December 30, 2010 Progress Report on Pooled Fund Study TPF-5(189):
"***Enhancement of Welded Steel Bridge Girders Susceptible to Distortion-Induced Fatigue***"

1. Introduction

Progress made for the reporting quarter between April 1, 2010 and December 30, 2010 includes the following highlights:

- ***Three-Girder 30' Specimens -***
  - Were subcontracted for fabrication to Central Texas Iron Works (CTIW),
  - Shop drawings have been reviewed and submitted,
  - Finite element analyses of specimens is ongoing,
  - Casting of concrete deck slabs has been completed,
  - Six steel load cells have been fabricated, and are being gaged at the University of Kansas for use in the test set-up.

- ***9' Girder Specimens -***
  - Were fabricated at Builders Steel, and have been received at the University of Kansas Structural Testing Laboratory,
  - The first test set-up has been completed, and testing is scheduled to begin shortly,
  - Finite element analyses of 9' specimens is ongoing.

- ***Component Level Testing -***
  - PICK-treated tensile fatigue specimen testing has continued,
  - PICK-treated tensile fatigue specimens have been sent for metallographic analysis,
  - CFRP-treated tensile specimen testing has continued.

- ***Analytical Parametric Investigation -***
  - A finite element study concerning the effects of skew, load placement, and cross frame stiffness continues; approximately 2,000 3 million DOF 3D ABAQUS models have been completed to-date to assess the effects of these different parameters.

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

The 30' three-girder specimens were subcontracted to Central Texas Iron Works (CTIW) for fabrication. Shop drawings have been received, reviewed, and returned. It is anticipated that the specimens will start arriving at the University of Kansas for testing in February, 2011.

Casting of concrete deck slabs for the test bridges is complete (Fig. 1). Five panels will be attached to the top flanges of the three girders using tensioned bolts through holes in the slab and girder flanges to create composite action. Concrete supports for the girder ends are under fabrication, and steel bearing supports have been designed.

Six load cells have been fabricated of steel, and are currently being outfitted with strain gages to measure load under each girder end (Figs. 2 and 3). Each load cell will be placed under a girder support to measure the force reaction at the support. This will allow the project team to assess load distribution in the bridge as testing progresses, and may aid in crack detection and propagation.

Fig. 1. Cast concrete deck slabs for the 30' bridge specimens

Fig. 2. Strain-gaging steel load cells for the 30' bridge test set-up

Fig. 3. As-fabricated load cells for the 30' bridge test set-up

3. 9' Girder Specimens

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*".

Fourteen 9' long girder specimens with approximately the same cross-section as the 30' specimens were fabricated by Builders Steel in Kansas City, MO, and have been received at the University of Kansas Structures Testing Lab. It is anticipated that each specimen can be tested in fatigue twice since there are two web gaps per specimen, by reversing orientation of the girder after an initial test. The first test set-up is complete, and testing is expected to commence within a week of publishing this progress report. One of the flanges of the test girder is rigidly restrained though bolts to the floor of the laboratory, representing the flange of a bridge girder that is made composite with a concrete deck. The other flange is unrestrained, representing the bottom flange of a girder in positive bending. A cross-frame is attached to the connection stiffener on the web of the girder, and is vertically loaded by an actuator at the other end of the cross-frame (Fig. 4). The actuator will pull upwards on the cross-frame, simulating the behavior that occurs in a bridge system when one adjacent girder moves downward relative to another girder attached via a cross-frame element. The test set-up is shown in Figs. 5 and 6.

There are two main focuses in the 9' specimen test program: (1) To determine the effectiveness of a bolt and plate washer installed in crack-stop holes in extending the distortion-induced fatigue life of the crack-stop hole retrofit, and (2) To develop the efficacy of CFRP materials in slowing or halting propagation of distortion-induced fatigue cracks once developed. Finite element models are being developed to guide placement and geometry of the CFRP material, as well as maximizing the efficacy of the bolted repair.

There is a significant advantage to examining parameters of the CFRP and bolt-and-plate washer repairs on 9' specimens before they are applied to 30' specimens, as there is economy of scale in the 9' specimen testing. It is anticipated that while some of the results for the 9' specimen testing will be of separate interest from the scope of TPF5-(189), many of the results for these two new studies may help to guide the progression of the 30' specimen testing. The 9' specimen test set-up has been designed such that it can run concurrently with the 30' specimen test set-up.

Detailed 3D finite element analyses are being performed using ABAQUS v6.9 to aid in this investigation. Progress thus far has included completion of the model geometry, including the tie-down system to the floor, all bolted connections, and inclusion of a pre-existing crack in the web gap region (Fig. 7). A series of models is being performed to investigate stress fields with differently sized cracks and crack-stop holes. Effectiveness of the addition of bolts and plate washer on reducing stress fields will be modeled in the coming project quarter. A screenshots showing the crack opening under distortion-induced fatigue is presented in Fig. 8, and a view of the web gap region is shown in Fig. 9.

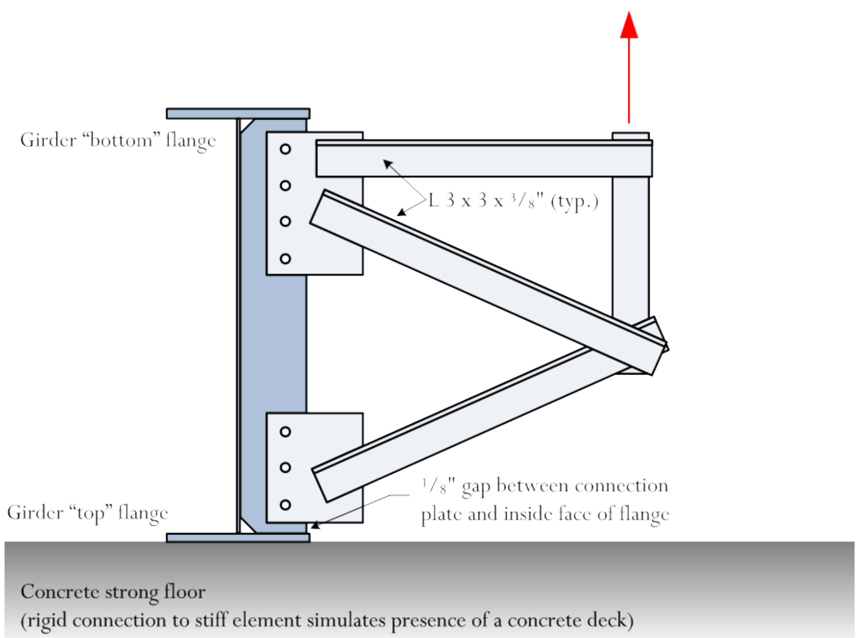

Fig. 4. Cross-section chematic of the test set-up for the 9' girder specimens

Fig. 5. Side view of the 9' test specimens


Fig. 6. Overall view of the test set-up for the 9' specimens

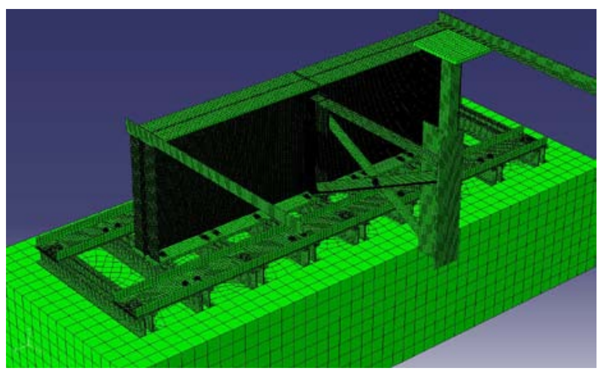
Fig. 7. Overall view of the finite element model for the 9' specimens

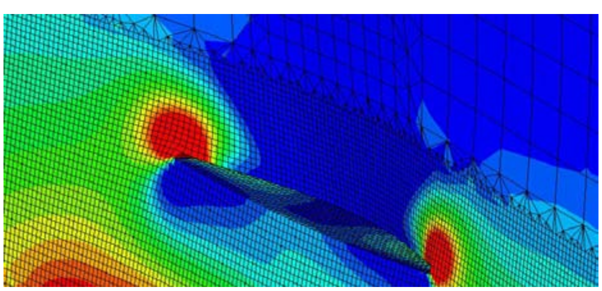
Fig. 8. View of the back of the web, showing the crack opening under distortion-induced fatigue

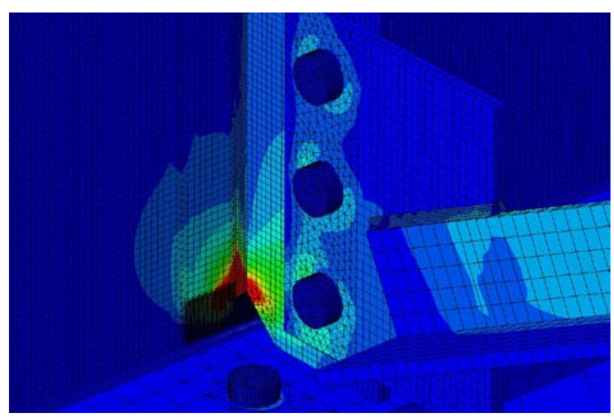
Fig. 9. Close-up of the web gap region displaying the distribution of maximum principal stresses

4. Component Level Testing

PICK-Tool Development and Testing Program

Testing has continued on component-level 1/8" and 1/4"thick specimens. Testing of control specimens and some treated specimens were reported during the last period, and further testing consisted of additional 1/8" treated specimens and 1/4" control specimens. It is hypothesized that treatment by the PICK tool increases the fatigue properties by inducing compressive residual stresses, strain-hardening the material, and reducing the grain size by inducing large static and dynamic pressures. To evaluate the efficiency of these modes, four additional specimens were treated with static pressure only while others were treated both statically and dynamically. Preliminary results from fatigue tests of these specimens seem to indicate an increase in fatigue life with static pressure treatment only, and a further increase in fatigue life with both static and dynamic treatment, as shown in the S-N diagram presented in Fig. 10.

A qualitative comparison of the results from static-only and dynamic-plus-static treatment was obtained by coating the area in the vicinity of the hole with a brittle coating. Stress Coat ST-70F was used as the brittle coating. A circle template was used to gage the approximate extent of the plastic region. The static-pressure-only shows that the plastic region extended to 19/64 in. (0.297-in). The statically plus dynamically treated specimens showed a plastic extent of about 3/8 in. (0.375-in), a 25 % increase in the radial extent of the plastic region. Brittle coating observations (Figs. 11-13) from the treated specimens qualitatively support the results shown on the S-N diagram.

Additional work is planned to identify the important aspects of the PICK tool treatment which contribute to the fatigue life improvement demonstrated through fatigue testing. It is hypothesized that these aspects are the tangential compressive residual stress, strain hardening which increases the yield strength, and changes in grain size and shape. Several techniques have been chosen to quantify each of these aspects. Extremely fine strain gages will be used to measure PICK tool performance as well as well as initial tangential tensile stress and final tangential residual compressive stress. Metallographic analyses consisting of micro-hardness traverses and grain size analysis are currently being performed to explore the work hardening and changes in grain size and shape. Finally, it is hoped that tangential compressive residual stress will be measured with neutron diffraction and matched against that measured with strain gages or modified Sach's boring method. If metallographic analyses are not conclusive, changes in grain size and shape will be explored with a Scanning Electron Microscope.

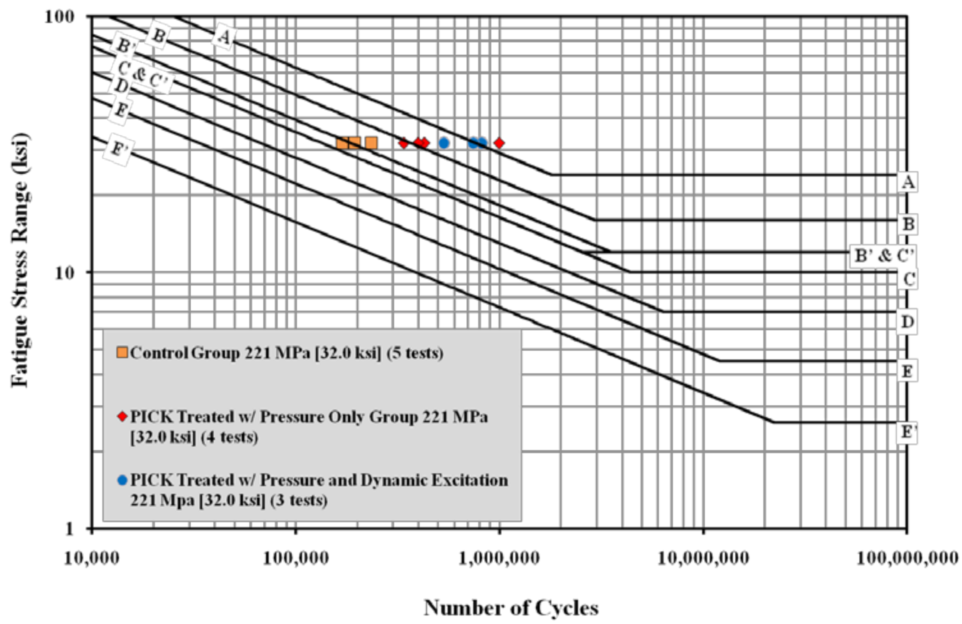

Fig. 10. S-N diagram showing results for untreated, static pressure-treated, and statically and dynamically treated specimens. All specimens were fatigue tested at 32 ksi, and data points refer to crack initiation.

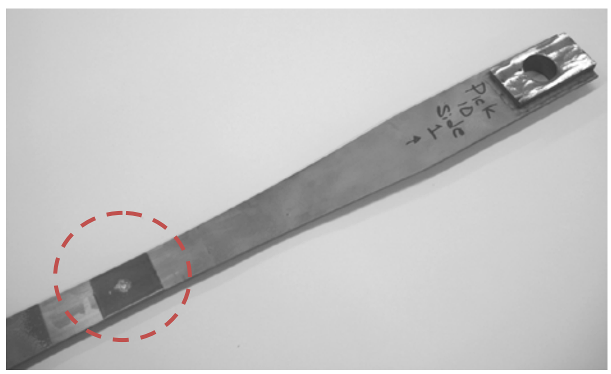

Fig. 11. View of the specimen with brittle coating applied around hole (circled region)

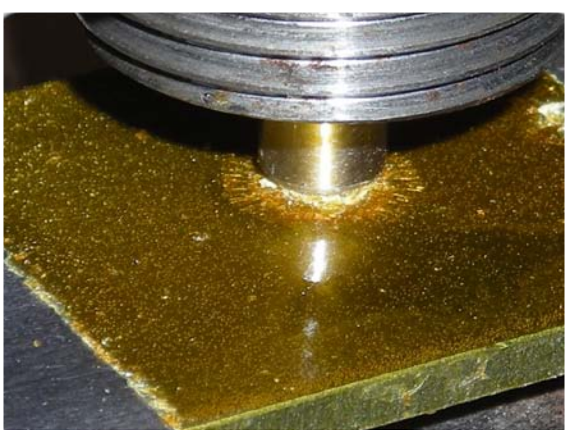

Fig. 12. Close view of the brittle coating undergoing cracking while the PICK tool is tightened in preparation for operation

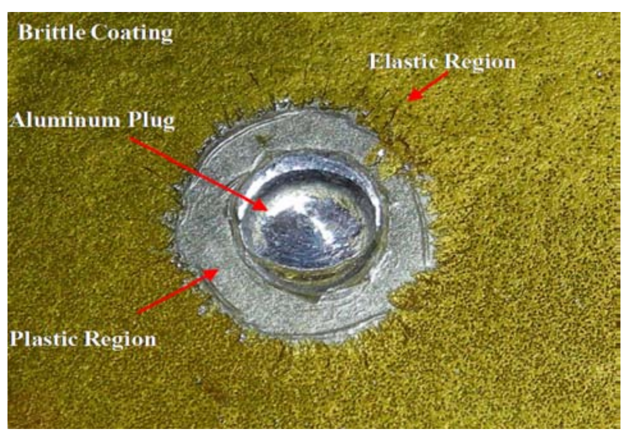

Fig. 13. Close view of the PICK-treated hole with brittle coating flaked-off in region of plasticity

CFRP-Treated Specimens

The project team has explored two research thrusts aimed at examining the effectiveness of CFRP as a fatigue-retrofit technique: (1) CFRP doublers tested in three-point bending on coverplate details, and (2) Flat CFRP doublers applied to pre-cracked tensile fatigue specimens. Results to-date of both of these research areas 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.

CFRP Doublers Used on Coverplate Details

Experimental tests and analytical simulations were carried out to investigate the fatigue performance of coverplate specimens in which the welded connections were reinforced with carbon fiber reinforced polymer (CFRP) overlays. Specimens were loaded in three-point bending induced by a cyclic load to evaluate the change in fatigue-crack initiation life of the welded connections caused by the attachment of the CFRP overlays.

Test results showed that when bond between the CFRP overlays and the steel was maintained, the reduction in stress demand was sufficient to extend the fatigue life of the welded connections from AASHTO fatigue category E in the unreinforced configuration to the infinite fatigue life range. Test results also showed that the fatigue strength of the bond layer was drastically improved by introducing breather cloth material (polyester fibers) within the bond layer.

The research focused on examining the effectiveness of various configurations of CFRP overlays, and comparing their performance to other methods of fatigue retrofitting, including ultrasonic impact treatment and weld grinding. Two types of CFRP overlays have been considered: those made using conventional lay-up techniques, and those created using a spray-on method (chopped fiber overlays). Parameters influencing the performance of the overlays were provided significant attention, such as geometric properties of the overlay, modulus of elasticity of the CFRP, thickness of the resin layer used to attach the CFRP overlay to the steel surface, and the presence of an unbonded region (gap) in the direct vicinity of the weld. Finally, fatigue life of the bond layer between the CFRP overlays and the substrate was closely differentiated from the fatigue life of the retrofitted steel specimens.

Pre-Cracked Tensile Fatigue Specimens Treated with CFRP

A total of five specimens with pre-existing fatigue cracks have been tested under cyclic loading to evaluate the performance of composite overlays to repair fatigue damage in steel structures (Fig. 14). Three of the specimens were repaired with Carbon Fiber Reinforced Polymer (CFRP) overlays. Two of these three specimens were repaired using multi-layered overlays prefabricated using CFRP plies, while overlays in the third specimen were fabricated using a spray fiber system. The remaining two specimens were used as control specimens.

The composite overlays were removed for inspection and re-attached every million cycles to track fatigue-crack propagation. It was found that specimens repaired with composite overlays had fatigue crack propagation lives each exceeding 3 million cycles, while the observed propagation life of untreated specimens was below 60,000 cycles. Results from a suite of Finite Element Analyses showed that the peak stress demand was reduced by approximately 80% with the addition of composite overlays when compared to untreated specimens, which was consistent with the observed change in fatigue-crack propagation life in the experiments.

Additional specimens are being tested as part of this research thrust. Thickness of the doubler plates is being varied, as well as the thickness of the steel.

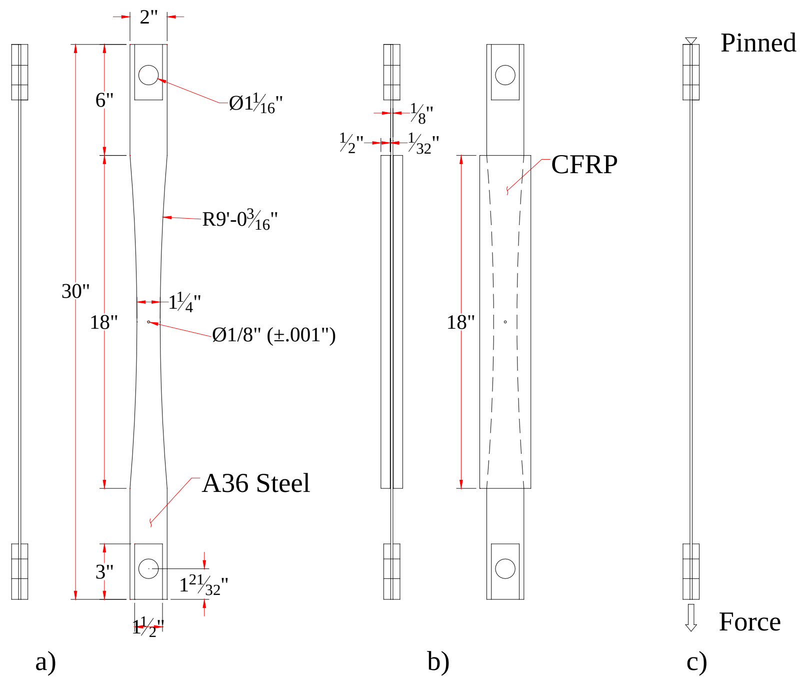

Fig. 14. Schematic of the tensile fatigue specimens outfitted with CFRP doublers

5. Analytical Investigation

A finite element study concerning the effects of skew, load placement, and cross frame stiffness has continued with strong progress over the reporting period; approximately 2,000 3 million DOF 3D ABAQUS models have been completed to-date to assess the effects of these different parameters.

The finite element models being used in parametric analysis were refined to include additional details and improve the quality of results. Welds have been added both between the girder flanges and webs and the between the connection plates and girder webs. Additional load configurations have been analyzed which include fatigue truck placement to induce maximum positive moment and maximum negative moment in a single bridge girder.

Sub-models were created to guide the selection of cross-frame members and connecting elements. The results of sub-modeling were implemented in the parametric analysis bridge models to generate a more comprehensive understanding of bridge geometry effects on distortion-induced fatigue. Bridge geometry, specifically girder spacing and skew angle, directly determined the length of the cross frames. As cross frames become longer, their stiffness decreases if the same bracing member cross sections are used. In the same way, as the braces become skewed and bent plates are used to connect the cross frames to the girder webs, the cross frame stiffness is reduced (Fig. 15). In many previous studies the change in cross frame length and stiffness due to changed bridge geometry has been neglected, though it plays significant role in the magnitude of web gap stresses generated and the load distribution in the bridge. Therefore, sub-models were created with the objective of understanding cross frame stiffness to create models with either constant cross frame stiffness with varied bridge geometry or varied cross frame stiffness with constant bridge geometry. Isolating this parameter will produce a more precise parametric analysis.

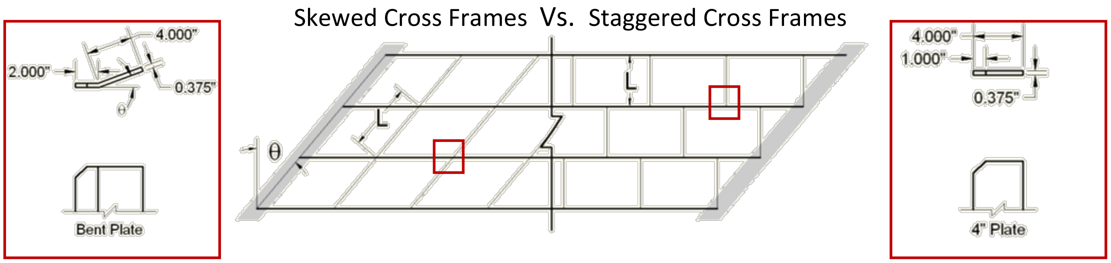

Fig. 15. Cross-frame layouts and connection stiffener geometries for bridge analyses

A series of influence surfaces of web gap stresses was generated to correlate load placement on the deck with the location and magnitude of maximum web-gap stresses in a bridge. A baseline no-skew bridge was investigated, along with a 40 deg skewed bridge (both staggered cross-frame orientation and parallel-to-skew cross-frame orientation were investigated). Understanding the relationship between load placement and web-gap stresses aided in the determination of fatigue truck placement in the parametric analyses.

6. Upcoming Tasks

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

30' Three-Girder Specimens:

- Specimens are expected to start arriving at the KU Structures Testing Laboratory,
- Supports will be cast; steel bearings will be fabricated for the girder ends,
- Test set-up will be completed for the first bridge.

9' Girder Specimens:

- Fatigue Testing of the 9' girders will begin
- Finite element analyses will continue

Component-Level Studies:

- Treatment and testing of ¼" thick PICK-treated specimens will continue,
- Metallurgical analyses of PICK-treated specimens will be completed,
- 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.

Analytical Investigation:

- It is expected that the analytical investigation concerning the effects of skew, cross-frame placement, and load placement will be completed.

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 is anticipated that this TPF5-(189) project meeting will be scheduled for late spring, 2011.***

7. Conclusion

TPF5-(189) has posted strong progress this reporting period. The 30' three-girder bridge assemblages are currently under fabrication, and are expected in February, 2011. Fourteen 9' girder lengths were received, and the test set-up is complete to start fatigue testing those specimens. Component-level testing is progressing well, and a significant parametric analysis of bridge geometry effects on distortion-induced fatigue is close to completion.

8. 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.

- 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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