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 # *TPF-5(189)*	**Transportation Pooled Fund Program - Report Period:** ☐Quarter 1 (January 1 – March 31) ☐Quarter 2 (April 1 – June 30) ☐Quarter 3 (July 1 – September 30) X 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 #):** **KAN00063732**	**Project Start Date:** 08/31/2008
Original Project End Date: **08/31/2011**	**Current Project End Date:** **08/31/2013**	**Number of Extensions:** **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
$1,060,000.00	$968,688.67	90%

Quarterly Project Statistics:

Total Project Expenses	Total Amount of Funds	Percentage of Work Completed

This Quarter	Expended This Quarter	This Quarter
$25,454.72	$25,454.72	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
Weekly research group meetings have continued to take place this quarter.

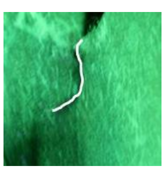
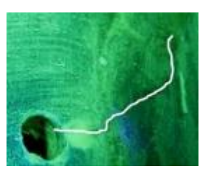
Contract Status
The contract is in-force, and operating on an end date of August 31, 2013.

Technical Updates

1. 30 ft. Three-Girder Specimen

Experimentally, four trials have been performed on the 30 ft. bridge specimen. Trial 5 is currently underway in the laboratory. Figures of crack growth can be seen in the images provided in Tables 1 and 2. Table 1 depicts cracking patterns in the North Girder, and Table 2 depicts cracking patterns in the South Girder. A summary of the cracking patterns resulting during the various trials is provided following Tables 1 (North Girder) and 2 (South Girder).

Table 1: Cracking patterns for Trials 1 – 4 for the *North Girder*

	Trial 1	Trial 2	Trial 3	Trial 4
Interior, North Girder, Left Side			 	

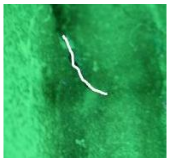
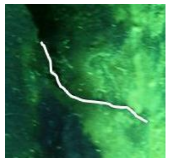
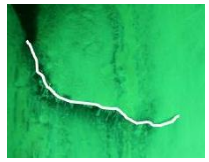
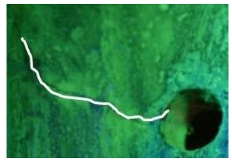
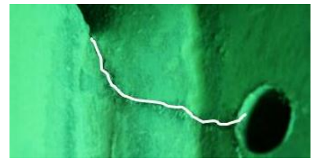
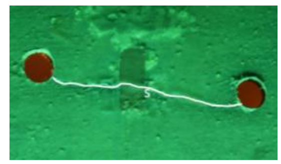
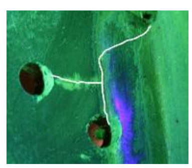
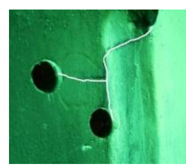
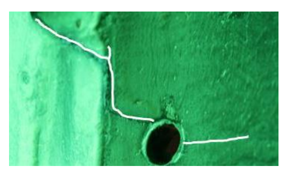
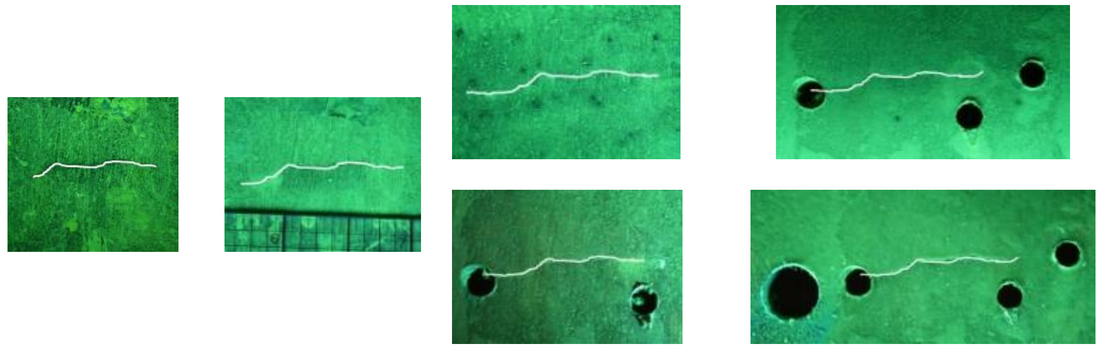
Interior, North Girder, Right Side			 	
Exterior, North Girder	N/A	N/A	N/A	

Table 2: Cracking patterns for Trials 1 – 4 for the *South* Girder

	Trial 1	Trial 2	Trial 3	Trial 4
Interior, South Girder, Left Side			 	
Interior, South Girder, Right Side			 	 

Exterior, South Girder



Trial 1

Trial 1 consisted of the unretrofitted bridge subjected to cyclic loading between 6 - 60 kips. Cracking was first noticed at 20,000 cycles. These were allowed to continue propagating until 150,000 cycles was reached. At this point, the longest crack in the bridge was 1-in. long.

Trial 2

After cracking reached 1 in., the double angle and back plate retrofit was applied to the bridge in the top web gaps of both the North and South exterior girders, as shown in Figures 1-3. It should be noted that crack-arrest holes were not drilled at the tips of the cracks in this test trial, to produce the most demanding test for the retrofit.

Figure 1. View of double angles and backing plate retrofit on interior face of an exterior girder.

Figure 2. View of double angles and backing plate retrofit on interior face of an exterior girder.

Figure 3. View of double angles and backing plate retrofit on exterior face of an exterior girder (backing plate shown)

After the bridge was subjected to 1.2 million cycles cycling between 6 - 60 kips in the retrofitted condition, the retrofit was removed and the bridge was inspected for cracking. No crack growth was noted on the interior face of the south girder;

however, the through-thickness crack grew $^3/_8$ in. Some crack growth was also noted in the cracks on the interior face of the north girder. On the left side of the stiffener, cracking extended from $^5/_{16}$ in. to $^{11}/_{16}$ in., while on the right side of the stiffener, cracks grew from $^3/_8$ in. to $^3/_4$ in.

Trial 3

In Trial 3, the same double angles and backing plate retrofit was applied to the north and south girders, however, the cyclic loading was increased to 8 - 80 kip. It should be noted that, again, crack-arrest holes were not drilled at the crack tips, in an attempt to create a very demanding test of the retrofit. Once the retrofit was removed, cracks were inspected, and it was found that the crack lengths had modestly increased. On the south girder, spider cracking on the stiffener left side increased by $^1/_4$ in. and the increase in the through-thickness crack was found to be $^3/_{16}$ in. Spider crack growth seen on the left side of the stiffener was found to be $^7/_{16}$ in., while the right side of the stiffener experienced $^1/_4$ in. crack growth.

Trial 4

Since additional crack growth occurred in Trial 3, $^1/_4$-in. dia. crack-arrest holes were drilled at the crack tips to smooth out the sharp cracks. In Trial 4, cycling was induced between 10 - 100 kip. The crack-arrest hole diameter was intentionally kept small so as to maintain demanding test parameters.

At approximately 650,000 cycles, a faint clicking noise was noticed coming from the connection stiffener in the north girder. After inspection, no change in bridge response was noticed. While under inspection at 1.061 million cycles, the cross frame between the north and center girders was found to be cracked through the depth of the connection tab plate, as seen in the following images. It appears that the crack started at the bottom corner of the weld toe where the angle framed into the tab plate.

Figure 4. View of crack in the cross frame table plate before removal of the cross frame

Figure 5. View of cracked tab plate after cross frame removal

After inspection of the web gap regions, it was noticed that the north girder through-crack developed between the two drilled crack stop holes. On the south girder, minimal crack growth was seen in the through web crack while the spider crack on the right side of the south girder grew through the ¼-in. dia. crack-arrest hole and $^7/_{16}$-in. beyond the hole. At the tip of this extended crack, a ½-in. dia. hole was drilled for the start of the next trial (Trial 5).

Three points are worth noting regarding Trial 4:

(1) While cracking did propagate during this test, the load demand was quite severe. Additionally, the crack-arrest holes were much smaller than is commonly used the field, and were purposefully installed as such to create a demanding test.
(2) Only minimal crack propagation was sustained within the top web gap regions, and a significant crack was produced in the connection between a cross frame member and tab plate. This indicates that the location most susceptible to cracking was *shifted* from the sensitive web gap regions to a detail that is generally not highly susceptible to fatigue cracking. This finding indicates that a high level of protection was provided to the web gap regions.
(3) Because the cross frame tab plate cracked through, uneven load distribution occurred in the web gap regions.

Therefore, the south girder likely experienced much higher stress ranges than would have been induced had the north cross frame been undamaged. Because of this, crack growth in the south girder should not be taken as indicative of the 10 – 100 kip load range.

Following discovery of the damaged cross frame, the cracked cross frame was removed from the bridge and repaired. The repaired cross frame was exchanged with an undamaged cross frame from the end support region of the bridge. Trial 4 was halted, due to the fact that load redistribution occurred when the cross frame cracked. Therefore, Trial 4 is not considered to be a controlled test of the retrofit's effectiveness, in that the retrofits in the North and South girder likely experienced varying and unequal stress levels; however, Trial 4 still has merit in that it showed that the retrofit was capable of shifting the "fragile" location in the bridge to a region outside the web gap region.

2. 9 ft. Girder Specimens

Testing has continued on Specimens 3 and 4, both of which have been previously subjected to multiple test trials.

Specimen 3

This quarter, Specimen 3 was retrofitted with a steel-CFRP sandwich composite. Specimen 3 had a crack extending 14-in. into the web, and a 21.5-in. long crack between the flange and web at the onset of testing. Therefore, this specimen was severely distressed and posed a significant demand for a retrofit. CFRP fabric, 1/16-in thick, was applied to the interior and exterior sides of the girder as shown in Figures 6-8. The CFRP bridged the vertical cracking between the stiffener and the girder web. After the CFRP was in place (bonded to the specimen with West 105 resin), two 19-in. long steel angles were placed between the interior face of the web and the connection stiffener, and a 24"x24"x$^{1}/_{2}$" steel backing plate was placed over the CFRP on the fascia side of the girder. The CFRP was allowed to cure under the applied steel elements.

The specimen was subjected to fatigue for 1.2 million cycles at a load range of 0.1 - 5.7 kips, after which, the retrofit was removed and cracks inspected. No crack growth was noted.

Figure 6. View of the steel-CFRP sandwich retrofit applied to Specimen 3 (interior face of girder; left side of connection stiffener) – steel angle has been removed from the CFRP in this view

Figure 7. View of the steel-CFRP sandwich retrofit applied to Specimen 3 (interior face of girder; right side of connection stiffener) – steel angle has been removed from the CFRP in this view

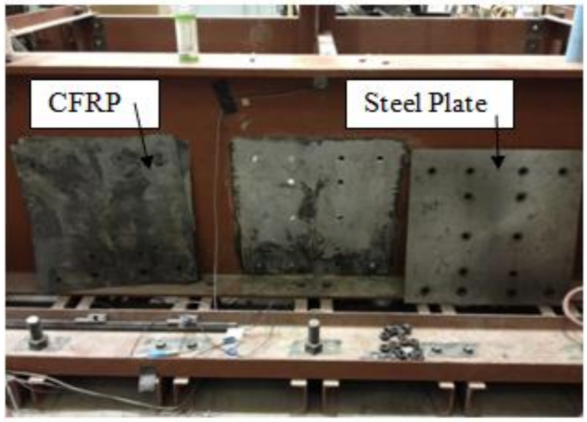


Figure 8. View of the steel-CFRP sandwich retrofit after both the steel and CFRP components of the repair have been removed from Specimen 3 (fascia side of girder)

Specimen 4

Specimen 4 was fatigue tested with a load range of 1 - 3 kips with a series of small-diameter crack-arrest holes this quarter. The purpose of this particular test sequence has been to gain a greater understanding of crack-arrest hole performance under distortion-induced fatigue loading. To accomplish this, cracking was allowed to develop, and then very small crack-arrest holes were drilled ($^1/_4$-in. dia.). The specimen was then subjected to fatigue testing, and crack propagation was observed in the left vertical crack on the stiffener side (Figure 10), and in the flange-to-web weld crack (Figure 9). For those cracks that reinitiated at the crack-arrest holes, the cracks were allowed to propagate a small distance. Then, ½-in. dia. crack-arrest holes were drilled at the tips of the newly propagated cracks. Currently, Specimen 4 is being cycled again and monitored for crack reinitiation and propagation.

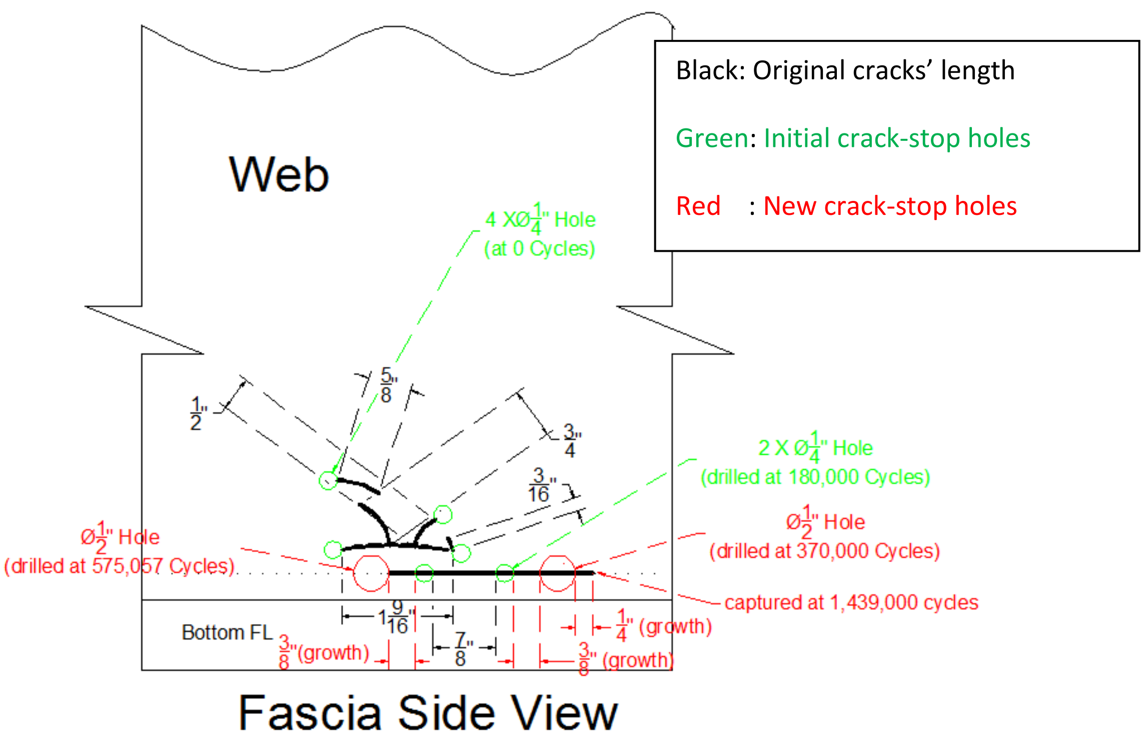


Figure 9. Schematic of crack-arrest holes on fascia side of Specimen 4

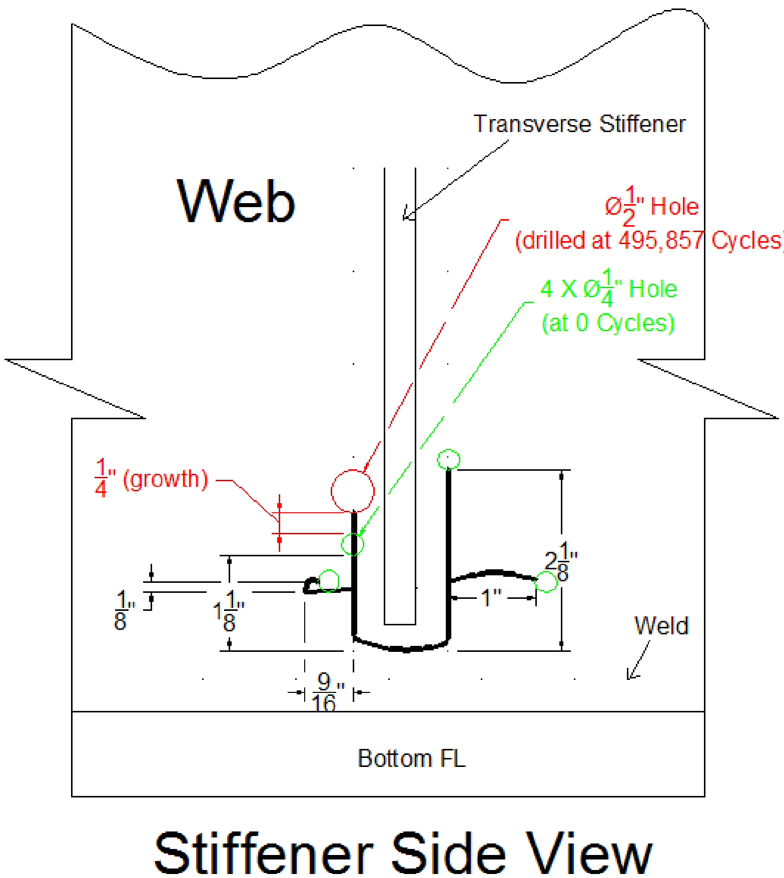


Figure 10. Schematic of crack-arrest holes on interior side of Specimen 4

Anticipated work next quarter:

- Fatigue testing will continue on the 30-ft bridge. Evaluation of the double angles with backing plate repair will be continued, and will include slightly larger ($^{1}/_{2}$-in. dia.) crack-arrest holes as necessitated. A finite element parametric analysis is being performed to investigate various retrofit configurations.
- Fatigue testing of Specimen 3 is complete. A new specimen (Specimen 5) will be installed in the test setup.
- Fatigue testing of Specimen 4 will continue, with the goal of better understanding the performance of crack-arrest holes in distortion-induced fatigue.

Significant Results:

The angles with backing plate retrofit is performing well under demanding fatigue loading in the 30-ft bridge setup. Some crack propagation has been noted while the retrofit is in place, however, it should be noted that the retrofit thus far has been applied over cracks that either had no crack-arrest holes, or very small crack-arrest holes (1/4-in. dia.). Testing taking place this quarter will include slightly larger crack-arrest holes (1/2-in. dia.) for the cracks that did reinitiate through the 1/4-in. dia. crack arrest holes. Additionally, a crack was found to have formed in a cross-frame tab plate, indicating that the angles with backing plate retrofit was capable of protecting the web gap to the extent that a significant crack was forced to a less sensitive region.

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.

Richardson, T., Alemdar, F., Bennett, C., Matamoros, A., and Rolfe, S. "Evaluation of the Performance of Retrofit Measures for Distortion-Induced Fatigue Using Finite Element Analysis," National Steel Bridge Alliance (NSBA) World Steel Bridge Symposium (WSBS) 2012 Proceedings, April 18-20, 2012.

Richardson, T., Alemdar, F., Bennett, C., Matamoros, A., and Rolfe, S. (2012). "Retrofit Measures for Distortion-Induced Fatigue," *Modern Steel Construction*, American Institute of Steel Construction (AISC), 52 (4), 32-34.

Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., and Rolfe, S. (2012). "Use of CFRP Overlays to Strengthen Welded Connections under Fatigue Loading," *Journal of Bridge Engineering*, American Society of Civil Engineers (ASCE), 17(3), 420-431.

Kaan, B*,* Alemdar, F., Bennett, C., Matamoros, A., Barrett-Gonzalez, R., and Rolfe, S. (2012). "Fatigue Enhancement of Welded Details in Steel Bridges Using CFRP Overlay Elements," *Journal of Composites for Construction*, American Society of Civil Engineers (ASCE), 16(2) 138-149.

Hassel, H., Bennett, C., Matamoros, A., and Rolfe, S. (2012). "Parametric Analysis of Cross-Frame Layout on Distortion-Induced Fatigue in Skewed Steel Bridges," Accepted for publication in the *Journal of Bridge Engineering*, American Society of Civil Engineers (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).