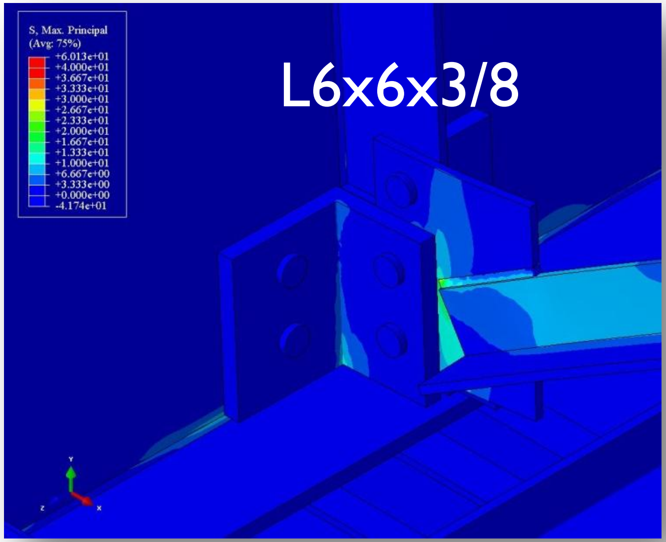
- **Web-to-Stiffener Angles with Backing Plate**

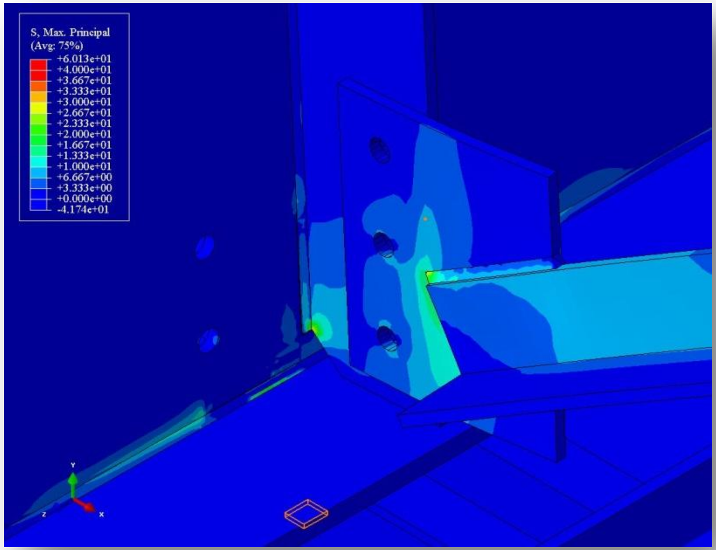


- Retrofit was first applied in bottom web gap_{test} and later applied in the top web gap_{test}.

Mitigation Methods Under Development

- **Web-to-Stiffener Angles with Backing Plate**

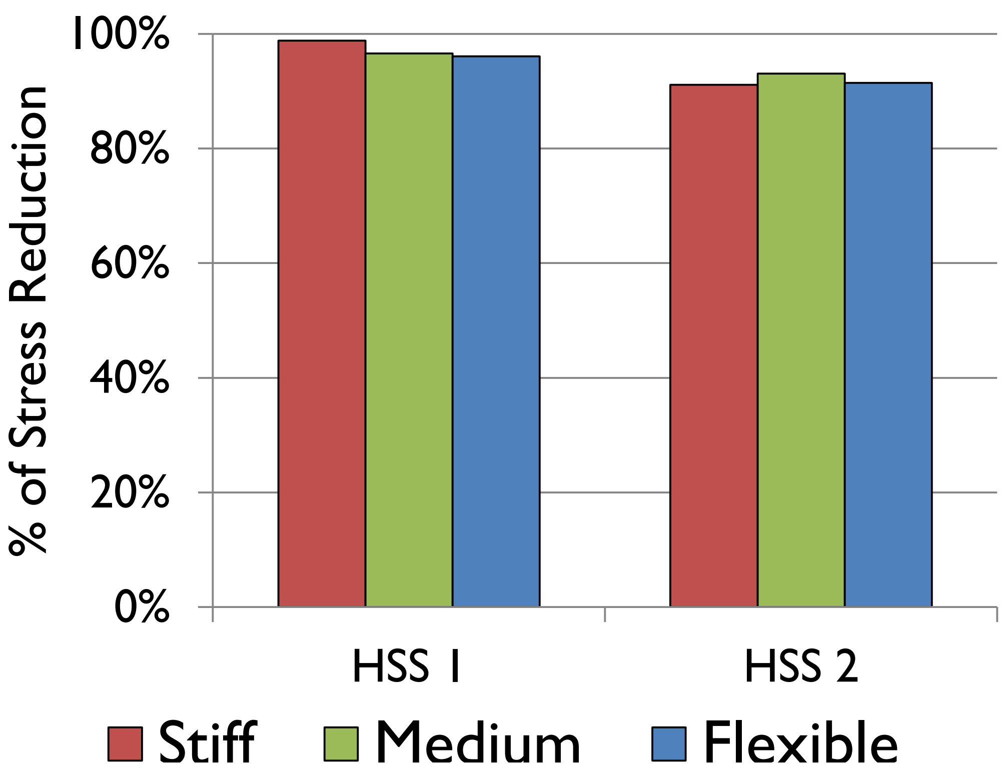




- Retrofit was first applied in bottom web gap_{test} and later applied in the top web gap_{test}.

Mitigation Methods Under Development

- **Web-to-Stiffener Angles with Backing Plate**



- **Stiff**:
  - 25 mm (1 in.) thick
- **Medium**:
  - 13 mm (0.5 in.) thick
- **Flexible**:
  - 6 mm (0.25 in.) thick

For models that have a 102 mm (4 in.) horseshoe crack and a 203 mm (8 in.) horizontal crack.

Mitigation Methods Under Development

- **Web-to-Stiffener Angles with Backing Plate**

Dimensions

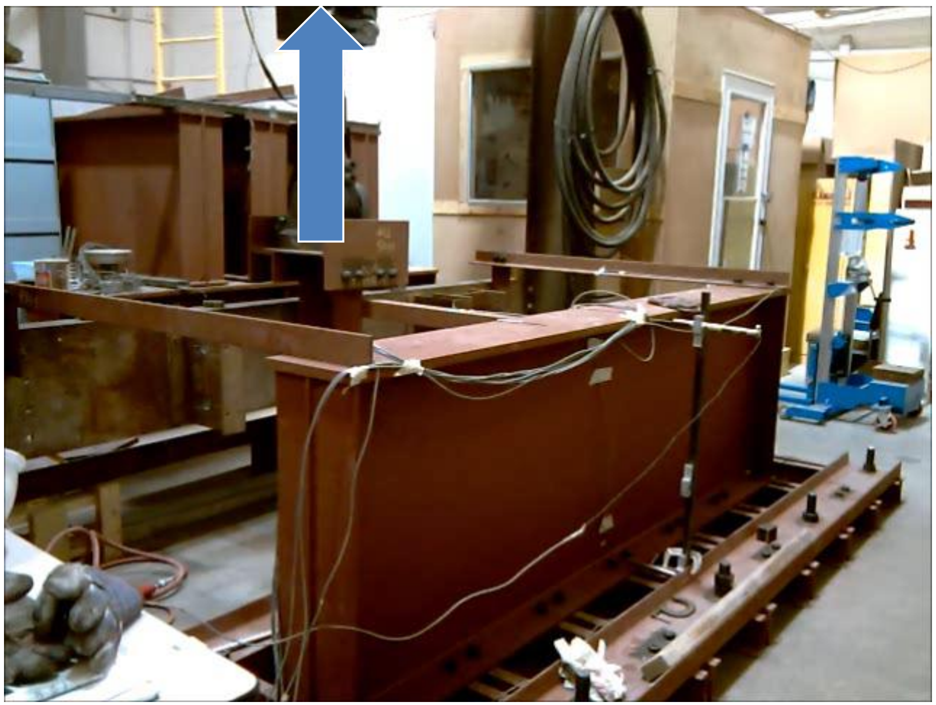
- Fourteen girders
- 112-in. long
- 34.5 × 3/8 in. web
- 1 in. thick top flange
- 0.625 in. thick bottom flange

Actuator under Load Control

- Max Load = 4.6 K
- Min Load = 0.8 K

Mitigation Methods Under Development

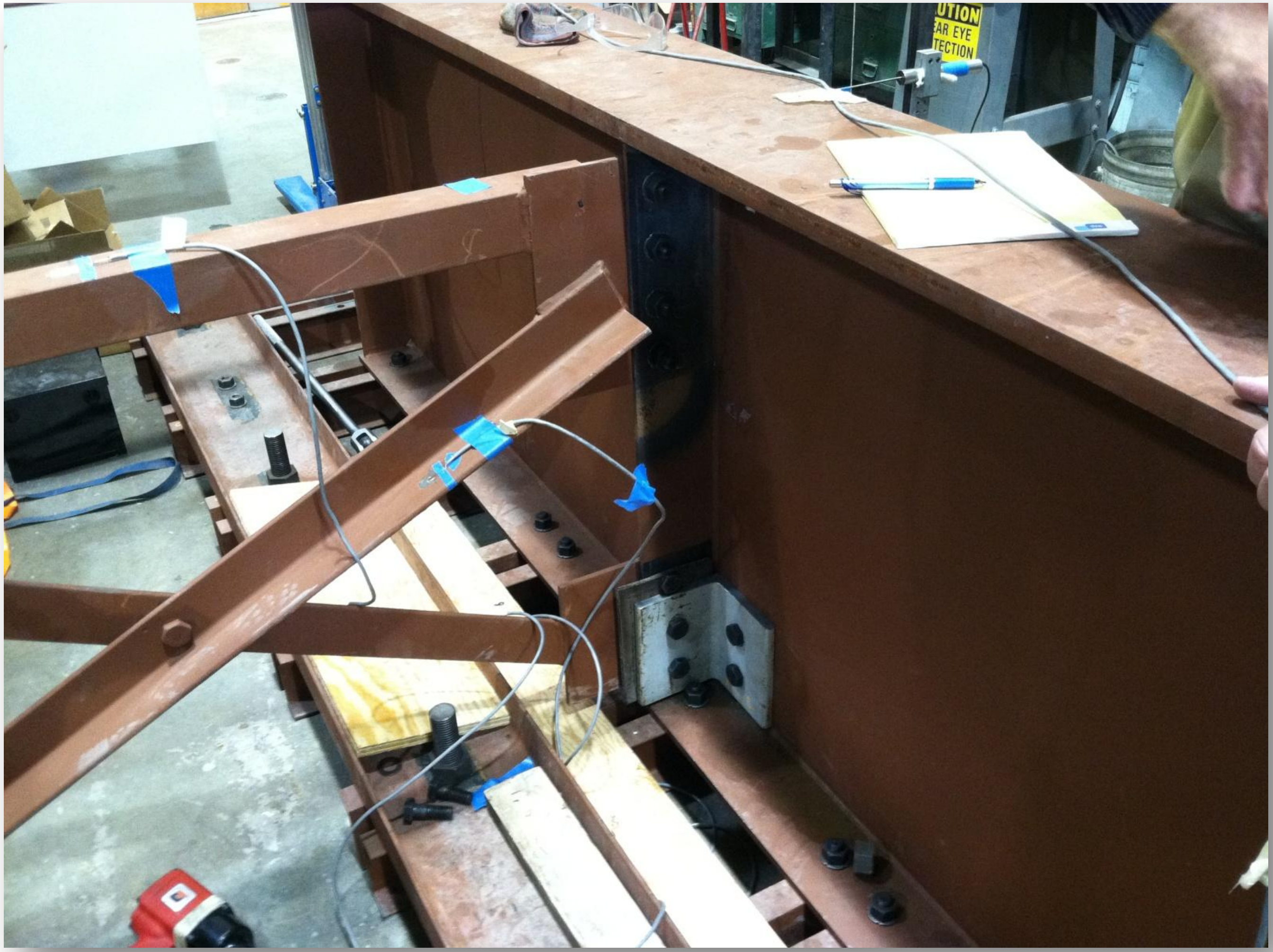
- **Web-to-Stiffener Angles with Backing Plate**



- Test set-up considerations:
  - Lab concrete strong floor acting as the "concrete bridge deck"
  - Loading is applied vertically upward at the cross-frame to simulate differential deflection between adjacent girders

Mitigation Methods Under Development

- **Web-to-Stiffener Angles with Backing Plate**

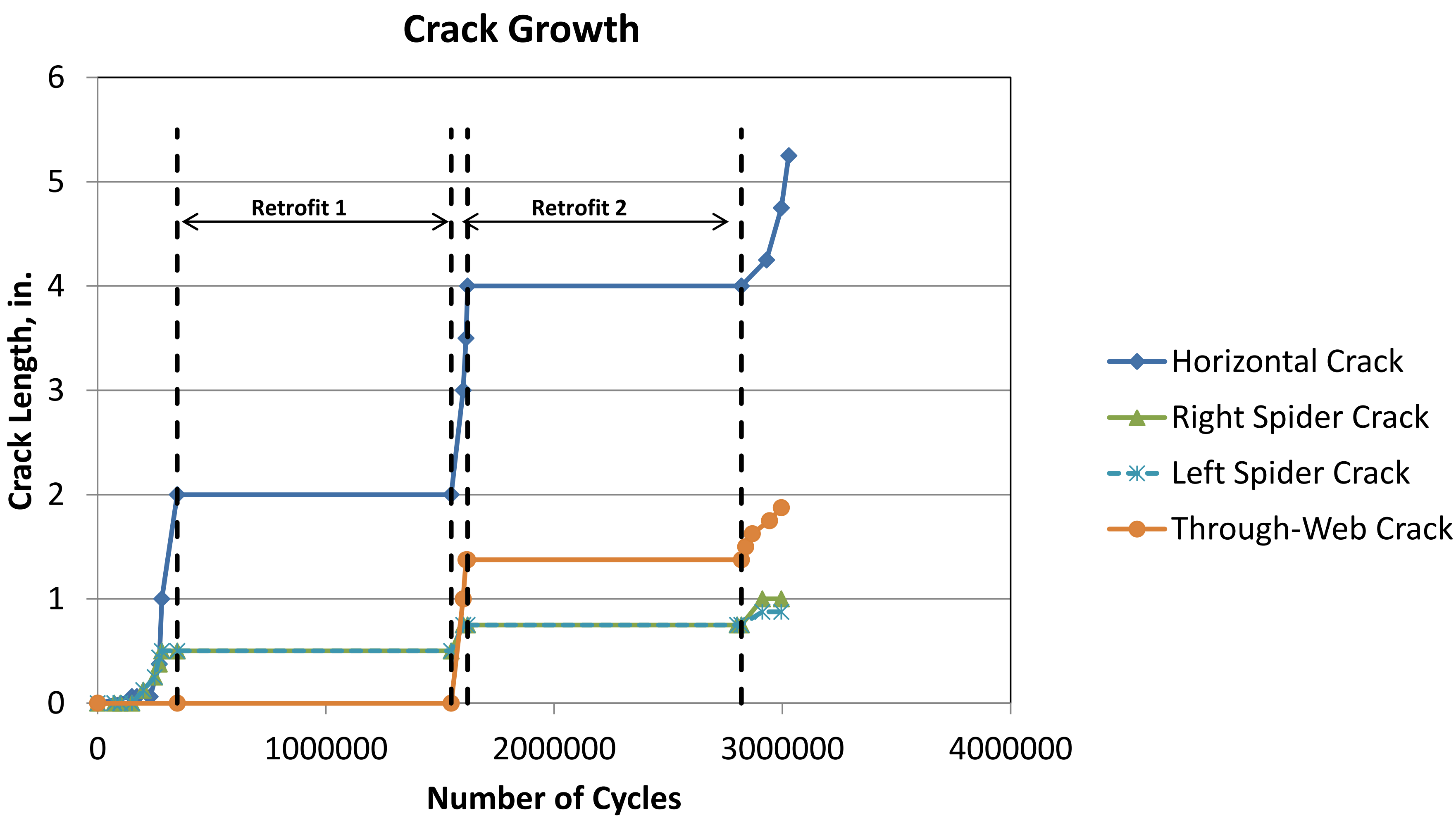


Mitigation Methods Under Development

- **Web-to-Stiffener Angles with Backing Plate**

Mitigation Methods Under Development

- **Web-to-Stiffener Angles with Backing Plate**



Mitigation Methods Under Development

- **Web-to-Stiffener Angles with Backing Plate**

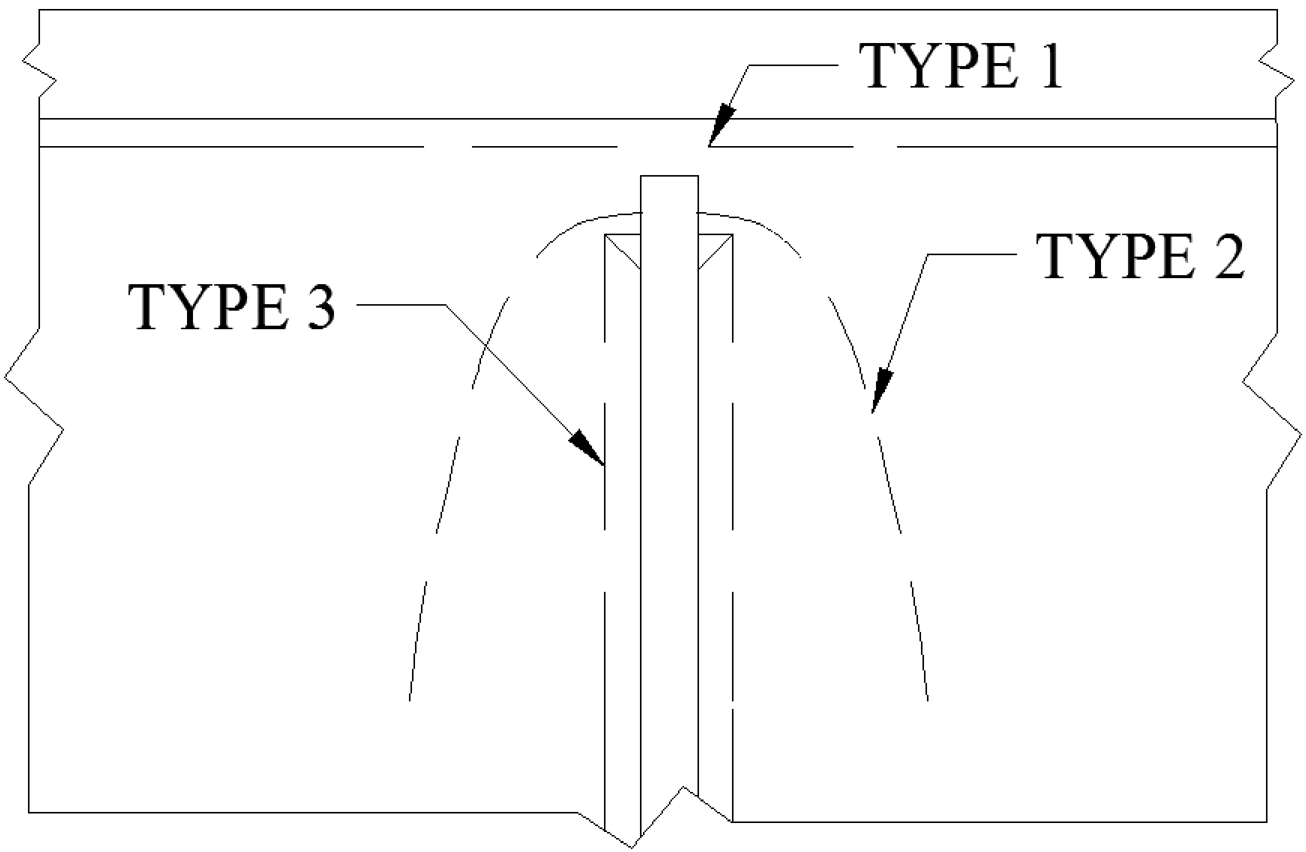
Mitigation Methods Under Development

For Deep Web Cracks

Sandwich Composite

Mitigation Methods Under Development

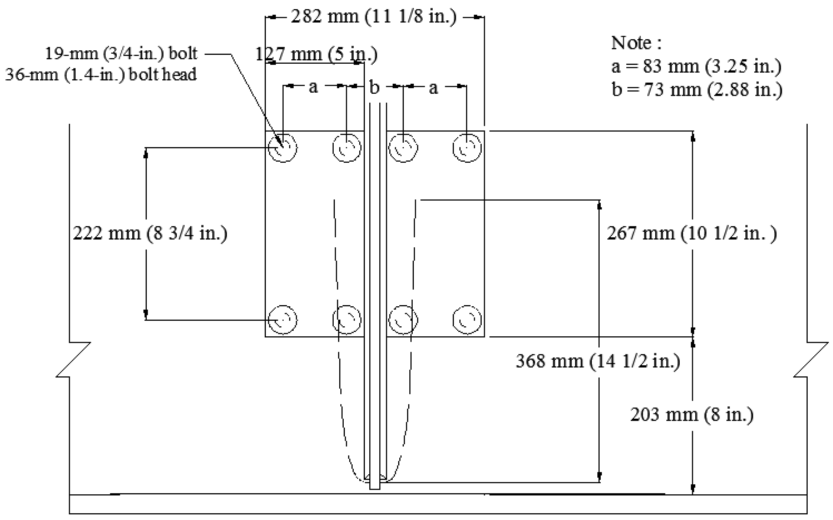
- Evaluation of retrofits for Type 2 cracking



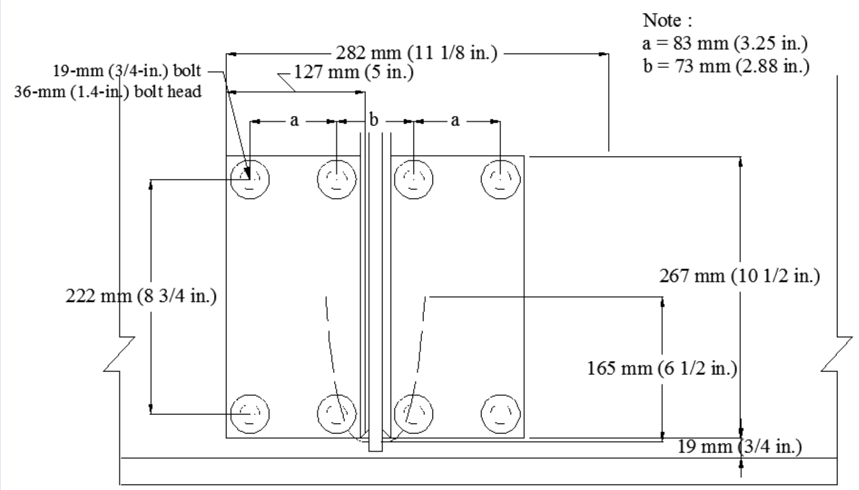
Mitigation Methods Under Development

- Distortion-Induced Fatigue

Repair for crack length equal to 1/4 web depth

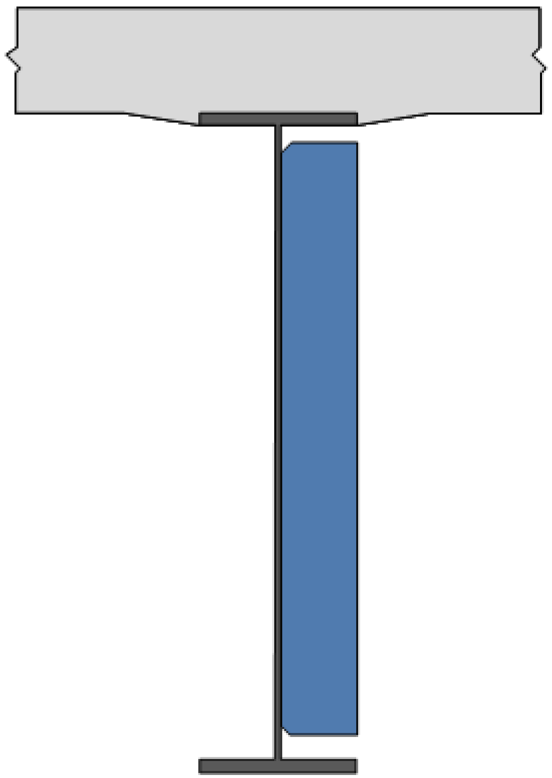


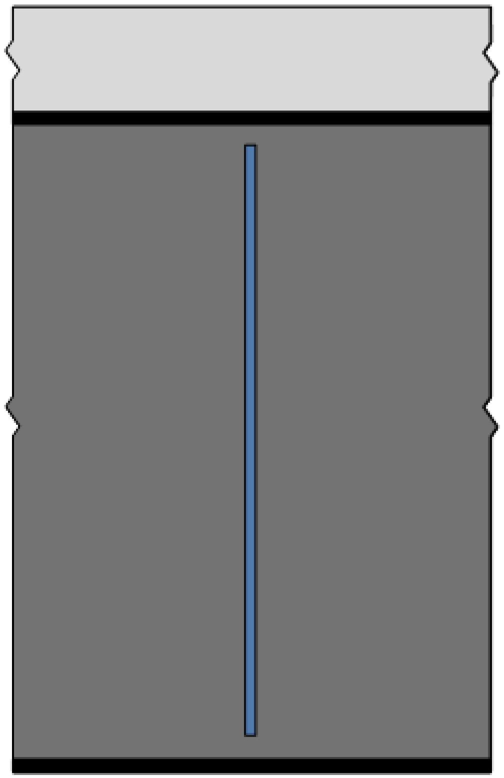
Repair for crack length equal to 1/8 web depth



Mitigation Methods Under Development

- Distortion-Induced Fatigue
  - CFRP / Steel Sandwich Composite

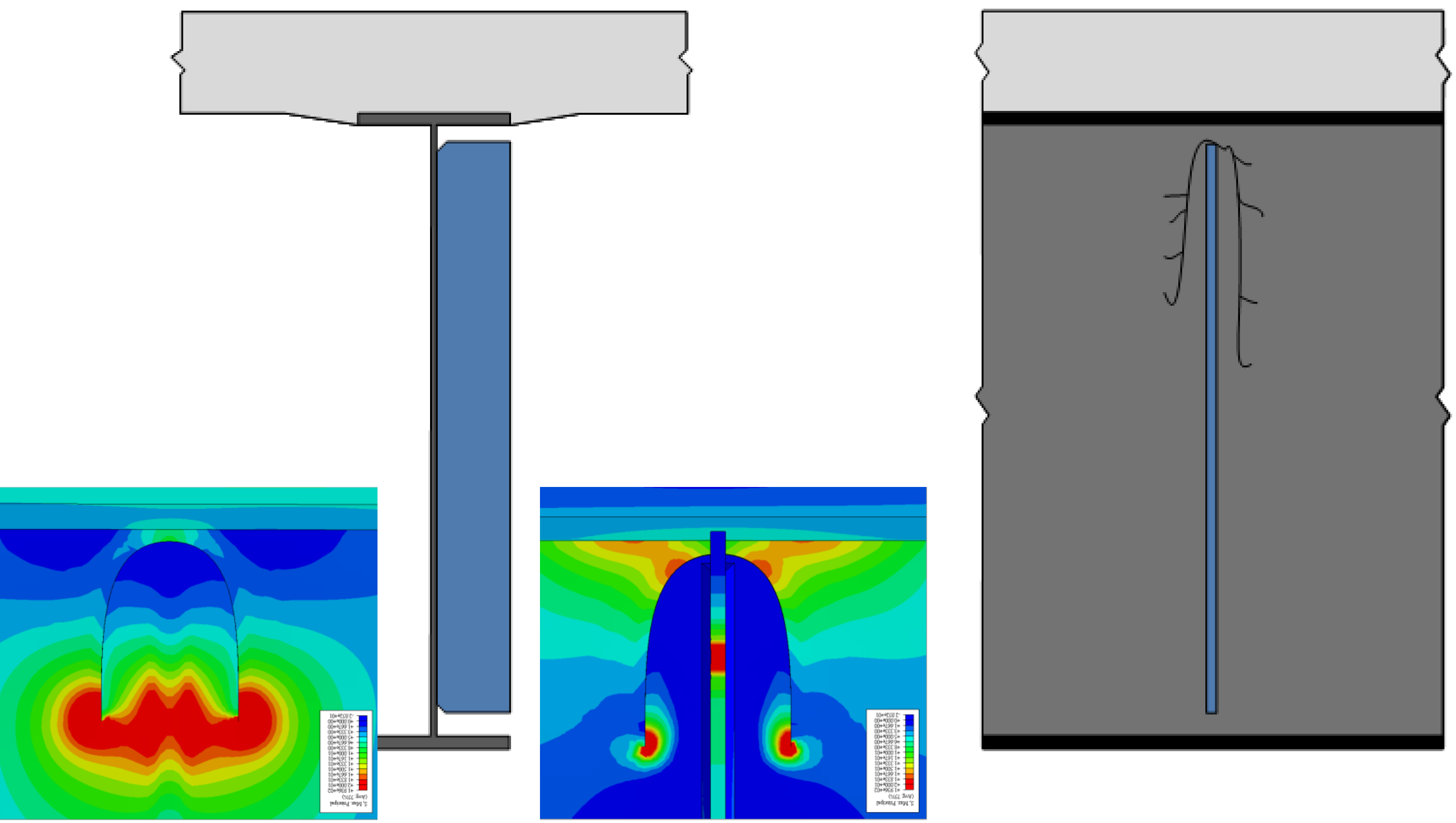




Uncracked girder

Mitigation Methods Under Development

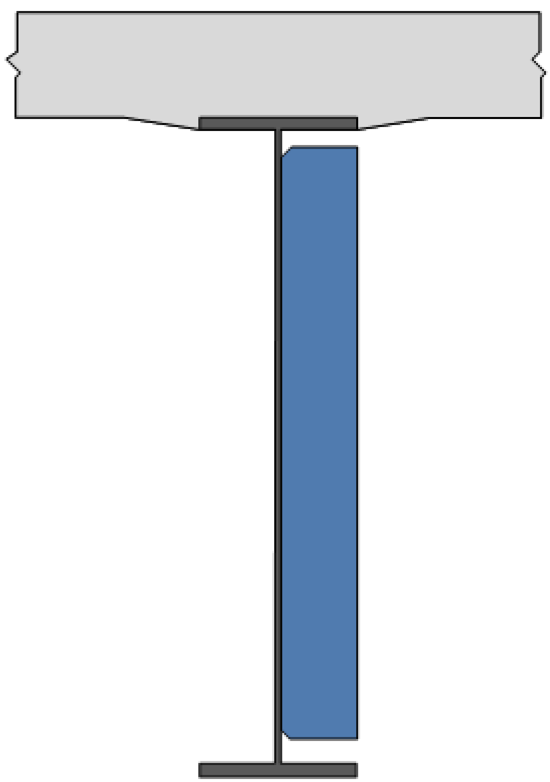
- Distortion-Induced Fatigue
  - CFRP / Steel Sandwich Composite

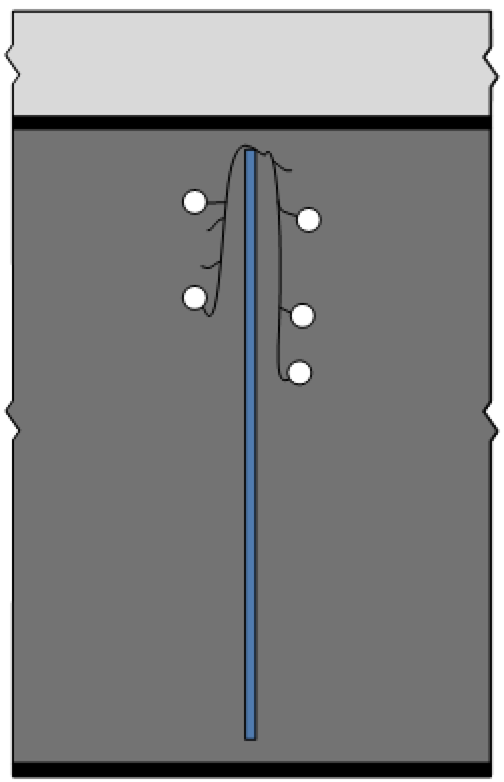


Cracked girder

Mitigation Methods Under Development

- Distortion-Induced Fatigue
  - CFRP / Steel Sandwich Composite

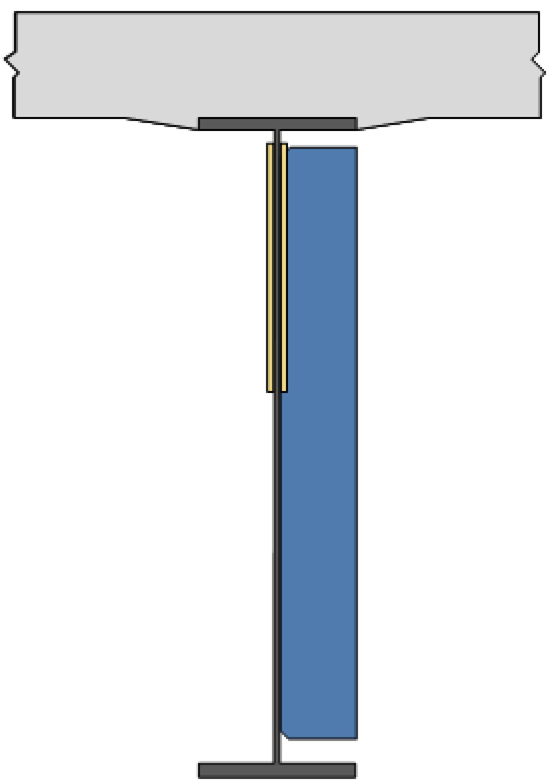


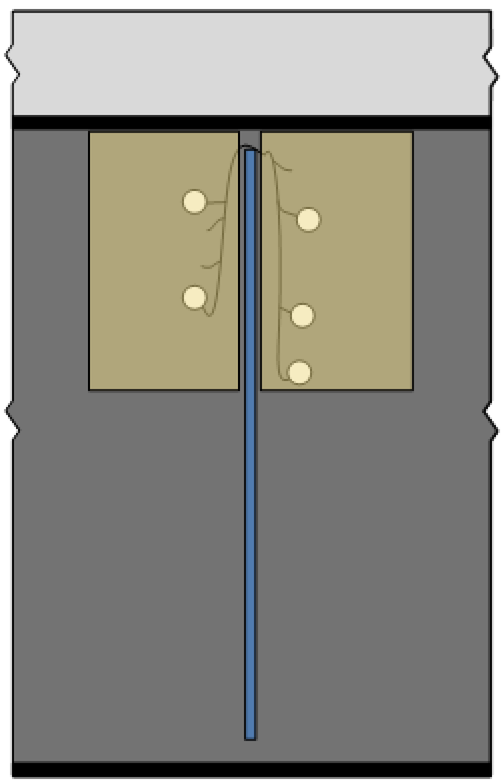


Cracked girder, with crack-stop holes

Mitigation Methods Under Development

- Distortion-Induced Fatigue
  - CFRP / Steel Sandwich Composite

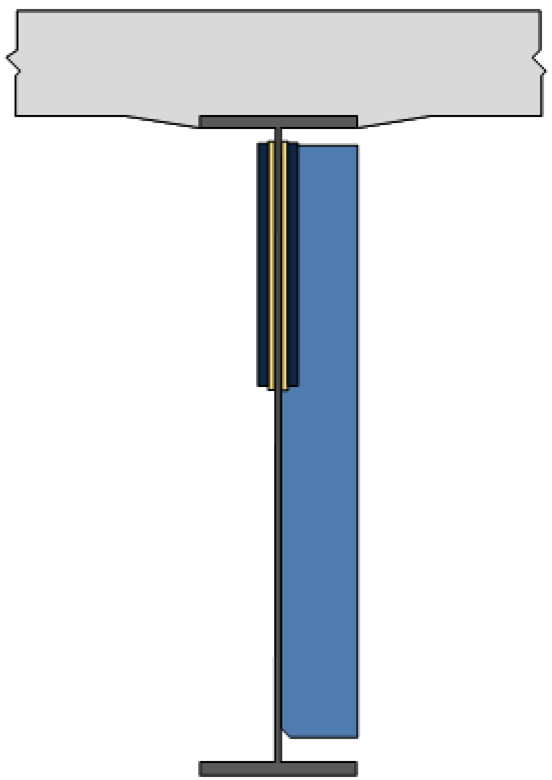


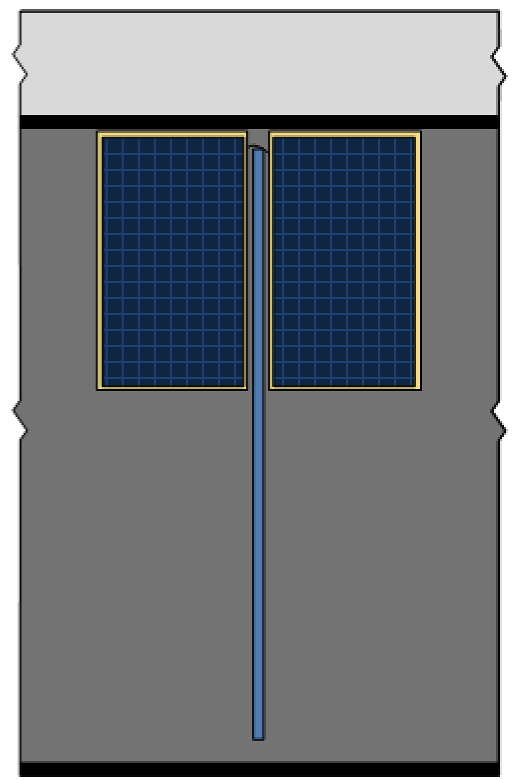


Cracked girder: resin layer

Mitigation Methods Under Development

- Distortion-Induced Fatigue
  - CFRP / Steel Sandwich Composite

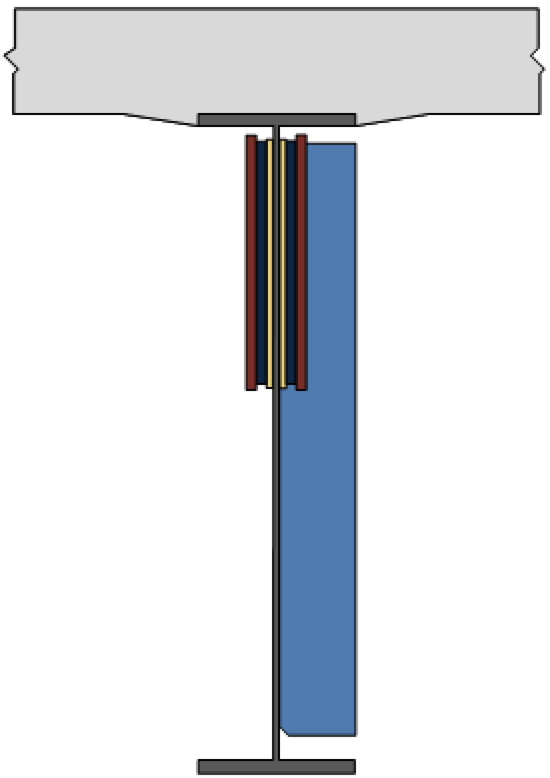


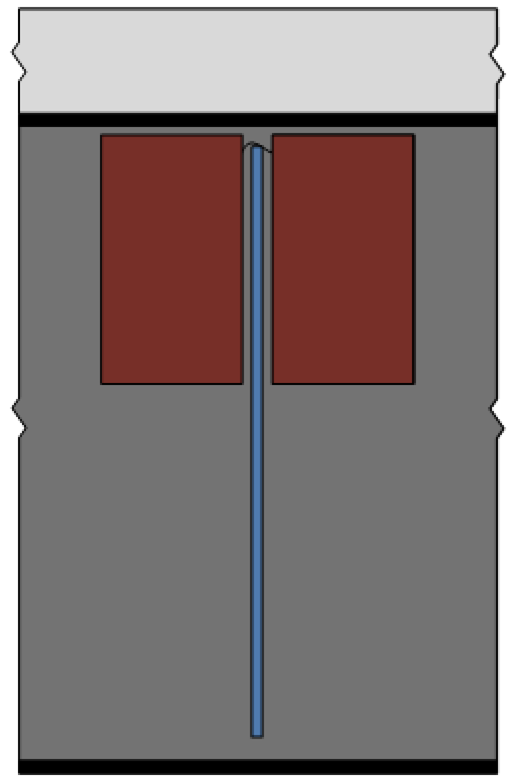


Cracked girder: resin layer + CFRP

Mitigation Methods Under Development

- Distortion-Induced Fatigue
  - CFRP / Steel Sandwich Composite

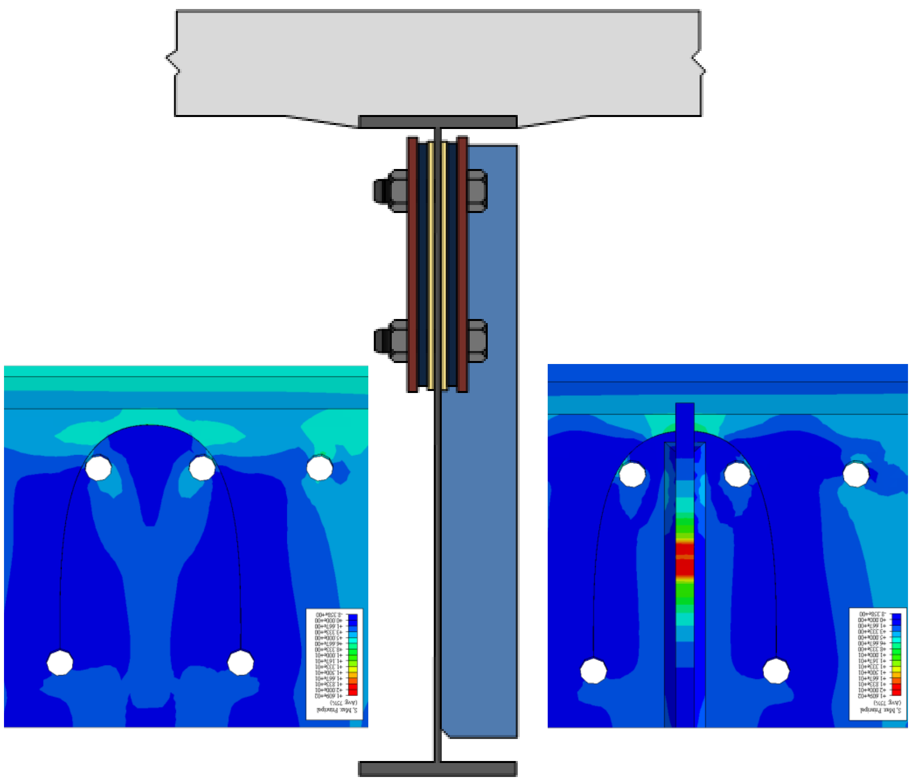


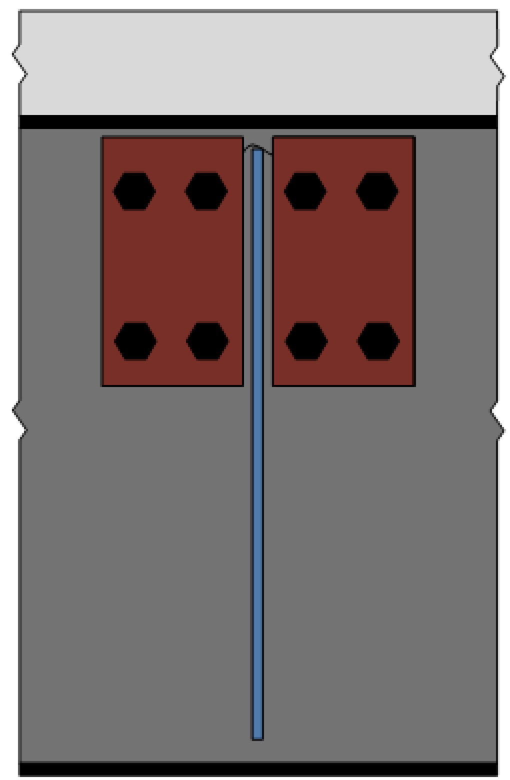


Cracked girder: resin layer + CFRP + steel

Mitigation Methods Under Development

- Distortion-Induced Fatigue
  - CFRP / Steel Sandwich Composite



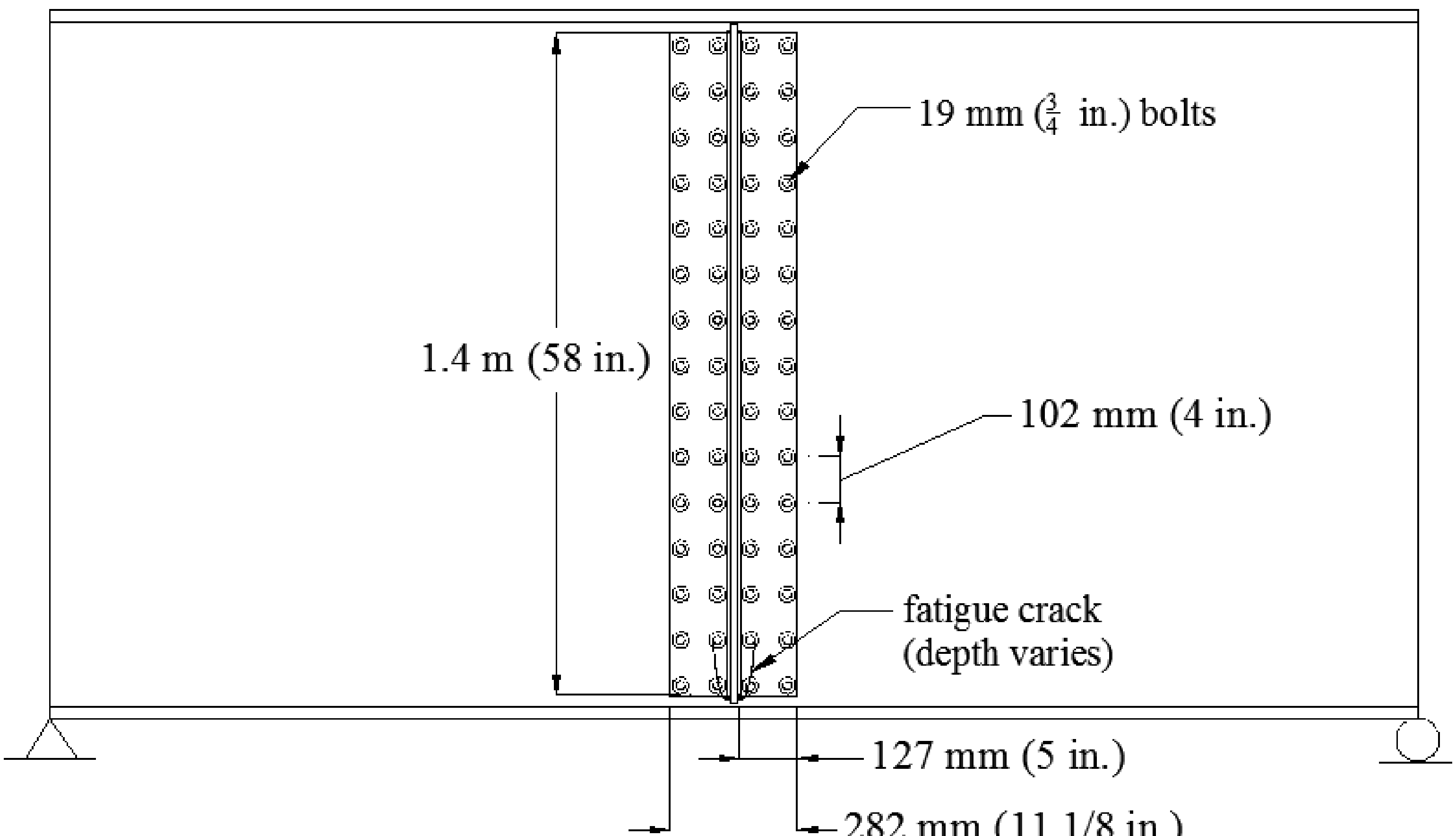


Cracked girder: resin layer + CFRP + steel + bolts

= Sandwich composite

Mitigation Methods Under Development

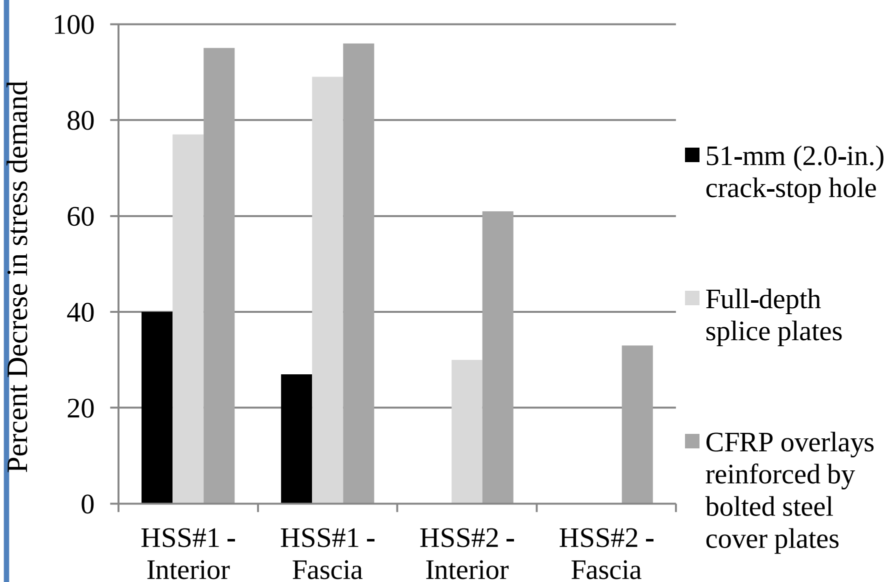
- Distortion-Induced Fatigue
  - Full-depth web splice



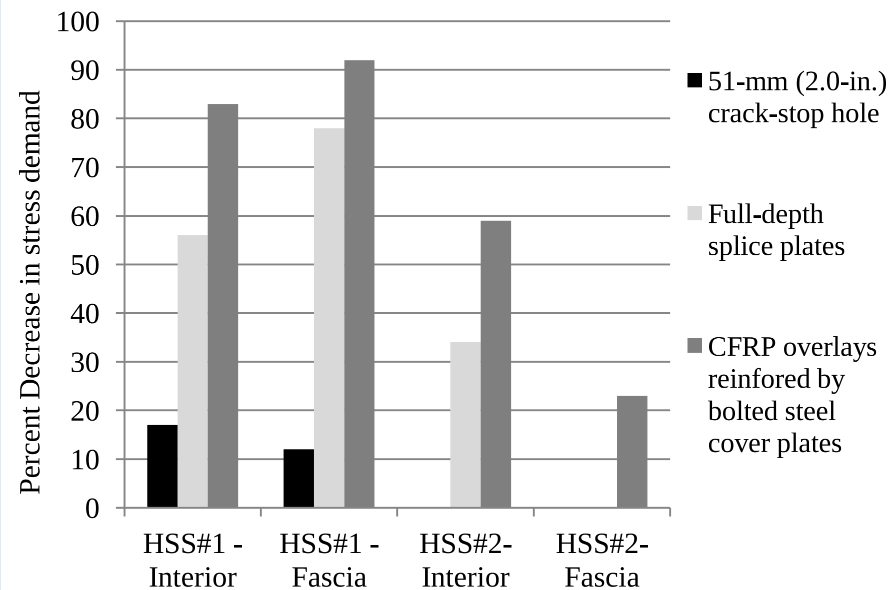
Mitigation Methods Under Development

- Distortion-Induced Fatigue

Repair for crack length equal to 1/4 web depth



Repair for crack length equal to 1/8 web depth



Mitigation Methods Under Development

Crack-Arrest Hole Improvement

PICK Tool

Mitigation Methods Under Development

- PICK Tool
  - The need for crack-stop hole treatment

Mitigation Methods Under Development

Problem:

Crack-stop holes are often not effective in halting crack propagation between inspection cycles

Present Solution:

Drill another crack-stop hole / provide a more substantial retrofit

Result:

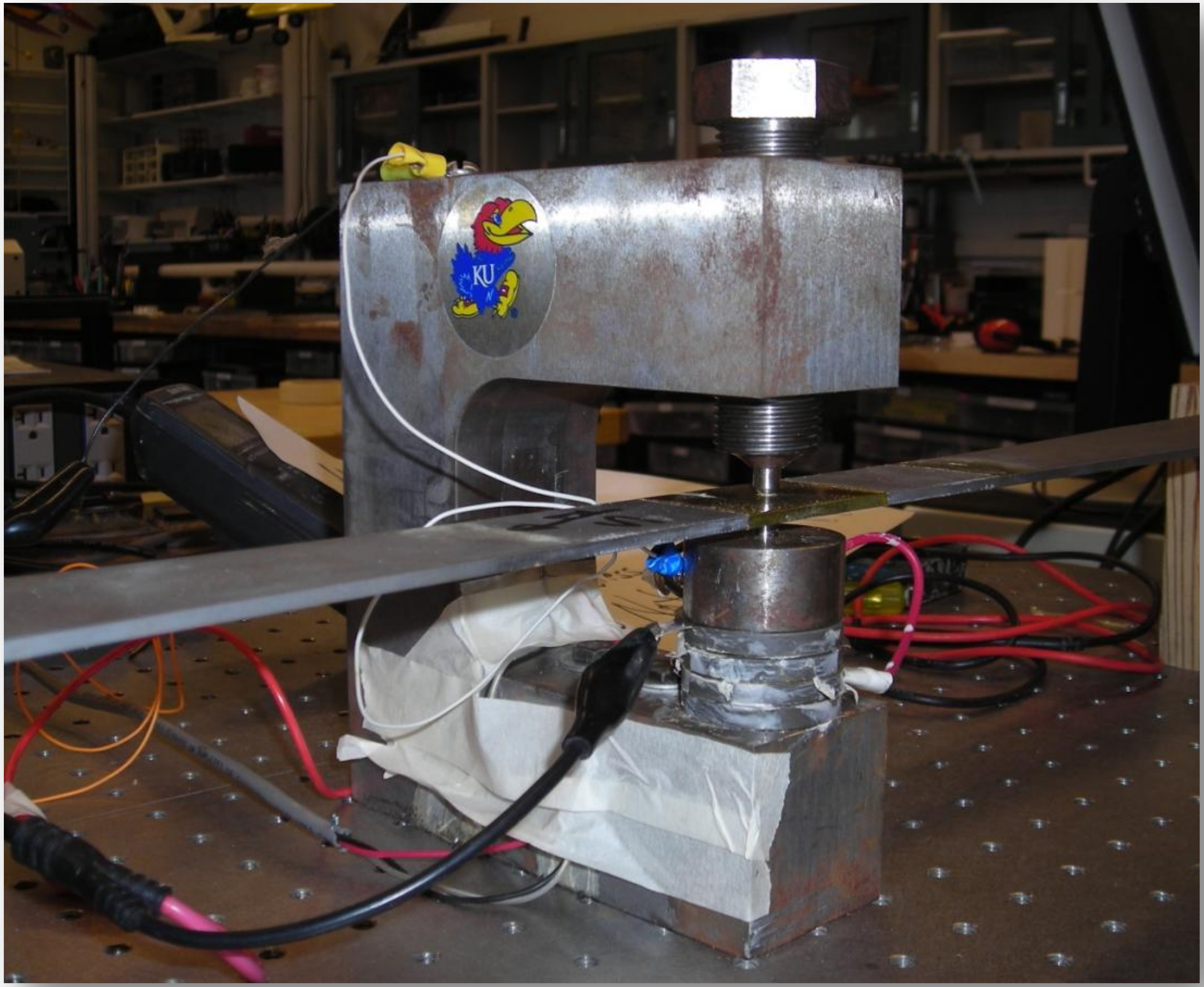
Cracks reinitiate / high expense due to increased maintenance

Proposed Solution:

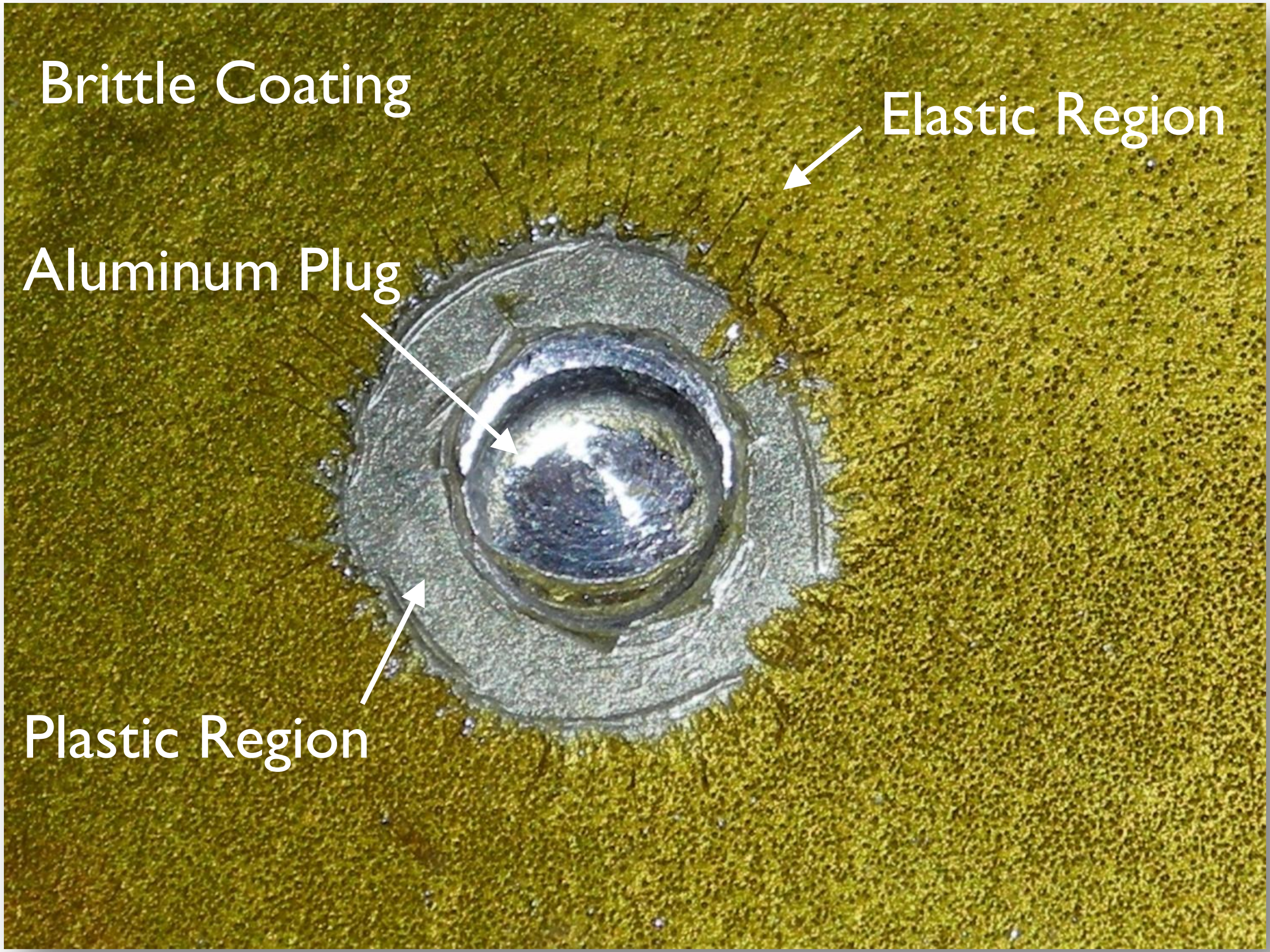
Develop a technique to cold work and refine grain structure of undersized crack-stop holes practical for application in the field to extend the applicable range of crack-stop holes.

Mitigation Methods Under Development

PICK tool

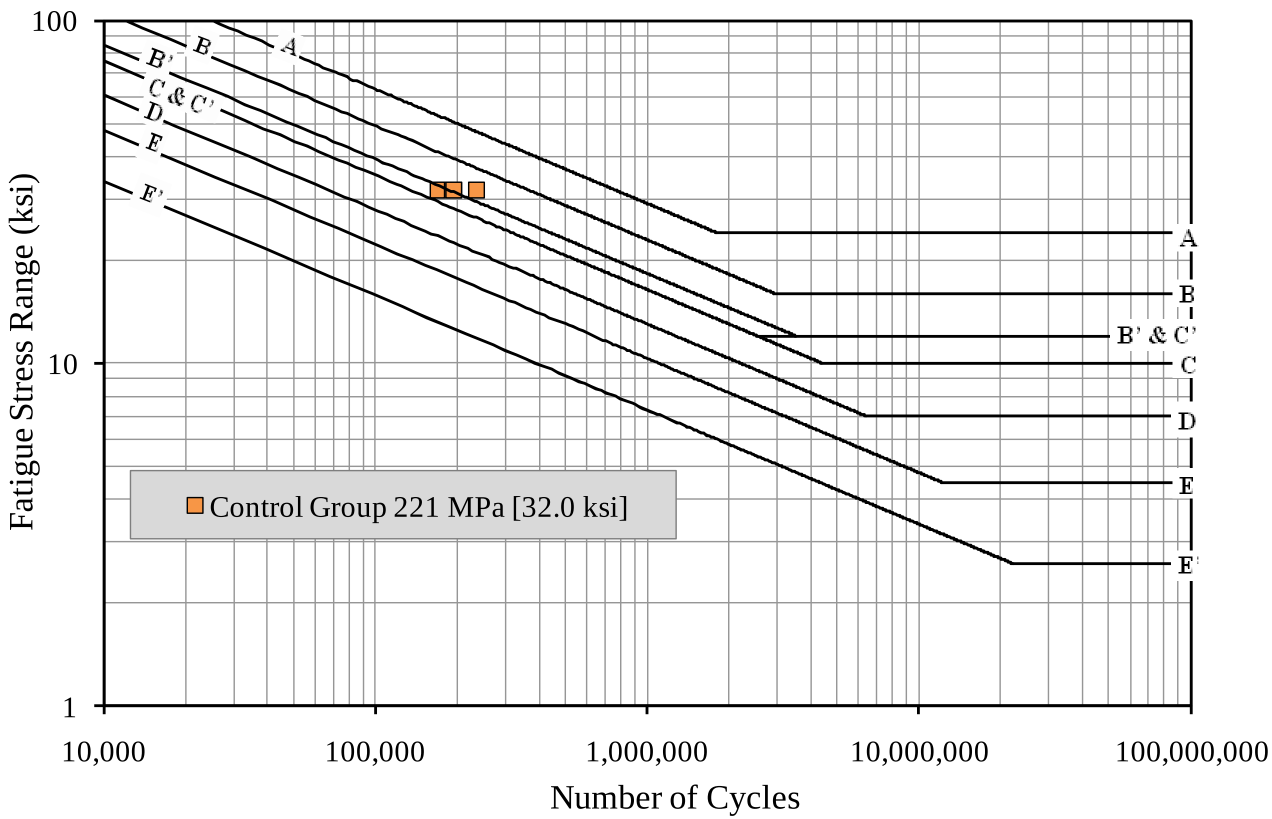


Mitigation Methods Under Development



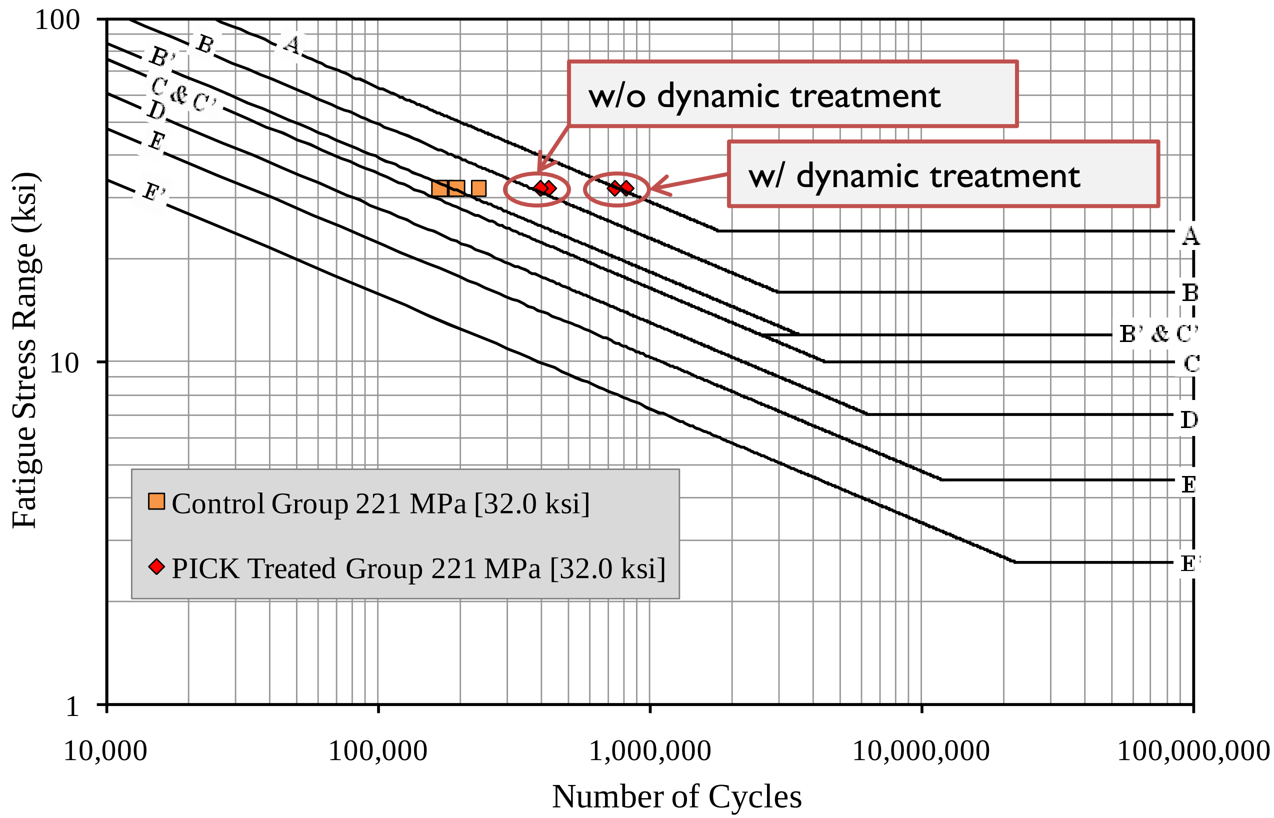
Mitigation Methods Under Development

SN Results



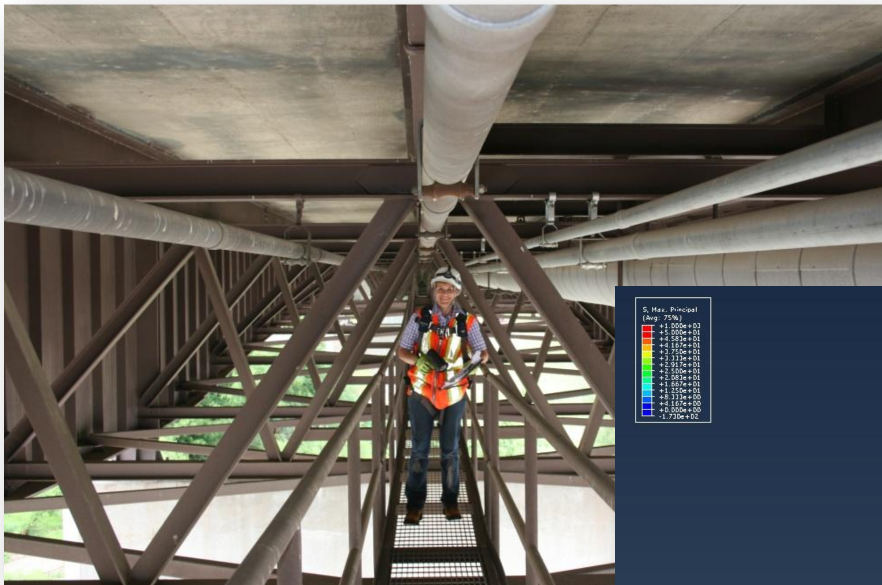
Mitigation Methods Under Development

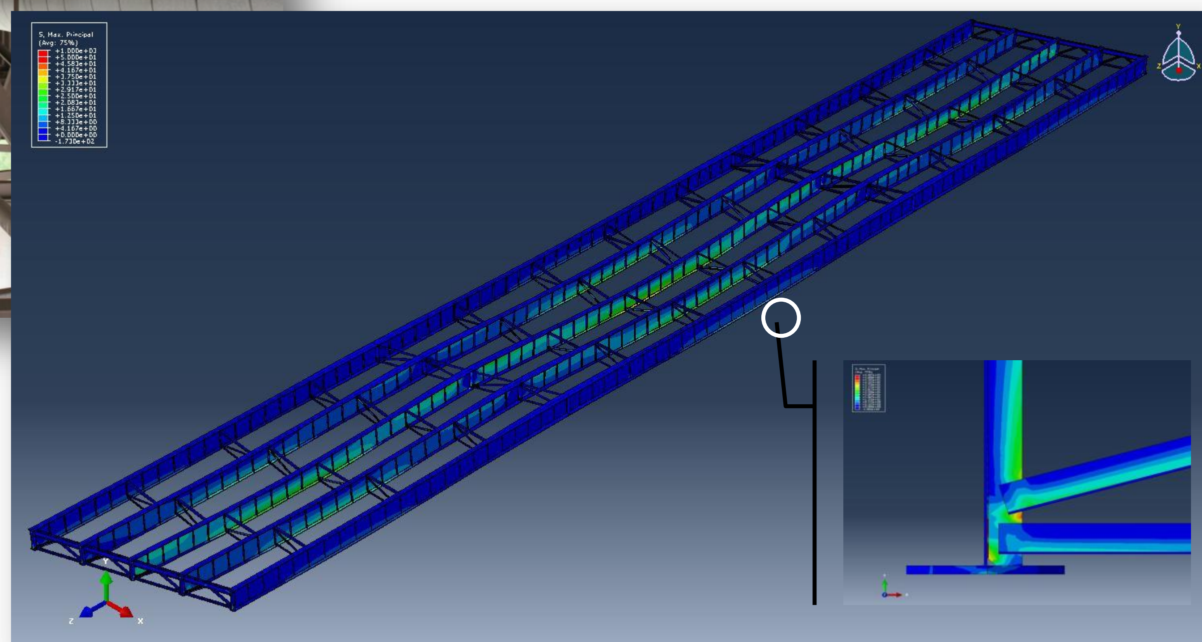
SN Results



Field Studies

Field Studies





Conclusions & Summary

- **Summary**
  - Three project thrusts aligned: experimental, simulation, and field.
  - Existing retrofit techniques have been investigated to form meaningful basis of comparison
  - New distortion-induced fatigue mitigation measures being developed are showing significant promise:
    - Web-to-Stiffener Angles with Backing Plate
    - Sandwich composite
    - Crack-arrest hole sizing, placement criteria, and hole treatments

Conclusions & Summary

- Anticipated use of combining these techniques will result in new mitigation measures for distortion-induced fatigue that are:
  - Effective
  - More easily implementable than existing techniques
  - More economical than existing techniques

Thank you

- TPF-5(189) "Enhancement of Welded Steel Bridge Girders Susceptible to Distortion-Induced Fatigue"
  CA, FHWA, IA, IL, KS, LA, NJ, NY, OR, PA, TN, WA, WisDOT, WY
- Kansas DOT (lead state)
- KU Transportation Research Institute (KU TRI)
- Oakridge National Laboratories & US DOE