FATIGUE TECHNOLOGY

Repairing and Preserving Bridge Structure by Innovative Crack Arrest Repair System

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Repairing and Preserving Bridge Structure by Innovative Crack Arrest Repair System

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ABSTRACT

Cracking in steel bridges compromises structural integrity and is concern for continued safe operation. Drill stops at the end of the detectable crack are ineffective in retarding crack growth. An innovative aerospace-derived technique that radially expands a high interference bushing into the hole induces residual compressive stresses around the hole. Tests confirm its effectiveness in arresting crack growth in A36 bridge steel. Tests and field installations are discussed confirming effectiveness in bridge preservation programs and improving structural integrity.

INTRODUCTION

Cracking in steel bridges is one of the number one causes for concern in bridge maintenance and preservation programs. In most cases a temporary repair will be installed to allow continued operation of the bridge to minimize the impact on local commerce and transportation until the cracked member can be replaced or a more permanent repair can be engineered and installed. If the bridge is part of a national highway infrastructure, the impact of total or partial bridge closure can have significant ramifications. The most commonly employed method of retarding the growth of cracks involves drilling a crack arrest hole (CAH) or drill stop at the end of the detectable crack to blunt the crack tip and reduce the stress concentration of the crack. This repair method is often ineffective because the required size of the CAH based on material properties, can be impractically large and is compromised by access or the available drill bits. It is not uncommon for the crack to re-initiate on the other side of the hole resulting in a string of various sized crack arrest holes associated with failed attempts at arresting the same crack, as shown in Figure 1. Repeated crack inspections (and associated maintenance and protection of traffic, MPT) increase maintenance costs and continued growth of cracks can lead to structural failure and/or bridge closure.

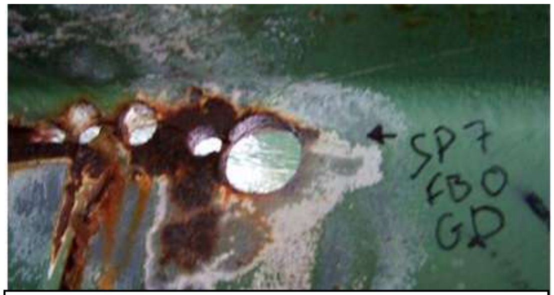


Figure 1. Photo of Multiple Attempts to Arrest a Crack

The effectiveness of a typical CAH can be further enhanced by installing interference fit bolts or fasteners in the hole to pre-load the area around the hole in tension, however, this method relies on the level of interference that can be attained and generally provides limited effectiveness. Surface treatment methods such as ultrasonic impact or shot peening around the hole have been shown to have little to no effect on retarding crack growth. It is also impossible to verify that the treatment has been applied correctly. The other method that has been effectively used by the aerospace and railroad industries is to induce a residual compressive stress around the hole by hole cold expansion. The split sleeve cold expansion method used by these industries for many years has been proven by test and in-service experience to enhance the fatigue life and damage tolerance of fastener and bolt holes. It is also applied to "stop drill" holes to retard the growth of cracks as a temporary structural repair method in aircraft structures. In this case, the addition of an interference fit pin or fastener into the cold expanded stop drill hole further improved the effectiveness in retarding crack growth.

A study reported in the Transportation Research Board Journal No 2200 [1] looked at inducing residual compressive stresses in bridge drill stops using a novel piezoelectric method. It showed potential for bridge applications to enhance the effectiveness of CAH in bridge steels; however its application on bridges for this purpose was not practical.

A practical solution that incorporates both beneficial induced residual compressive stresses and an effective high interference fastener was presented at the 2011 New York Bridge conference [2]. The method known as "StopCrackEX" was adapted from the aerospace industry. It utilizes an initially clearance fit bushing that is placed into the CAH which is then radially expanded using an expansion mandrel that is pulled through the inside diameter of the bushing as shown in the process depiction in Figure 2.

Figure 2. Schematic of the StopCrackEX Process

The synergistic radial expansion of the bushing yields the bushing as well as the steel surrounding the hole. The result is a high interference fit bushing in the hole and a zone of residual compressive hoop stress around the hole. The zone of the stress field is seen when viewed through a photoelastic coating in Figure 3. It extends about one diameter around the hole and all the way through the thickness. The magnitude of the residual stress adjacent to the edge of the hole is approximately equal to 2/3 of the tensile yield stress of the material. This induced residual compressive stress around the hole effectively shields the hole from the applied cyclic load and prevents further crack growth. In the following test program of large A36 steel coupons under typical cyclic bridge loading, not only did this expanded bushing method completely arrest the crack with a life improvement factor exceeding 60:1 over the conventional CAH, it also increased the load factor of the coupon by over 20%.

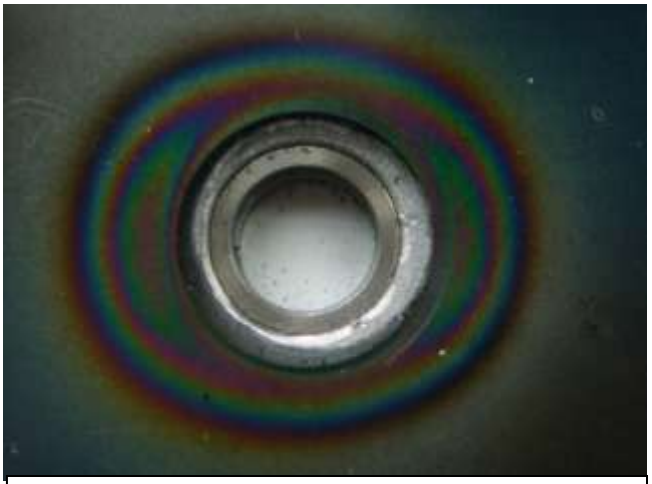


Figure 3. Induced Residual Compressive Stress Field around a StopCrackEX Bushing Viewed Through a Photoelastic Coating

Initial Test Overview

An independent test was conducted to investigate the effectiveness of the StopCrackEX process in stopping fatigue cracks in bridge steel. In the initial test, a total of seven typical "dogbone" specimens were machined from A36 steel (yield stress of 46.6 ksi and tensile strength of 70.1 ksi) with a small initial 0.015-inch EDM starter notch in order to promote the initiation and natural propagation of a fatigue crack. Specimen details are shown in Figure 4.

A naturally growing crack was then propagated to approximately 0.25 inch in length, measured from the edge of the specimen. Once the cracks were established, each specimen was repaired with either the StopCrackEX process or a typical CAH. Three samples were repaired using a conventional .50-inch CAH and 4 were repaired using the StopCrackEX process within the same .50-inch hole. After repair, each specimen was then cycled until a new crack was initiated and propagated to .150-inch on the other side of the CAH or StopCrackEX repair, or until 4 million cycles was reached, whichever was reached first.

An area that included the notch, crack, and repair area was polished to make it easier to visually monitor crack initiation and propagation with an optical microscope mounted on the test frame (see Figure 5). In each of the specimens, a crack was initiated and propagated to approximately 0.25 inch in length as measured from edge of the specimen.

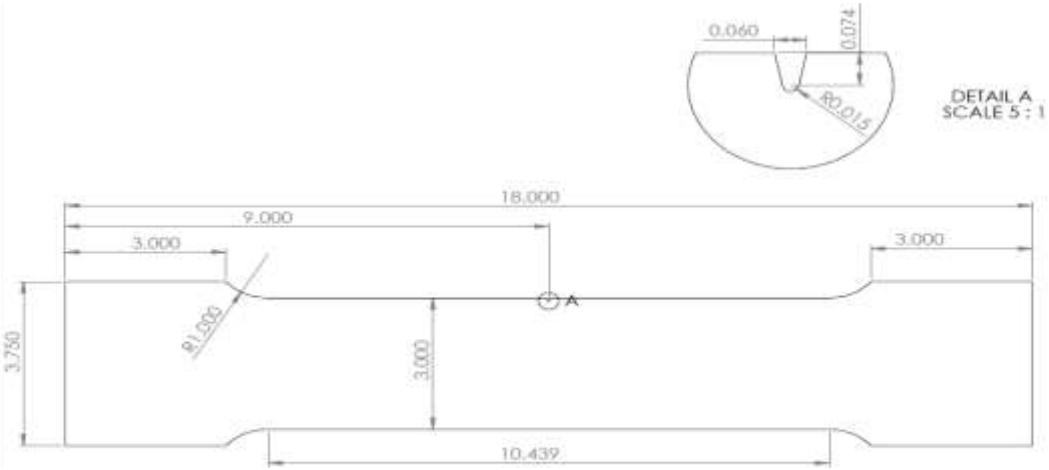


Figure 4. Machining Dimensions for the Test Specimens Showing the Initial Notch

Figure 5. MTS Test Machine Fitted with Hydraulic Grips and an Optical Microscope

The testing was done in two parts, pre-cracking and post-repair testing. Pre-cracking was performed at 10 Hz using constant amplitude sinusoidal loading at 25 ksi gross stress and a stress ratio of 0.05. Cracks were initiated and propagated to approximately 0.25 inch (including the notch) for each of the test specimens.

Repair

After pre-cracking, each of the seven specimens was repaired with either a typical 0.50-inch drill stop CAH or using the StopCrackEX process installing the bushing into the same diameter hole. The center of the hole was placed 0.630 inch from the specimen edge (Figure 6), which put the edge of the holes approximately 0.06 inch in front of the crack tip in each of the 7 specimens.

Figure 7 shows the CAH repair configuration and Figure 8 the StopCrackEX specimen with the bushing installed. The StopCrackEX bushings were installed by FTI technicians.

Figure 7. Picture of a CAH Repaired Crack

Figure 8. Picture of a StopCrackEX Repaired Crack

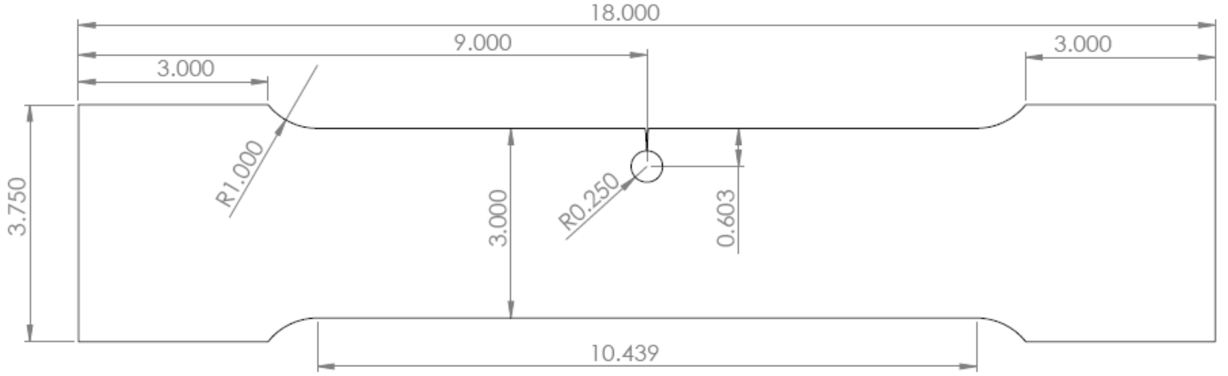


Figure 6. Test Specimen with the Repair Hole Location

Post Repair Observations

After repair, the objective was to determine the number of cycles to crack through to the edge of the hole and then to reinitiate and propagate a crack approximately 0.150 inch on the other side of the hole. If a crack did not initiate within 4 million cycles the test was terminated. The cycle count for each event was observed and recorded in Table 1.

Additional Follow-on Testing

Specimen #7 was further cycled after the completion of the original test to see how many cycles it would take to initiate a 0.15-inch crack on the other side of the bushed hole. Testing was terminated at 20 million cycles with no evidence of a crack. This equates to greater than 65 times life improvement over the CAH configuration.

Table 1. Post-Repair Testing Results

Specimen	Retrofit Method	Crack length (inches)	Max Net Stress (ksi)	R	Cycles to break hole	Cycles to become a through crack	Cycles to reinitiate	Crack Length (inches)
1	StopCrackEX	0.29	20.5	0.05	580,000	1,700,000	4,000,000	No crack
2	StopCrackEX	0.285	20.5	0.05	250,200	300,000	4,000,000	No crack
3	CAH	0.298	20.5	0.05	15,600	17,500	230,000	0.145
4	CAH	0.264	20.5	0.05	5,868	7,000	440,000	0.149
5	StopCrackEX	0.265	20.5	0.05	700,000	4,000,000	4,000,000	No crack
6	CAH	0.265	20.5	0.05	4,165	6,000	250,000	0.14
7	StopCrackEX	0.262	20.5	0.05	210,000	3,700,000	4,000,000	No crack

The average cycle count required to grow the crack to the hole and break into the hole was 8,544 cycles for the CAH and 435,050 for the StopCrackEX process. The average cycle count for the CAH to reinitiate a crack on the other side of the hole was 306,667 cycles. An example of one of the CAH specimens is shown in Figure 9. None of the StopCrackEX processed specimens initiated a crack in the bushing or anywhere else around the circumference of the hole and, consequently, the tests were all stopped at 4 million cycles. A summary of these results is shown in Figure 10.

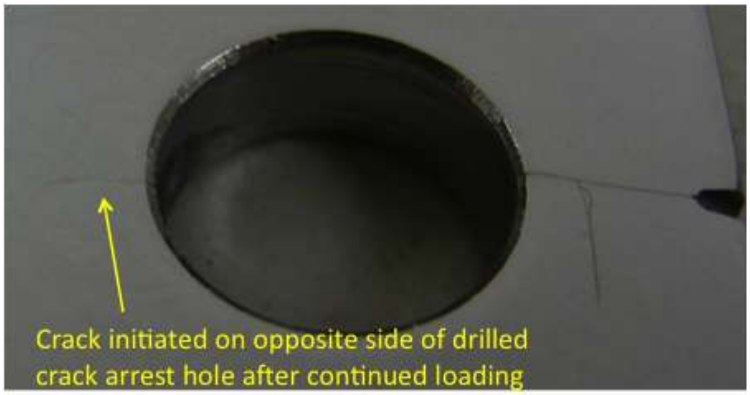


Figure 9. New Crack That Initiated After Being Drilled with a Crack Arrest Hole

Specimen #1 was reloaded in the test frame and cycled at progressively increasing load (stress level) to see what the load improvement factor would be with the StopCrackEX repair installed. It was cycled at 2 ksi increase (22.5 ksi) for a further 2 million cycles with no evidence of crack initiation, then a further 2 ksi (24.5 ksi) for 2 million cycles more and again no crack initiation. Finally after an additional 2 ksi to 26.5 ksi, it failed after a further 381, 835 cycles. This equates to a 20% minimum load improvement factor. The significance for bridge preservation is that even with an unanticipated load increase the StopCrackEX repaired hole would not require more frequent inspections or additional reinforcing repair/ maintenance.

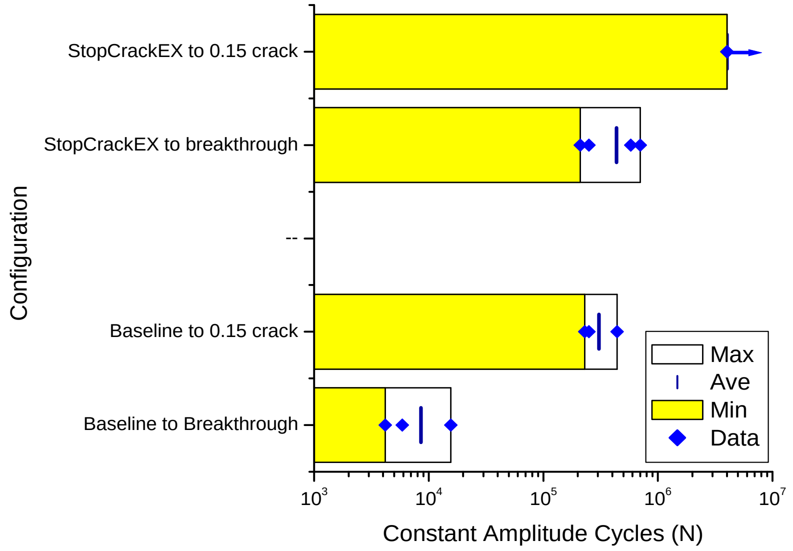


Figure 10. Summary of the Test Results

Second Coupon Test Program

One of the more prevalent cracks on bridges occurs along the weld associated with the attaching flanges of beams. The cracks run along the weld as shown in Figure 11. Drill stopping these cracks involves drilling a 1.0-inch diameter hole at the end of the crack as shown in Figure 12. This hole is difficult to drill as it cuts into the hard weld material, can compromise the welded joint locally and has been shown to be ineffective in stopping many cracks of this nature. In dealing with one of the Department of Transportation districts, FTI was asked to evaluate the effectiveness of StopCrackEX when drilled at a tangent to the crack path and not into the weld. A test plan was derived to examine the effectiveness of this configuration.

Figure 12. Typical Crack Arrest Hole at End of Weld Crack

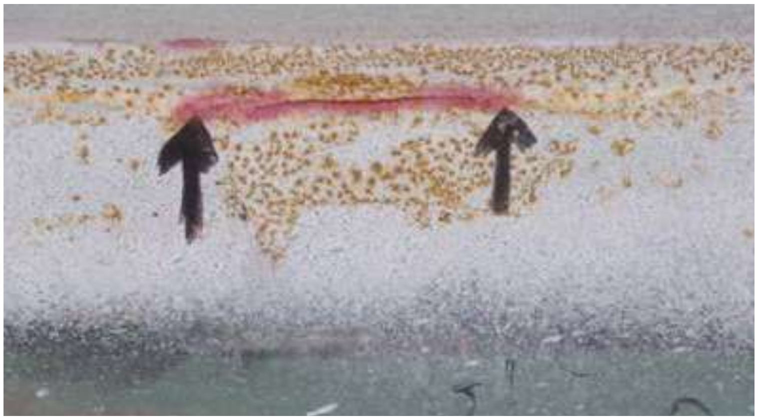


Figure 11. Typical Weldment Crack

Test Plan

A specimen was designed to simulate the welded flange configuration. A narrow slot was EDM machined into the coupon and a "flange" was welded adjacent to it. The coupon was cycled and naturally growing cracks were again propagated from each end of the slot. Three coupons were repaired with conventional drill stop holes as shown in Figure 13. They were again cycled and observed until cracks emanated from the opposite side of the CAH. This formed the baseline to compare the effectiveness of StopCrackEX in a further three coupons.

Figure 13. Simulated Welded Flange Coupon with Crack Arrest Holes at Each End of Crack

StopCrackEX was applied adjacent to the path of the crack, slightly ahead of the crack tip and away from the weld as shown in Figure 14. The coupons were again cycled and observed. In this case the crack continued to grow, albeit at a much slower rate, and then seemed to arrest for a long period before eventually breaking through into the hole and after sometime to reinitiate on the other side of the hole. Crack growth was again very rapid once the crack reinitiated on the other side of the hole. This was most likely caused by the fact that total crack length in the specimen had reached a critical crack length for the width of the coupon under the stress level tested resulting in fast fracture.

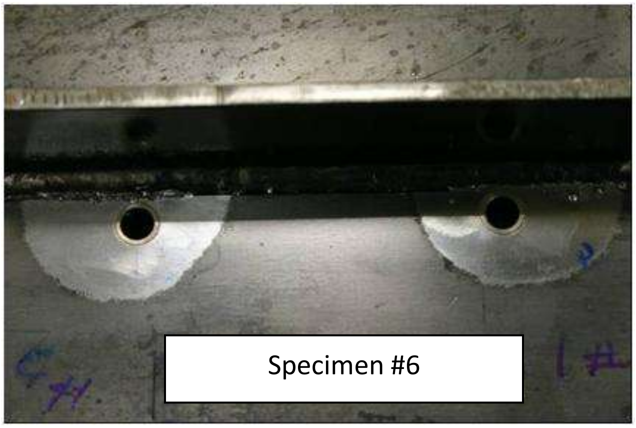
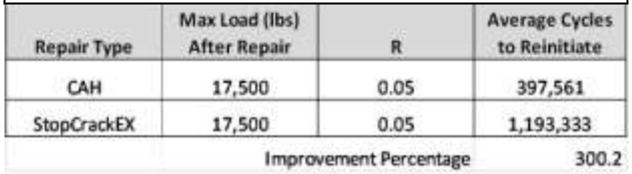


Figure 14. StopCrackEX Placed Adjacent to Crack Growth Path in Test Specimen

Table 2 summarizes the results of the coupon test program comparing the offset StopCrackEX to that of the same size CAH. The StopCrackEX method showed an average of at least three times the number of cycles to reinitiate a crack on the other side of the hole compared to the CAH configuration. Further evaluation and testing will be required to optimize the location of the StopCrackEX hole relative to the edge of the weld line, or crack growth path and the tip of the crack.

Table 2. Results of Test Program with Offset StopCrackEX



Repair Type	Max Load (lbs) After Repair	R	Average Cycles to Reinitiate
CAH	17,500	0.05	397,561
StopCrackEX	17,500	0.05	1,193,333
	Improvement Percentage		300.2

FIELD EVALUATIONS

A number of field evaluations are currently underway to evaluate StopCrackEX on actual bridges under in-service load conditions. These trials involve both configurations; at the end of a crack and adjacent to welds under flanges. There are two cases with the conventional crack in the web and the application just ahead of the crack tip. New Jersey DOT has three cracks they are monitoring on the Manahawkin Bridge. The second case is with the New York Dot and evaluation of a crack in a web on a bridge across the Delaware River. Figure 15 shows the crack and the post repair with StopCrackEX.

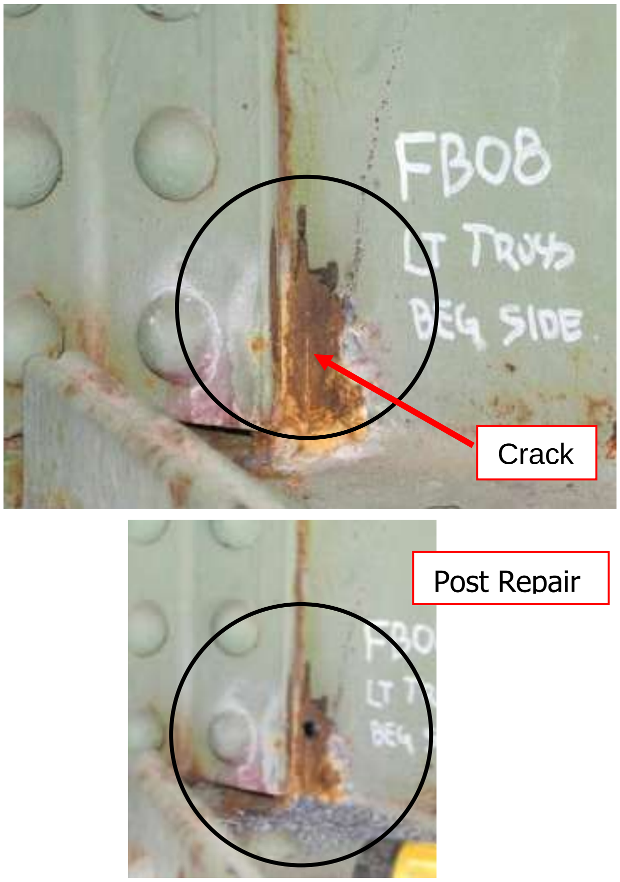


Figure 15. Web Crack Repair with NYDOT

In the trial application adjacent to the weld with the New Jersey Turnpike Authority (NJTA), six candidate cracks were identified and the standard drill stop hole was applied to one end of the crack and StopCrackEX at the other end. An example is shown in Figure 16. These repairs will be monitored over the coming year. It is interesting to note that installation of StopCrackEX took about one third of the time to drill the CAH because it had to be drilled through the hard weld material.

Figure 16. Typical Crack Arrest Hole at One End of Crack and StopCrackEX on the Other

SUMMARY

Until now conventional drill stops or crack arrest holes have been the industry accepted method of delaying crack growth by reducing the stress concentration at the crack tip. The reality is that cracks often re-initiate on the other side of the hole necessitating further rework, possibly a more extensive repair, and further ongoing inspection and monitoring to ensure continued safe operation of the bridge. These repeated crack inspections increase maintenance, operational and long term preservation costs with costly remobilization. Failure to arrest the crack can cause primary structural component failure and/or bridge closure.

Inducing residual compressive stresses around holes is an effective way to prolong crack growth. The compressive stress provides crack closure and reduces the stress amplitude around the hole which effectively retards fatigue crack propagation. StopCrackEX is a convenient and cost effective way to enhance conventional CAH by inducing residual compressive stress around the hole. Furthermore, the presence of the expanded bushing is a positive visual indication that the crack arresting procedure has been incorporated in a particular crack arresting hole.

The independent coupon test program confirmed the effectiveness of the StopCrackEX process when compared to conventional drill stops. Results showed at least a 12 times improvement in life when compared with the CAH and over 60 times life improvement in one coupon that was subsequently cycled to 20 million cycles with no evidence of a crack initiating on the other side of the bushed hole. Additional long term assurance is provided since the induced beneficial residual stresses facilitate operations at higher operating stress levels that will aid long term preservation of the structure. Ongoing testing is being conducted to measure the effectiveness of StopCrackEX in delaying propagation of cracks in the vicinity of weldments without compromising the integrity of the weld itself.

CONCLUSIONS

Conventional crack arrest holes are ineffective in arresting the growth of cracks on bridge structural members. Inducing beneficial residual compressive stresses around the CAH is a method, proven over many years of use in the aerospace industry, of extending fatigue and crack growth life of fatigue critical holes. Incorporation of StopCrackEX into CAH is shown by tests in bridge steel coupons to significantly increase the crack growth life and in fact provide possible terminating repair action by arresting further growth of cracks. When used in conjunction with bridge preservation and maintenance, StopCrackEX will provide significant cost savings to bridge owners by forestalling major repairs, extending repeat inspection intervals, and minimizing disruption to local infrastructure. It will enhance the overall structural integrity and safety of the bridge structure.

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