<u>March 31, 2011 Progress Report on Pooled Fund Study TPF-5(189):</u>
"***Enhancement of Welded Steel Bridge Girders Susceptible to Distortion-Induced Fatigue***"

1. Introduction

Progress made for the reporting quarter ending March 31, 2011 includes the following highlights:

- ***Three-Girder 30 ft. Specimens -***
  - Test girders were received at the University of Kansas from Central Texas Iron Works (CTIW),
  - Six steel load cells have been gaged, calibrated, and set on the bridge supports at the University of Kansas for use in the test set-up.
  - Finite element analyses of specimens is ongoing.

- ***9 ft. Girder Specimens -***
  - Two 9 ft. specimens have been tested in fatigue; distortion-induced fatigue cracking has occurred. Retrofits are being applied
  - Finite element analyses of 9 ft. specimens is ongoing.

- ***Component Level Testing -***
  - Digital imaging correlation is being used to determine the level of strain induced by PICK.
  - Specimens have been sent to Oakridge National Laboratories (ORNL) for X-ray diffraction and neutron diffraction.
  - PICK-treated tensile fatigue specimen metallographic analysis has been performed.
  - CFRP-treated tensile specimen testing has continued.

2. 30 ft. Three-Girder Specimen Test Set-Up

Test specimens, fabricated by Central Texas Iron Works, arrived March 16, 2011. This shipment included steel for six test setups, and all fabricated steel was received in excellent condition. Construction for first test setup is well-underway. Steel support fabrication at Rice Precision was completed March 28, 2011, and the concrete "pier" supports for bridge girders have been set. Strain gaging of the steel girders to measure web gap stress and flexural stresses is underway.

Determination of the cyclic load range to be applied to the 30' bridge test set-up was explored through Finite Element Modeling (FEM) of the full bridge testing setup. An FEM has been developed for the 9 ft. specimens that correlates well with experimental testing (discussed in section 3). Based on 9 ft. specimen models and experimental testing of the 9 ft. specimens, crack propagation follows maximum principal stresses. To determine appropriate load application for the full (30 ft.) bridge specimens, stresses determined through FEA were compared and matched between the two specimen types. The cyclic load range that was determined for the 30' bridge specimens is 60 kips.

Fig. 1. Shipment of girders from CTIW received at the KU Structures Lab for use in 30 ft. girder test set-up

Fig. 2. View of web gap region in segment of test girder intended to develop fatigue failure

Fig. 3. View of one of the typical cross-frames to be used in the bridge test set-up

3. 9 ft. Girder Specimens

As discussed in the Dec. 30, 2010 progress report, the Kansas Department of Transportation (KDOT) is supporting two new projects that directly complement work being performed inTPF5-(189), and progress on work done is included here as it is closely related to TPF5-(189). The projects are entitled "*Extending Useable Lives of Steel Bridges by Halting Distortion-Induced Fatigue Crack Propagation Using Fully-Tightened Bolts and Plate Washers"* and "*Repairing Existing Fatigue Cracks in Steel Bridges Using CFRP Materials*".

Two 9-ft girder specimens have been tested so far. The first specimen was cycled at 2 Hz, under a load range of P_{min}=0.5 kips and P_{max}=5.0 kips, until 740,000 cycles were achieved. The first specimen tested included an initial, prefabricated crack of known length in the web gap region, as shown in Fig. 4. The purpose of doing this was to ensure a repeatable mode of cracking between specimens. However, it was found that during fatigue loading, the prefabricated crack propagated quite slowly and cracking initiated at the connection stiffener-to-web welds.

Fig. 5 shows a view of the finite element model for the 9 ft. specimens zoomed into the web gap region (the connection stiffener and flange have been removed from view). The prefabricated "starter" crack can be seen towards the bottom of the figure. Crack locations have been superimposed on the screenshot, and correlate to the state of cracking after 200,000 fatigue cycles. There are two items in particular to note: (1) the FE results hot spot stress locations correlated extremely well with the locations of physical crack initiation and growth observed in the experimental tests; and (2) even with a "starter" crack in the web gap region, cracking still initiated in the connection stiffener welds. The stiffener-to-web weld cracks propagated quite quickly, and therefore, subsequent tests were performed without an initial, pre-fabricated crack.

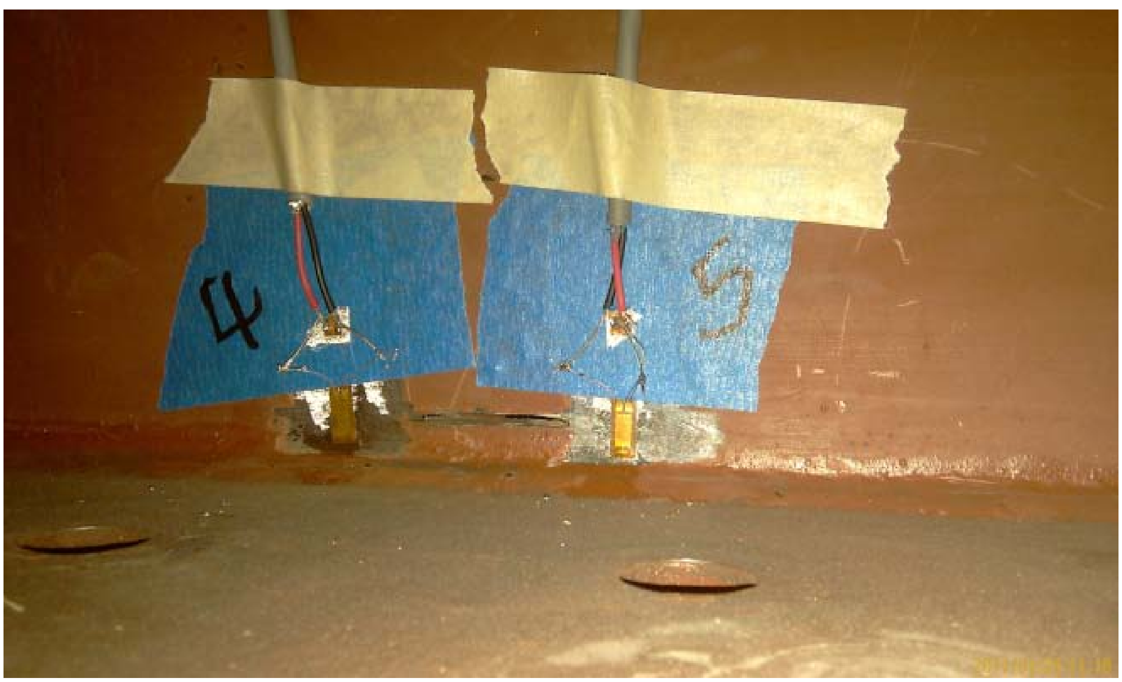

Fig. 4. View of starter crack and strain gages on outside (fascia) side of girder web.

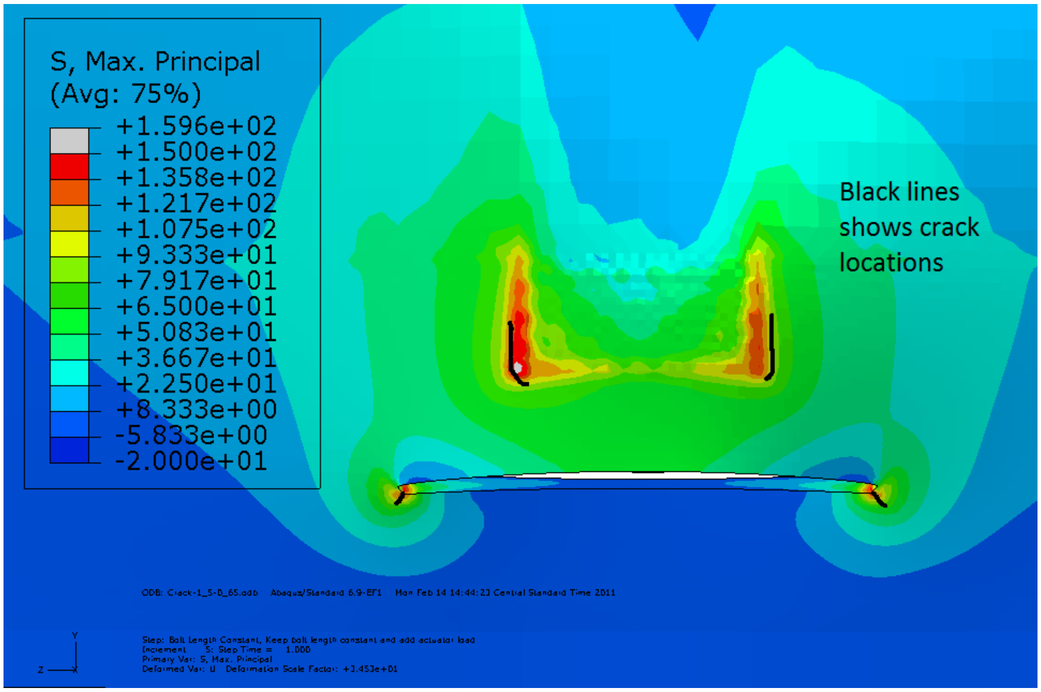

Fig. 5. Finite element model predictions of maximum principal stress in the web gap region of the 9 ft. specimen test set-up. Crack diagrams from the physical test have been superimposed in black on the model screenshot.

No "starter" cracks were fabricated in the second specimen, and cracking initiated early in testing in two locations: the stiffener-to-web weld, and the flange-to-web weld. The location of the cracking again correlated very well with finite element predictions. Based on this, the load range being used (4.5 kips) was confirmed as a reasonable choice for initiating and propagating cracking in the test set-up. After approximately 400,000 cycles had been applied to the test set-up, the horizontal flange-to-web crack had grown to approximately 6 in., and the vertical cracks along the connection stiffener weld were approximately 4 in. long.

Some problems were experienced with the test set-up during the second test. The actuator load cell electronics malfunctioned, disrupting the test and bending the connection stiffener and damaging the cross-frame. To bring testing on-line again in as efficient manner as possible while a new load cell is on order, the 110-kip actuator assembly was exchanged with another assembly available in the lab (55-kip capacity). The connection stiffener was heat-straightened, and a new cross-frame assembly installed. At the time of writing, testing had commenced once again. The horizontal crack has been propagated to 8 in., and the vertical cracks propagated to 6 in. The first repair is currently being installed on the specimen.

Multiple retrofit techniques, including steel plates, steel angles, and carbon fiber reinforced polymer (CFRP) configurations have been modeled to examine their relative effectiveness. Many have shown promise. It was decided to pursue a double-angle retrofit first, in which angles are connected to the girder's web and the connection stiffener. This retrofit has shown potential in the FE analyses, details of which are shown in Figs. 6, 7, and 8. This retrofit is particularly promising amongst steel retrofits as it does not require attachment to the flange, which can be difficult to achieve without welding or removal of a portion of the bridge deck to access the top of a top flange for bolting. Results of testing this retrofit, applied over aggressive levels of cracking, will be reported in the June 2011 progress report.

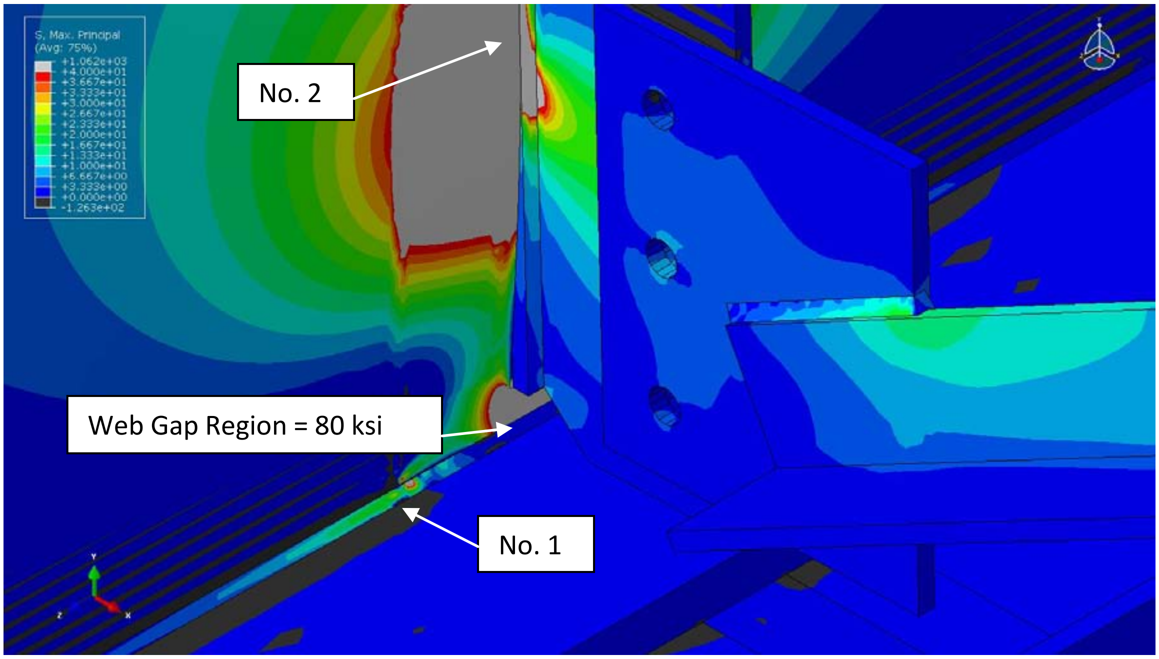

Fig. 6. Finite element results for 9 ft. specimen with 6 in. horizontal flange-to-web crack (Crack No. 1) and 4 in. vertical connection stiffener weld crack (Crack No. 2)

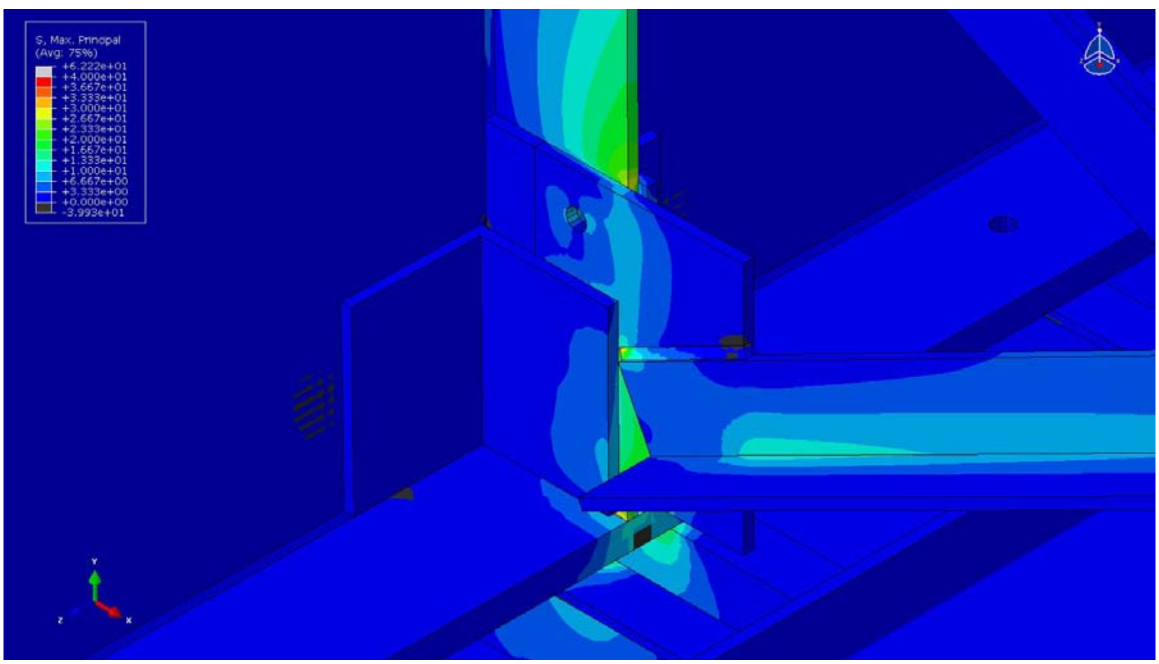

Fig. 7. Angle retrofit being applied to Specimen #2. Angles are be applied to both side of the connection stiffener.

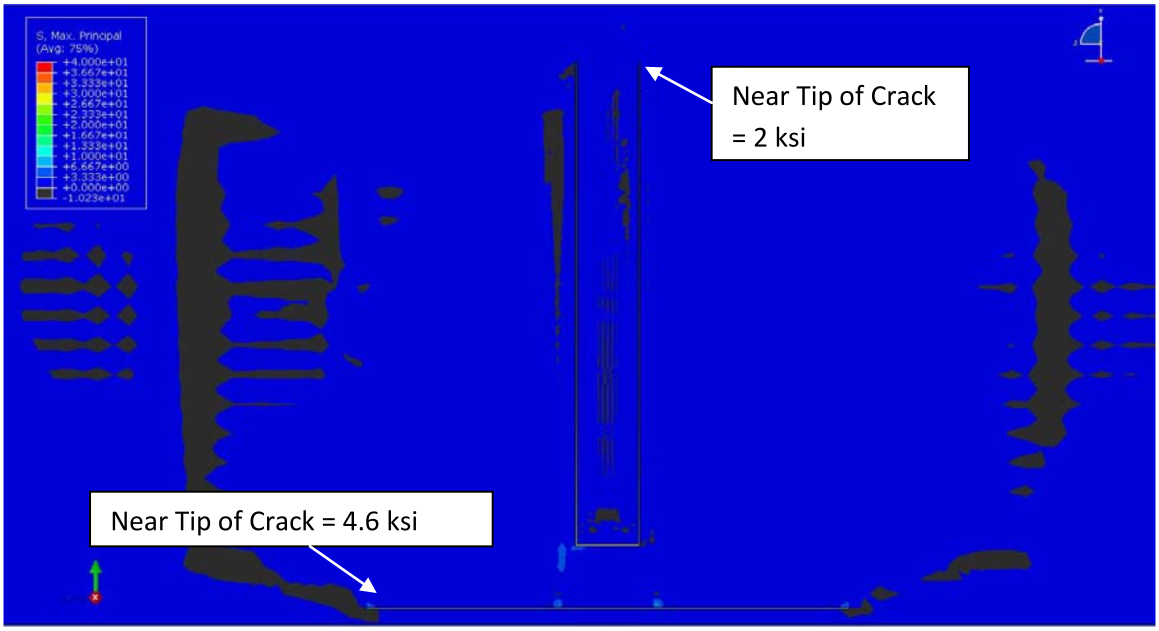

Fig. 8. Finite element results after the angle retrofit is applied. Stresses are shown on the web for both hot spots (crack locations #1 and #2, as shown in Figure 5).

4. Component Level Testing

PICK-Tool Development and Testing Program

Efforts were heavily focused on evaluation of the PICK technology this quarter. The different techniques pursued are described:

- **Metallurgical Examination:**
  Metallurgical examination was completed of one specimen which had been treated with the PICK tool. It was thought that the PICK tool would affect the steel in three ways:
  - The material would be work hardened.
  - As a result of the work hardening and work from the piezoelectric wafers, the grain size of the steel would be reduced.
  - The dislocation density would be increased and inclusions would migrate to form distinct bands.

  The metallurgical examination consisted of optical grain size comparison and micro-hardness traverses. These both indicated the presence of substantial work hardening but the grain size reduction was limited to very near the work hardened surface. No indications of increased dislocation density or inclusion migration were found.

- **Neutron and X-Ray Diffraction:**
  An agreement has been met with Oak Ridge National Laboratories (ORNL) to work with them to use their facilities to measure residual stress in two PICK-treated specimens using X-ray diffraction to measure surface residual stress and neutron diffraction to measure internal residual stresses. Testing will be conducted at ORNL from May 8 - May 27, 2011, and results should be reportable in the June 2011 progress report.

- **Digital Image Correlation (DIC):**
  A Digital Image Correlation (DIC) technique has been developed to measure surface strains during and after treatment with the PICK tool. The procedure utilizes a micro-hardness indenter to place points on the surface of the pretreated specimen and photograph these with a digital camera through a microscope. At intervals during treatment and after treatment, the specimen is removed from the PICK tool and photographed again. By comparing the change in lengths between the indentations, tangential and radial strains can be determined at various stages of treatment, over very small distances. DIC results are intended to provide a quantitative evaluation of the performance of the PICK tool and to be used to refine PICK treatment protocol.

- **Strain Gaging:**
  Strain gages have been applied in the direct vicinity of the drilled hole, and are being used to measure strains induced during and after PICK-treatment.

CFRP-Treated Specimens

The project team has explored two research thrusts aimed at examining the effectiveness of CFRP as a fatigue-retrofit technique:

(1) Flat CFRP doublers applied to pre-cracked tensile fatigue specimens.
(2) CFRP doublers tested in three-point bending on coverplate details, and

Results to-date of both of these research focuses have highlighted the effectiveness of CFRP materials to significantly slow crack initiation in uncracked specimens (often to run-out), and to extend the fatigue life of a pre-cracked tensile specimen to run-out. Research focused primarily on use of flat CFRP doublers on pre-cracked tensile specimens in this reporting quarter.

- **Pre-Cracked Tensile Fatigue Specimens Treated with CFRP:**
  Testing of pre-cracked tensile specimens treated with CFRP doublers has continued. The initial crack length of these CFRP treated specimens was set at 0.3 in. Results of these tests have been encouraging.
  Shown below is the updated test matrix with the number of cycles of failure for each specimen based on current available data (missing values from the table represent specimens that are either in the process of being tested or analyzed).

Table 1: Cycles to failure of 0.125 in. and 0.25 in. thick steel specimens with CFRP treatments of varying thickness

	Stress Range (ksi)		
	24 ksi	**32 ksi**	**38 ksi**
1/8" thick steel specimen			
No CFRP	3,800	50	N/A
1/16" thick CFRP	340,700	55,800	21,700
1/8" thick CFRP	1,450,095	313,050	82,300
1/4" thick CFRP	TBD	TBD	TBD
1/4" thick steel specimen			
1/16" thick CFRP	--	TBD	--
1/8" thick CFRP	--	170,600	--
1/4" thick CFRP	--	617,300	--

The 0.125 in. thick cross-section being tested has a width of 1.25 in. at the reduced section, with a 0.125 in. diameter hole drilled at the center of the reduced section. Therefore, the 0.3 in. initial crack length in the steel before CFRP is applied is a significant reduction in the steel net section area for the 0.125 in. specimens. The cycle counts that are reported correlate to the point at which the steel cross-section experiences fracture (full propagation through the remaining 0.2625 in. of steel section on one side of the drilled hole in the 0.125 in. thick specimens).

5. Upcoming Tasks

The following tasks are anticipated to occur in the next project quarter:

30' Three-Girder Specimens:

- The first bridge test set-up will be completed (girders gaged, set, and concrete deck bolted to the steel girders)
- The first bridge fatigue test will be performed.

9' Girder Specimens:

- Two to three additional 9 ft. girder specimens will be tested in fatigue, and will receive retrofits for evaluation.
- Finite element analyses will continue.

Component-Level Studies:

- Treatment and testing of ¼" thick PICK-treated specimens will continue,
- Neutron diffraction and X-ray diffraction will be completed at Oakridge National Research Laboratories (ORNL)
- Further quantitative experimental stress analysis techniques will be applied (e.g. strain gages) to further determine the state of residual stress around the treated holes,
- Fatigue testing of CFRP-treated pre-cracked tensile specimens will continue.

Other:

- ***An invitation will be extended to DOT representatives to participate in a project meeting and tour at the University of Kansas while testing of the 9' and 30' girders is underway. It was initially anticipated that the TPF5-(189) project meeting would be scheduled for late spring, 2011. Due to a later delivery date for the 30 ft. girders, and problems described with the 9 ft. girder test set-up, late summer 2011 is the new target timeframe.***

6. Conclusion

TPF5-(189) has posted strong progress this reporting period. The 30' three-girder bridge assemblages have been received, and the test set-up/specimen preparation is nearing completion. Testing will commence during the next reporting period. Testing is underway on fourteen 9 ft. girder lengths; distortion-induced fatigue cracking has been obtained, and a first repair technique is being applied. Component-level testing for PICK treatment and CFRP repair techniques is progressing well.

7. List of Related Publications

A list of in-print publications produced by the project team in direct relation to TPF5-(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.

- 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.

Contact Information

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