FATIGUE TECHNOLOGY

Mitigating Bridge Structural Fatigue Cracking Using Aerospace Derived Technology

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ABSTRACT

Fatigue cracking of structures is common to all metals subjected to cyclic tensile loads. Cracks in steel bridges are a regular occurrence and a growing concern in aging bridges. The most common mitigation method for fatigue cracking in bridge steel is to drill a crack arrest hole (CAH), commonly referred to as a "drill stop" at the end of the visible crack to reduce the stress concentration at the crack tip. Often, this is not sufficient to impede crack growth and the cracks then emanate from the drill hole and continue in the steel member. A technology developed for the aerospace industry mitigates hole cracking (in "drill stops" and in bolt holes) by using a hole cold expansion method. This process induces a compressive residual hoop stress around the hole to shield it from the effects of cyclic tensile loads applied in-service. A derivative of the Split Sleeve Cold Expansion method, pioneered by Fatigue Technology (FTI), cold expands an initially clearance fit bushing into a hole at a high interference level. When used in a CAH, the process known as "StopCrackEX" has been shown to retard or totally arrest cracks in common bridge steel.

This paper will review the cold expansion processes, describe the residual stresses induced, and show how they enhance the fatigue life of holes. It will also present independent comparative test data showing how StopCrackEX arrested the growth of cracks in fatigue test coupons when compared to the generally accepted CAH method.

INTRODUCTION

As of 2007, there were 599,766 bridges in the National Bridge Inventory (NBI) and approximately 32% of those bridges are either steel or continuous steel superstructures [1-4]. By 2020 the majority of these bridges will exceed 50 years of age. Most of these steel bridges are constructed from numerous individual steel members that are connected by some combination of bolts, rivets, and welds. The most common problems at these connections or joints are corrosion and cracking or a combination of the two.

Cracking at steel bridge joints are primarily the result of local material fatigue failure. The joints are subjected to variable cyclic loads as road transport or train rolling stock traverse the bridge. Over time cracks can initiate at points of high stress concentration such as holes, structural details, fillet radii in gussets, defects from welds or from corrosion pits. Depending on the applied load or stress, the frequency of the loading cycle and the magnitude of the stress concentration, these cracks will continue to grow over time. If a fatigue crack is allowed to grow and reach a critical crack length, fracture may occur resulting in structural failure of the member or collapse of the entire structure [5]. At a minimum, these cracks will compromise the integrity of the structure and/or jeopardize the safety of the people using the bridge. Furthermore, catastrophic failure of a bridge member will result in possible closure of the bridge and create major disruption to travel and local commerce infrastructure.

Retarding or arresting the growth of fatigue cracks will result in significant cost savings to the bridge industry and owners by preventing structural failure, minimizing the need to implement supplemental structural inspections, avoiding significant repair costs and possibly preventing bridge shut down to complete more permanent/temporary repairs. A commonly employed method in bridge maintenance and repair to slow down progression of these fatigue cracks is to crack arrest holes (CAH), also known as use drill stops. The objective is to reduce the stress concentration at the crack tip to slow the rate of crack propagation [6]. This method is often ineffective in the short term, particularly if the primary cause of cracking is left unaddressed, the crack tip is missed, or the load factor on the bridge remains high. This issue is not unique to the bridge industry. The aerospace industry suffers from the same metal fatigue issues and consequences. This paper describes a method derived from the aerospace industry to dramatically increase the effectiveness of these CAHs.

HOLE COLD EXPANSION METHODS

All metal structures subjected to cyclic tensile loads can develop cracks that will typically originate at a hole or point of high stress concentration. In aerospace, fastener holes are a main source of high stress concentration and are the sites for fatigue crack initiation. It has long been known that induced compressive residual stresses around holes, under the right circumstances, can be effective in extending the fatigue life of metal components [7-11]. As a result, hole cold expansion became the most widely used and cost effective method of controlling initiation of fatigue cracks and retarding the growth of cracks from defects in holes in aircraft structures [12]. The Split Sleeve Cold Expansion method, pioneered by Boeing and Fatigue Technology, improves the fatigue life of holes in metallic structure by generating a large, controllable zone of permanent residual compressive stress around the hole. The resultant compressive stress is formed as a result of plastic yielding of the material by mechanical expansion of the hole. This is accomplished by pulling an oversized expansion mandrel, pre-fitted with a lubricated split sleeve, through the hole locally yielding the surrounding material, see Figure 1. The subsequent elastic “springback” of the material lying beyond the plastically deformed hole creates the residual compressive stress field. A typical photoelastic fringe pattern and the resultant residual radial and circumferential stress generated by cold expansion are shown in Figure 2. These beneficial stresses effectively shield the hole from the cyclic tensile loads and can increase the fatigue life of the structure by more than 3 to 10 times [13].

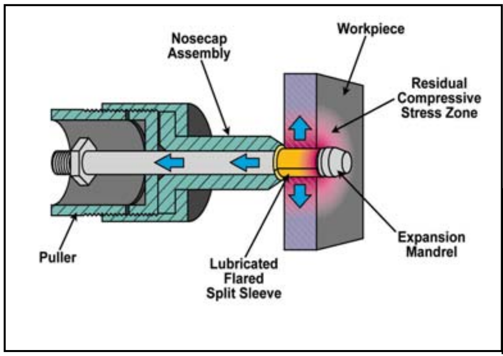

Figure 1. Split Sleeve Cold Expansion of a Hole Inducing Residual Compressive Stress

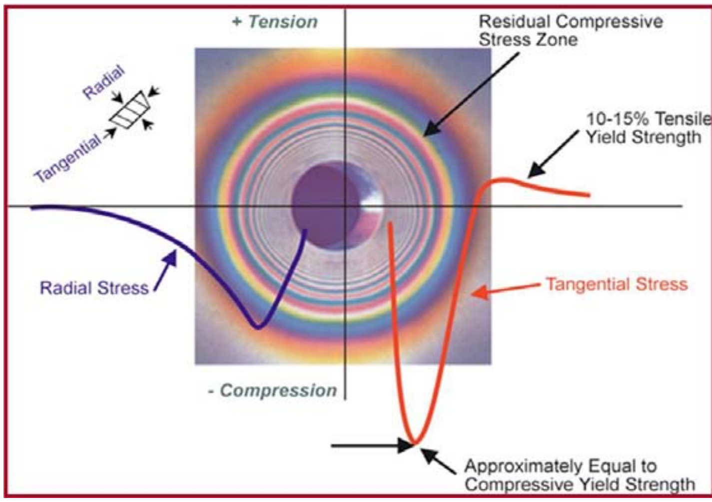

Figure 2. Residual Strain Pattern and Stress Distribution Around a Cold Expanded Hole As Viewed Through Photoelastic Material Bonded to Aluminum

Split sleeve cold expansion is equally effective in increasing the fatigue life of aerospace aluminum and titanium materials as it is in typical A36 bridge steels and railroad steels. Rail end bolt hole cracking in bolted rail track steel has been virtually eliminated by cold expanding the rail-end bolt holes [14]. Testing of single hole zero load transfer coupons, manufactured from A36 steel and subjected to axial fatigue loading, showed a 12:1 fatigue life improvement after cold expanding the hole compared to the baseline non-cold expanded hole coupons, as shown in Figure 3. Based on these results, the process was subsequently used by The California Department of Transportation (Caltrans) to shield fatigue critical fastener holes in bolted joints on an elevated truss bridge [15].

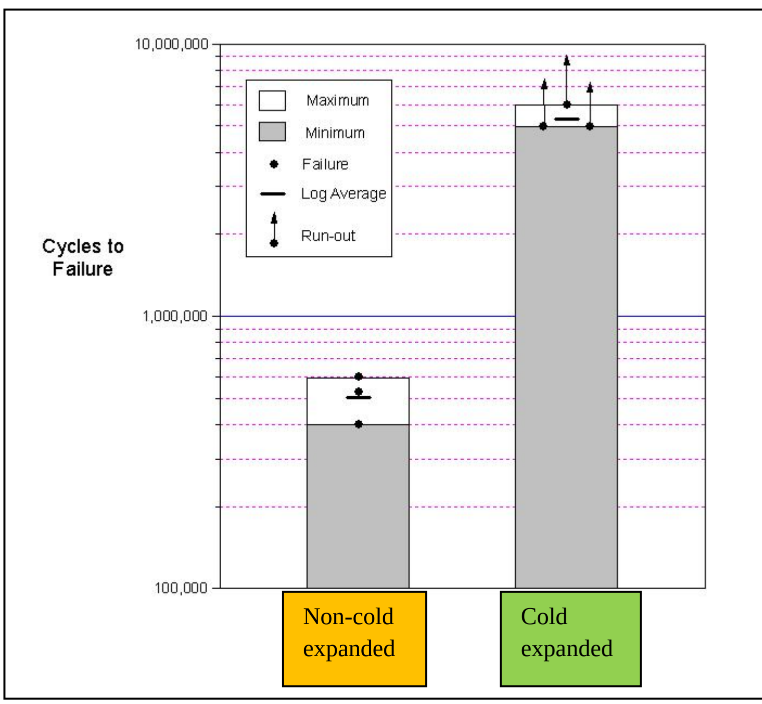

Figure 3. Constant Amplitude Fatigue Specimen: ZLT Dogbone Loading: 30 ksi net stress, R=+0.05 Environment: Ambient Lab Air

Derivative Cold Expansion Method

The ForceMate expanded bushing method, shown schematically in Figure 4, was developed to overcome many of the problems associated with "traditional" shrink or press fit bushing installations. It uses the principles developed to cold expand holes in metals to radially expand an initially clearance fit bushing into the hole at high interference fit and simultaneously impart beneficial residual compressive stresses around the hole.

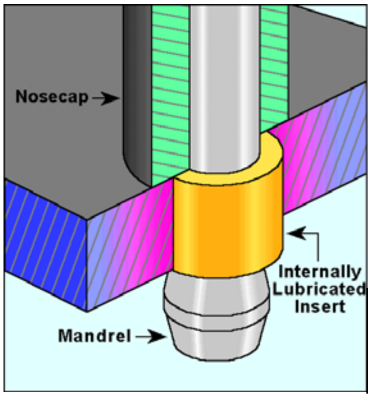

Figure 4. Schematic of the ForceMate Process

The ForceMate bushing, with a proprietary dry film lubricant on the inside surface, is placed over a tapered expansion mandrel which is then attached to a hydraulic puller unit. The mandrel/bushing assembly is placed into the prepared hole. Access to the front side of the hole only is required. The expansion mandrel is pulled through the bushing which is retained in the hole by the nosecap assembly. When the mandrel is drawn through the bushing, the bushing and surrounding metal is subjected to radial expansion forces. The radial expansion and subsequent unloading impart beneficial residual stresses around the hole and simultaneously installs the bushing with a high interference fit.

Fatigue life improvement of the expanded bushing installation is attributed both to the creation of residual compressive stresses in the metal surrounding the hole and to the reduction in applied cyclic stress range. Furthermore, the radially expanded interference fitted bushing will lower the mean stress at the hole [16]. These two effects work synergistically to significantly improve fatigue and crack growth life of the bushing installation.

IMPROVING FATIGUE LIFE OF CRACK ARREST HOLES

Cold expansion of crack arrest holes which "blunt" the crack tip and reduce the stress concentration is used in aerospace structures as a temporary repair method to slow crack propagation until a permanent repair can be installed. A recent study [11] looked at inducing residual compressive stresses in CAH using a novel piezoelectric method and showed potential for application in bridge steels. There are fundamental issues associated with CAH for bridge application because the size of the drill stop hole is often too large for practical implementation, and there are problems locating the tip of the crack. Determining the magnitude of the radial expansion needed to yield the material, the effectiveness or adequacy of the technique used and the practicality of the method used to accomplish the task under severe bridge maintenance conditions usually results in temporary repair at best. The need for ongoing inspection and reservation about the effectiveness of the CAH adds to the cost of maintenance and future repair.

The aerospace cold expansion method was found to be more effective if interference fit fasteners were installed into the cold expanded stop drill hole. Therefore the most effective repair became a two part operation. Capitalizing on this knowledge FTI tried accomplishing the inducement of the residual compressive stress with the interference fit of the fastener by installing a ForceMate high interference fit bushing in the drill stop hole using a process called "StopCrackEX". It was a simple one sided method that required little skill by the operator. To measure the effectiveness of the process an independent test was commissioned to compare StopCrackEX to a conventional drill stop or CAH.

TEST OVERVIEW/OBJECTIVE

Southern Utah Engineering was retained through Miceli Infrastructure Consulting, LLC (MIC) to conduct a series of independent fatigue tests investigating the effectiveness of the StopCrackEX process in stopping fatigue cracks in bridge steel. A test plan was designed in conjunction with MIC and FTI to compare typical CAH with the StopCrackEX process.

A total of seven specimens were prepared and tested in a 22-kip MTS test frame. All of the seven specimens were machined with a small initial starter notch in order to promote the initiation and natural propagation of a fatigue crack. In each of the seven specimens, a crack was initiated from the notch and 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 CAH. Three samples were repaired using a conventional .50-inch CAH and 4 were repaired using the StopCrackEX process within the .50-inch hole. After repair, each specimen was then cycled until a new crack was initiated and propagated to .15 inch on the other side of the CAH or StopCrackEX repair or 4 million cycles was reached, whichever was reached first.

Test Specimen

The test specimens were machined out of a single lot of A36 steel acquired from Curtis Steel of Las Vegas, Nevada. The supplied certification for the A36 steel documented the yield stress at 46.6 ksi and the tensile strength at 70.1 ksi. The minimum yield stress for A36 steel is 36 ksi and the tensile strength range for A36 steel is 58 ksi to 80 ksi. The test specimens were 3 inches wide by 0.25 inch thick in the test area (Figure 5). A 0.015-inch radius through notch was machined to a depth of 0.074 inch in depth (Figure 5 - Detail A) to promote crack initiation and propagation.

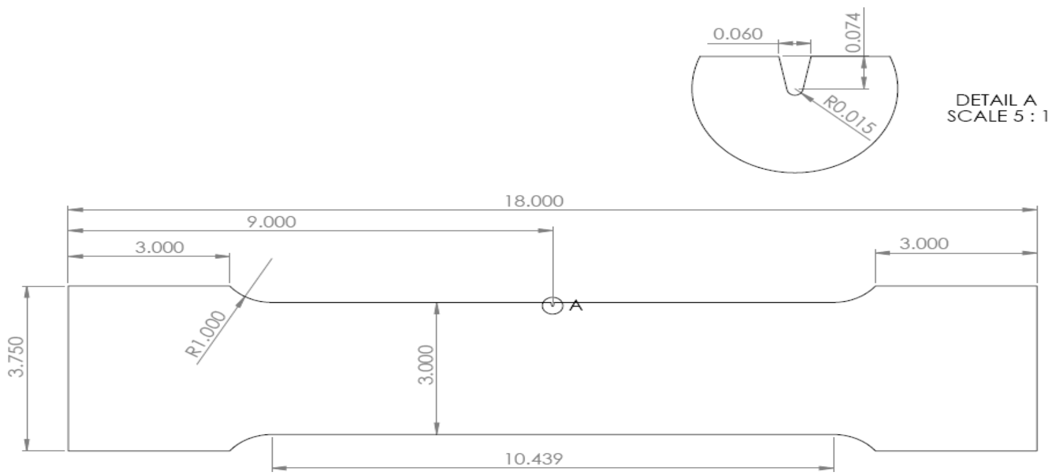

Figure 5. Machining Dimensions for the Test Specimens Showing the Initial Notch

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 6). In each of the 7 specimens, a crack was initiated and propagated to approximately 0.25 inch in length as measured from edge of the specimen.

Figure 6. MTS Test Machine Fitted with Hydraulic Grips and an Optical Microscope

Test Methodology

The testing was done in two parts, pre-cracking and post-repair testing.

Pre-Cracking

Pre-cracking was performed at 10 Hz using constant amplitude sinusoidal loading. The specimens were subjected to a gross stress of 25 ksi and a stress ratio of 0.05, based on the overall test section area (Table 1). Cracks were initiated and propagated to approximately 0.25 inch (including the notch) for each of the test specimens. The crack length was monitored and measured periodically by stopping the test and visually observing the crack with an optical microscope while the test specimens were loaded to 80% of maximum load. The cycle count to initiation and the cycle count required to propagate the crack to approximately 0.25 inch were recorded (Table 1).

Table 1. Specimen Dimensions and Pre-Cracking Data

Specimen	Thickness (inch)	Width (inch)	Max Gross Stress (ksi)	Max Load (lbs)	R	Cycles to initiate crack	Cycles for 0.25 inch crack
1	0.249	3.007	25	18,719	0.05	38,750	119,712
2	0.248	3.009	25	18,656	0.05	36,552	151,195
3	0.246	3.005	25	18,481	0.05	108,300	202,320
4	0.248	3.005	25	18,631	0.05	45,000	127,957
5	0.245	3.002	25	18,387	0.05	42,358	122,647
6	0.251	3.002	25	18,838	0.05	60,000	123,000
7	0.247	3.005	25	18,556	0.05	38,000	146,000

Repair

After pre-cracking, each of the seven specimens was repaired with one of two methods. Three specimens were repaired with a typical 0.5-inch drill stop CAH and 4 were repaired using the StopCrackEX process installing the bushing into the same diameter hole. The center of the hole was placed 0.630 inch from the edge (Figure 7), which put the edge of the holes approximately 0.06 inch in front of the crack tip in each of the 7 specimens.

Figure 8 shows the CAH repair configuration and Figure 9 the StopCrackEX specimen with the bushing installed. The StopCrackEX bushings were installed by FTI.

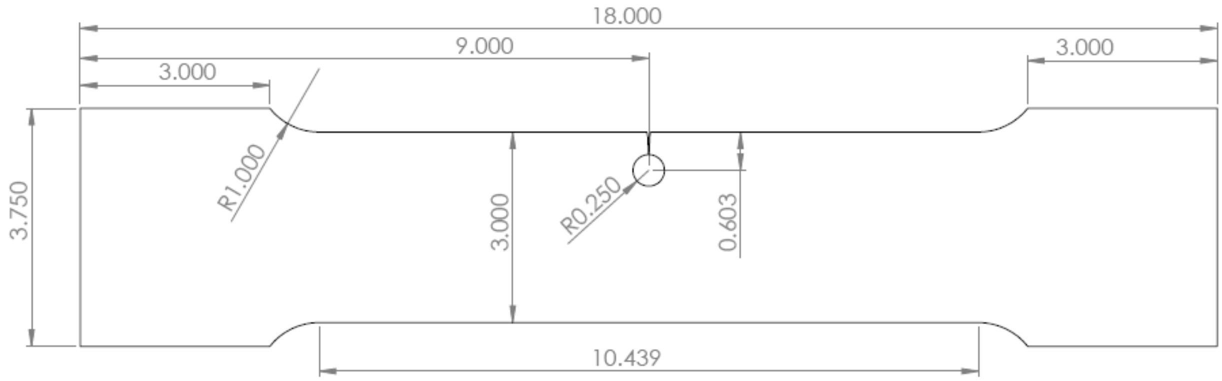

Figure 7. Test Specimens with the Repair Hole Location

Figure 8. Picture of a CAH Repaired Crack

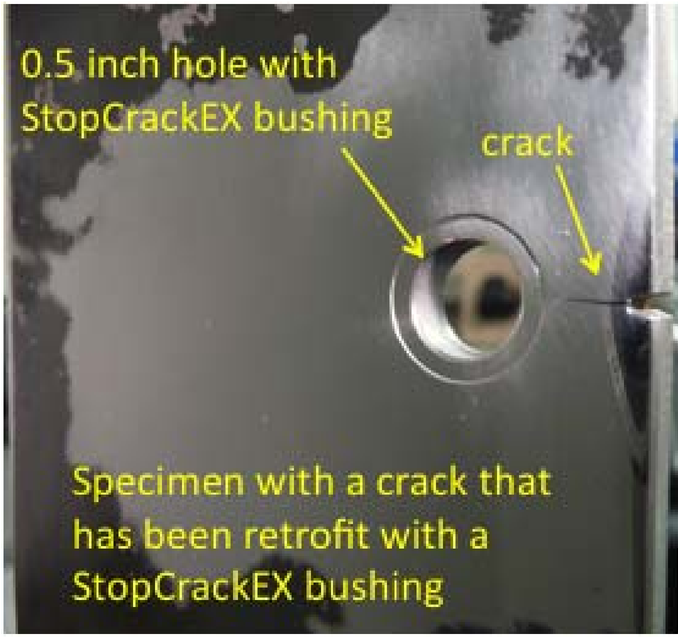

Figure 9. Picture of a StopCrackEX Repaired Crack

TESTS

The objective of the post-repair testing was to determine the number of cycles required to reinitiate and propagate a crack to approximately 0.15 inch. The post-repair testing was performed using constant amplitude sinusoidal loading at 10 Hz. The specimens were subjected to a maximum net stress of 20.5 ksi and a stress ratio of 0.05, based on the remaining net stress area after the repairs.

RESULTS

Two locations were monitored for crack propagation and initiation. Because the two methods of repair were placed 0.060 inch ahead of the cracks, the number of cycles for the cracks to break the edge of the hole was observed and recorded. More importantly, the opposite side of the repair was monitored for crack initiation and propagation to a crack of approximately 0.15 inch (Figure 10). The cycle count for crack initiation and propagation to 0.15 inch was observed and recorded in Table 2. If a crack did not initiate within 4 million cycles the test was terminated. The crack length was monitored/measured periodically by stopping the test and visually observing the crack with an optical microscope while the test specimens were loaded to 80% of maximum load.

Table 2. 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

Figure 10. New Crack That Initiated After Being Drilled with a Crack Arrest Hole

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 as shown in Table 4. It should be noted that the resulting cycle count for the CAH was for a through crack given that the crack broke through on both sides within a couple of thousand cycles. However, the StopCrackEX process was very effective at retarding the growth of the original crack. Three of the specimens with the StopCrackEX process took more than 1.7 million cycles for the crack to be visible on the second side of the specimen (Table 3). The average cycle count for the CAH to reinitiate a crack was 306,667 cycles. The StopCrackEX processed specimens never 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.

Note: Specimen #7 was continued to be cycled after the completion of the 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 60 times life improvement over the CAH configuration.

Table 3. Test Results Comparing Average Cycle Counts for Life

Retrofit Method	Average Cycle Count to Break Hole	Average Cycle Count to Reinitiate crack
CAH	8,544	306,667
StopCrackEX	435,050	4,000,000 (test stopped no crack)

SUMMARY

The conventional CAH, in theory, provides a method for postponing a more expensive retrofit or avoiding catastrophic failure. Ideally, a CAH lowers the stress concentration sufficiently to permanently stop crack re-initiation but in reality, cracks re-initiate and this temporary repair requires ongoing inspection and monitoring.

Inducing effective residual compressive stresses around holes is an effective way to prolong crack growth. The compressive stress reduces the stress amplitude around the hole which effectively retards fatigue crack propagation. In the aircraft industry, the cold working of holes has been successfully used for over forty years as a method for improving the fatigue life and damage tolerance of holes. FTI's StopCrackEX system is an extension of this proven technology.

StopCrackEX further enhances the residual compressive stress in arresting crack growth by expanding a high interference fit bushing into the CAH which will reduce the mean stress and stress amplitude, lower the stress concentration and stress intensity of the crack to significantly retard or arrest the rate of crack propagation and prevent crack re-initiation on the other side of the CAH. The presence of the StopCrackEX bushing is also a positive visual indication that the crack arresting procedure has been incorporated in a particular hole.

In an independent coupon test program, the StopCrackEX process showed at least over 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. Figure 11 shows a summary of the coupon test results.

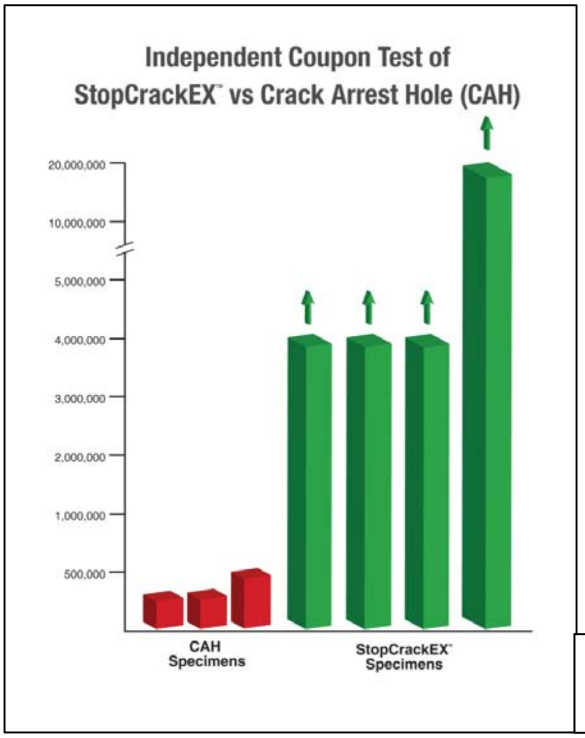

Figure 11. Summary of Coupon Test Results

CONCLUSIONS

There are a large number of metal structure bridges throughout the United States with many approaching or exceeding 50 years of age. Cracking from stress concentrations is becoming more prevalent and a positive economical method of arresting the growth of these cracks is needed. Conventional crack arrest holes are inadequate. Inducing beneficial residual compressive stresses around the CAH is a proven method of extending fatigue and crack growth life of fatigue critical holes. Incorporation of StopCrackEX into CAH is shown by test to significantly increase the crack growth life and in fact provide possible terminating repair action by arresting further growth of cracks. Use of StopCrackEX will provide significant cost savings to bridge owners when used as a replacement for the conventional CAH method 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.

ACKNOWLEDGEMENT

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Key Words—Fatigue cracking, bridges, drill stop, crack arrest hole (CAH), repair, bushing, cold expansion.