Arresting Cracks in Steel Bridges

Using Proven Aerospace Technology

Western Bridge Preservation Partnership – San Diego CA

May 12, 2013

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Objective

- Presentation will introduce expanded bushing method to enhance drill stop repairs
- Explain derivation of the process from aerospace hole cold expansion method
  - Used to extend the fatigue life and damage tolerance life of aircraft structures.
- Show by test how the enhanced drill stop method arrests the growth of cracks in test coupons
- Show examples of where the technology has been applied to steel bridges

Background

- Cracking in steel bridges is one of the major causes for concern in bridge maintenance and preservation
- Temporary repairs are often installed to allow continued operation of bridge
  - Minimize impact on local commerce/infrastructure
  - Buy time to effect more permanent repair/structural replacement
- Depending on effectiveness of repairs could lead to load limits on bridge
- Total or partial bridge closure can have significant ramifications and impact on local community and commerce

Typical Cracks in Bridges or Infrastructure

Cracks from welds

Cracks from bolt holes

Typical Fatigue Crack Identified with Dye Penetrant

Stopping Cracks in Bridges/structures

- Many cracks are repaired by cutting out the crack and welding a repair patch in place or adding doublers
  - Can change the stiffness and dynamic response of the member

- Most common method of preventing cracks from growing is by “drill stop” or crack arrest hole (CAH) at the crack tip
  - Objective to “blunt” the crack tip
  - reduce stress concentration at crack tip

Generally used as a temporary repair option

Temporary Repair – Drill Stops

- Drill-stop method often not effective
  - Size of CAH based on material properties can be impractically large
  - Compromised by access or available drill bit

- ➢ Fails to arrest crack growth
- ➢ Miss the crack tip
- ➢ Residual tensile stress at crack tip
- ➢ Cracks reinitiate on other side of drill stop hole
- ➢ Can lead to structural failure and/or bridge closure

Requires repeat inspections/monitoring

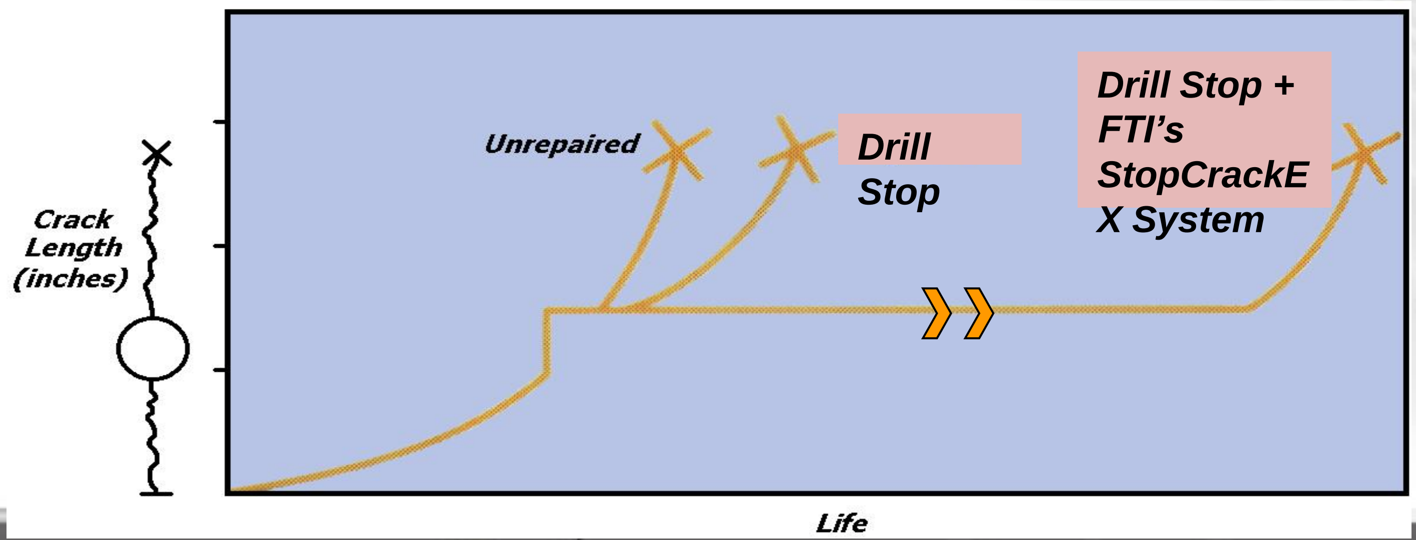
Enhancing Drill Stops

- Variety of methods tried
  - Installing interference fit bolts or fasteners
    a) Method relies on effective interference
  - Pre-stressing crack tip
  - Surface treatment methods
    a) Ultrasonic impact
    b) Shot peening around hole
- Pre-stressing hole using novel piezoelectric method
  - Application on bridges not practical
  - No convenient way of verifying hole was correctly expanded

- Methods shown to have little or no effect in retarding crack growth
  - Especially if driving stresses are high or crack is near critical crack length
  - No convenient way to measure effectiveness of temporary repair
- Does not eliminate need for ongoing monitoring/inspection

Enhanced Drill Stop Method

- Derived from over 40 years experience in the aerospace industry, improved drill stop method effectively arrests crack growth
  - “StopCrackEX” is adapted from hole cold expansion and expanded bushing technology developed for aerospace industry
  - Installs high interference fit bushing that simultaneously induces beneficial compressive residual stress around the bushing
  - Shown to arrest further growth of cracks in test coupons
  - Provides a positive indication hole has been treated

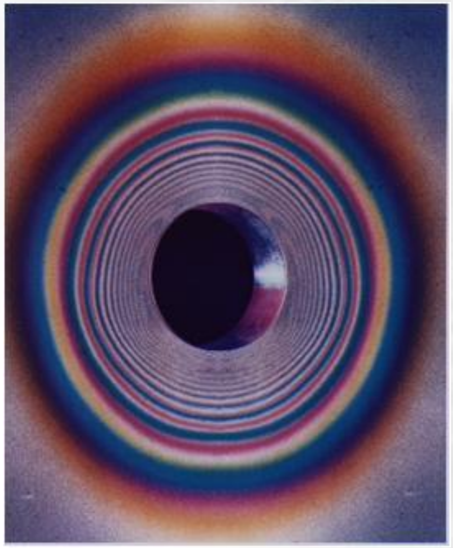


Enhancing Drill Stops
Derivation from Aerospace Technology

Fatigue Life Improvement of Holes

- Hole cold expansion (cold working) developed by aerospace industry to improve fatigue life and damage tolerance of holes in aircraft structures
  - Induces a zone of residual compressive stress around and through the hole
    a) Extends radially one diameter from hole

- Hole cold expansion proven to be very effective in eliminating rail-end bolt hole cracking in railroad industry



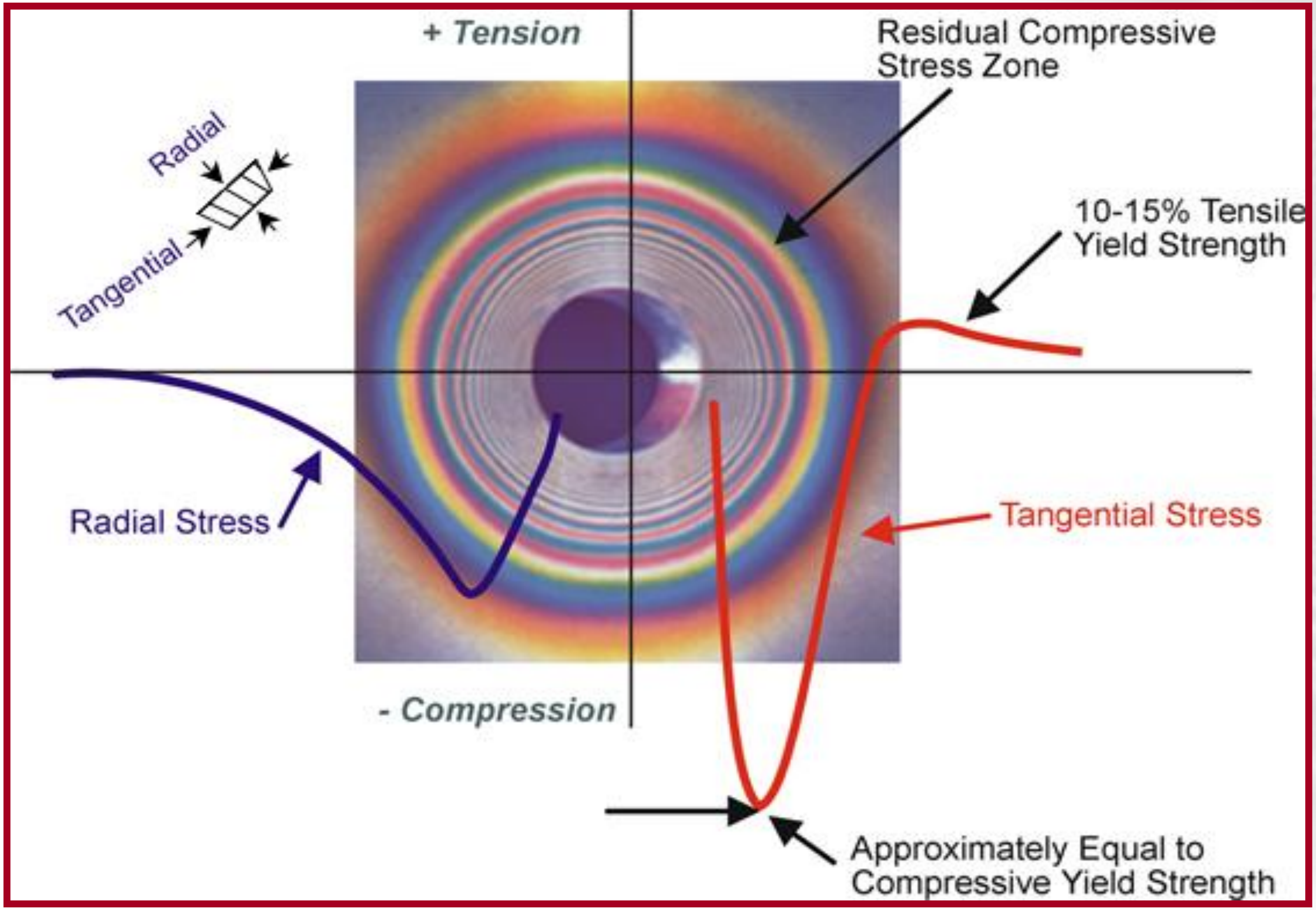
Hole is effectively "shielded," reducing effective stress intensity factor, and therefore the propagation fatigue cracks.

Split Sleeve Cold Expansion Overview

- One-sided process
- Effective in all metals including A36 bridge and railroad steels
- Typically increases fatigue life by a factor of 10:1
- Arrests growth of small cracks present in the hole prior to cold expansion

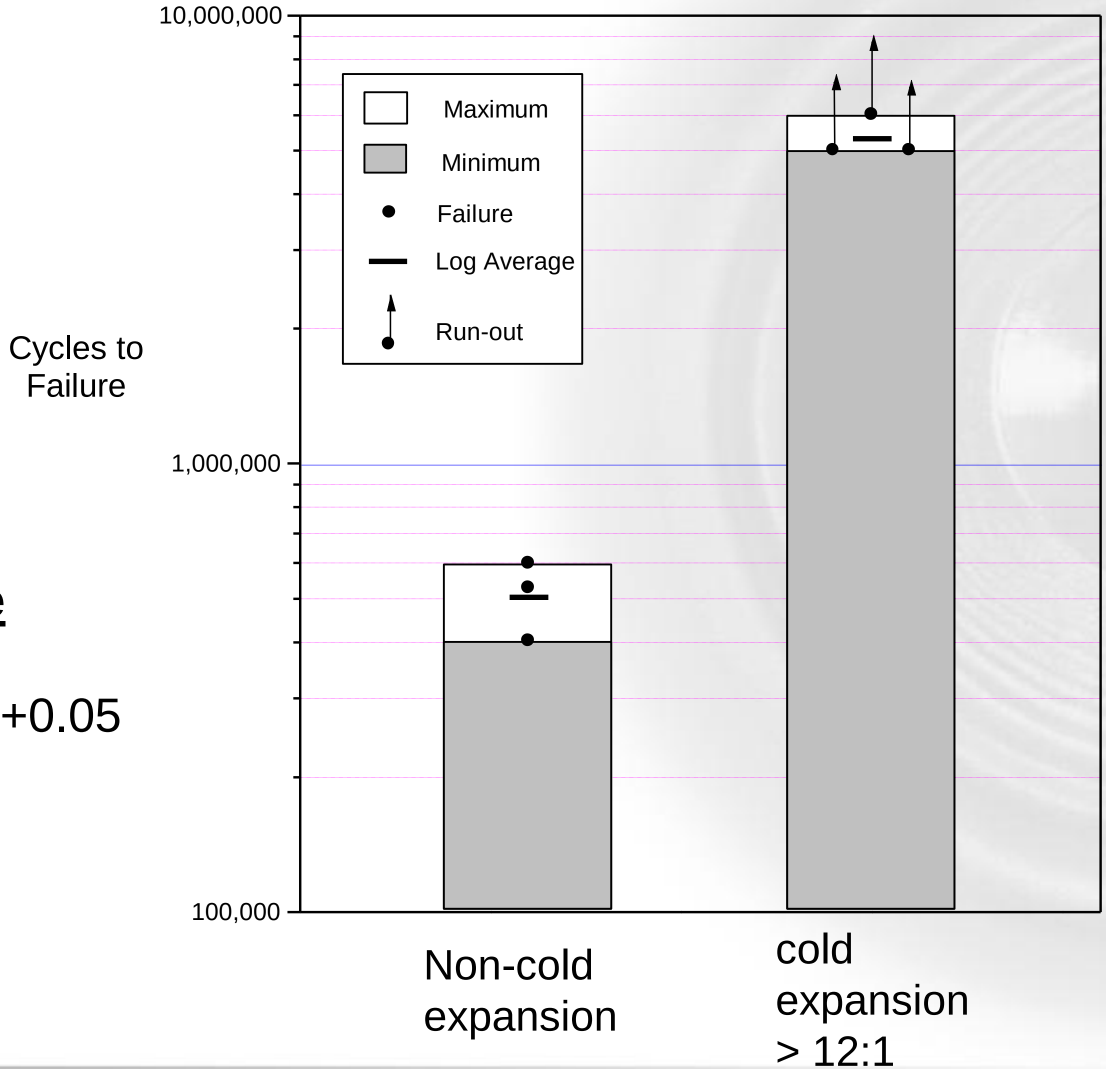
Generates large, controllable zone of residual stress surrounding the hole

Residual Stress Distribution From Cold Expansion



A36 Steel under Axial Fatigue Loading

Process was used by CALTRANS to extend fatigue life of elevated highway truss joint holes



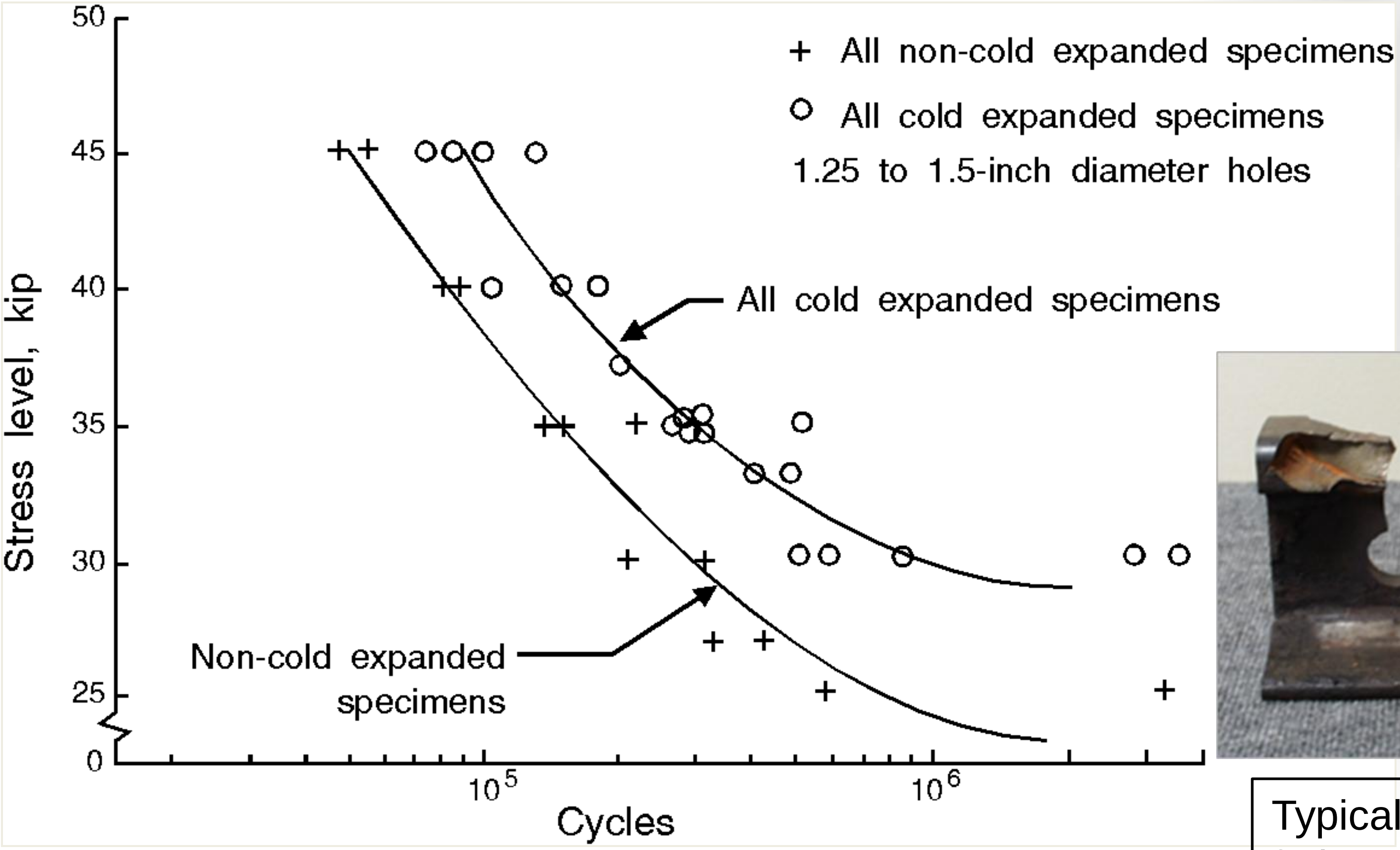
Constant Amplitude Fatigue

Specimen: ZLT Dogbone

Loading: 30 ksi net stress, R=+0.05

Environment: ambient lab air

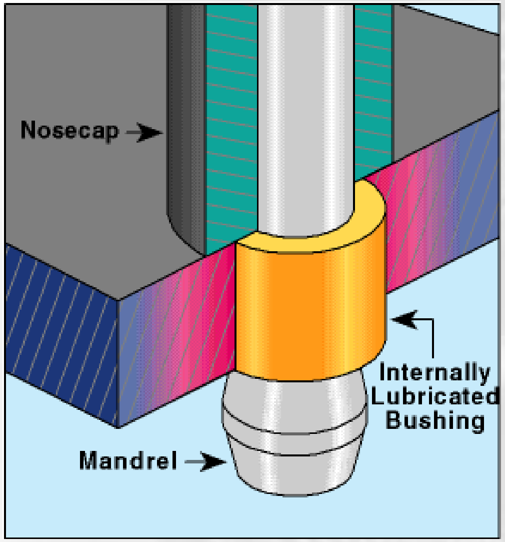
Increase in Fatigue Life for Cold Expanded Holes—U.S. DOT Rail Fatigue Results



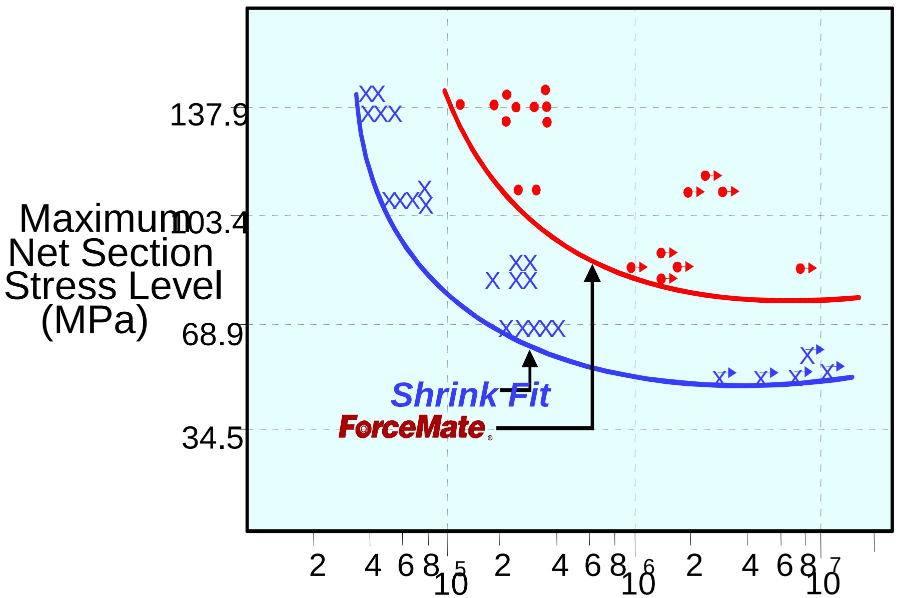
Typical rail-end bolt hole fatigue failure

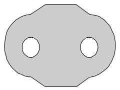
Further Derivative of Cold Expansion Process
ForceMate Expanded Bushing Method

- Clearance fit bushing is expanded radially into hole at high interference fit
  - Locally yields surrounding material and induces a residual compressive stress around bushing
- Lowers the mean stress at the hole and reduces the applied stress amplitude
- **Greatly enhances fatigue life of the bushed hole**



Typical Fatigue Life Comparison
Shrink Fit Vs ForceMate Bushings





Test Specimen
7075-T651

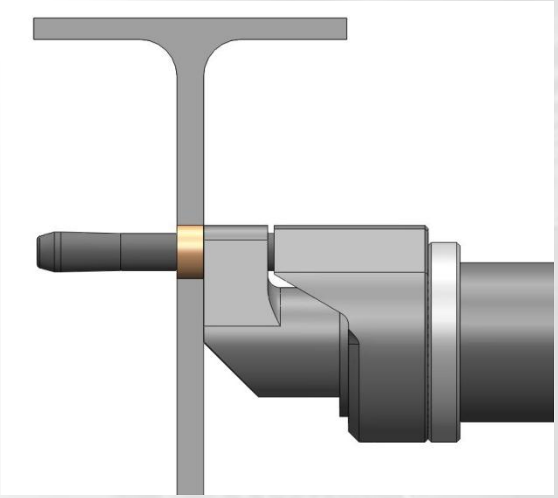
Load Conditions:
Constant amplitude
10 Hz
R = .05
Beryllium Copper Bushings

- **ForceMate Failure**
- x **Shrink Fit Failure**
- → **No Failure**

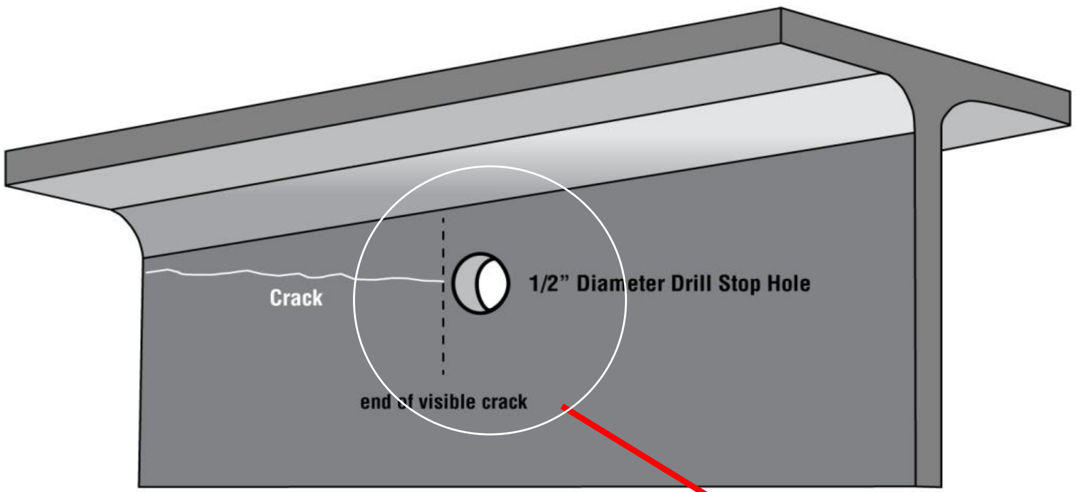
Champoux & Landy
ASTM STP 927
1987

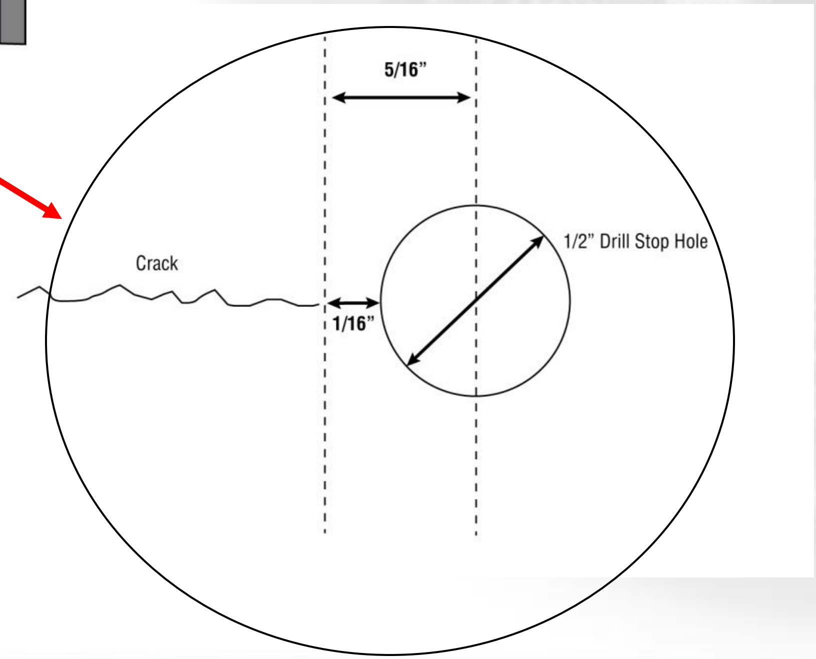
“StopCrackEX” Enhanced Drill Stop Repair

- New method combines effectiveness of hole cold expansion and high interference fit “ForceMate” bushing
  - Induces a beneficial residual compressive stress around the bushing to shield it from the cyclic stresses
- Bushing reinforces hole and reduces applied stress and stress amplitude
  - Effective even if local stresses are high
  - Stainless steel bushing provides positive indication that hole has been enhanced
- Uses a smaller drill stop hole, ½" dia.
  - Typical drill stop 7/8 to 1.0 inch
- Coupon test program and FEA study validates effectiveness in arresting crack growth



Location of Drill Stop Hole

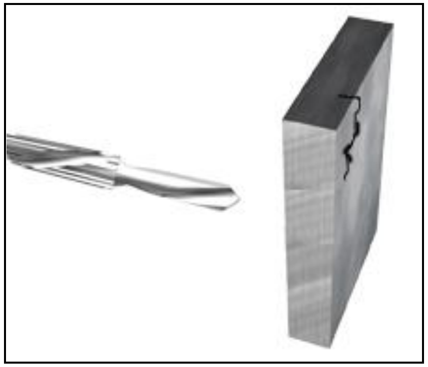




<u>Note:</u> the hole is drilled ahead of the crack tip to ensure it captures the tip to allow the crack to grow into the hole

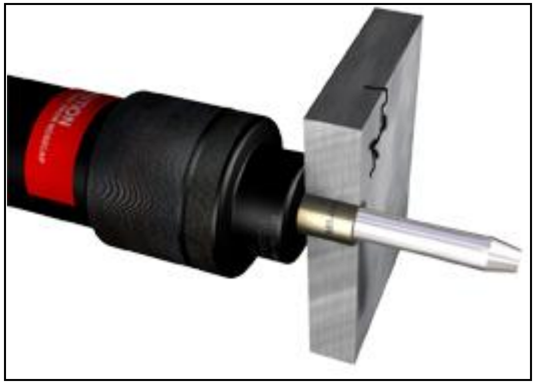
StopCrackEX Process

StopCrackEX Process Steps



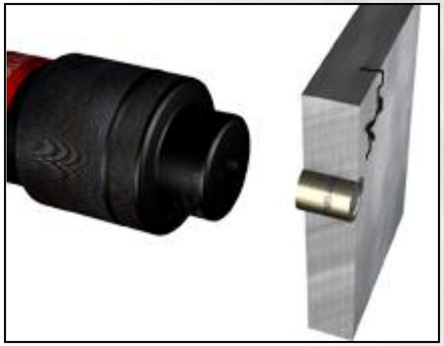
1. Locate crack tip and drill/ream 0.50" dia. hole 5/16" ahead of tip

2. Place bushing on mandrel and insert into puller



3. Place bushing in hole

4. Pull mandrel through bushing



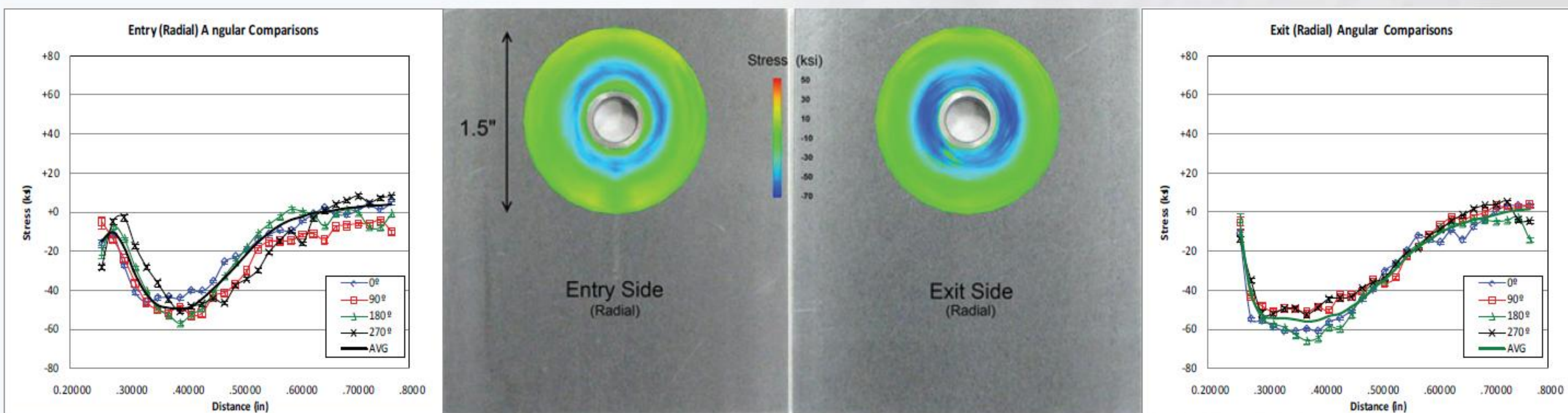
5. StopCrackEX Bushing installed

StopCrackEX
Viewed Through a Photoelastic Coating on Plate

Residual Compressive Stress Field from X-Ray Diffraction

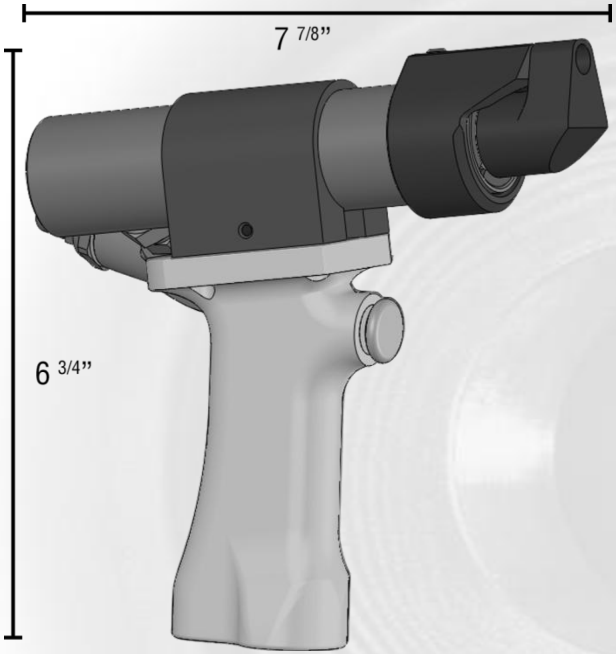
X-Ray Diffraction plots by
Proto Manufacturing Inc

Compressive Hoop Stress



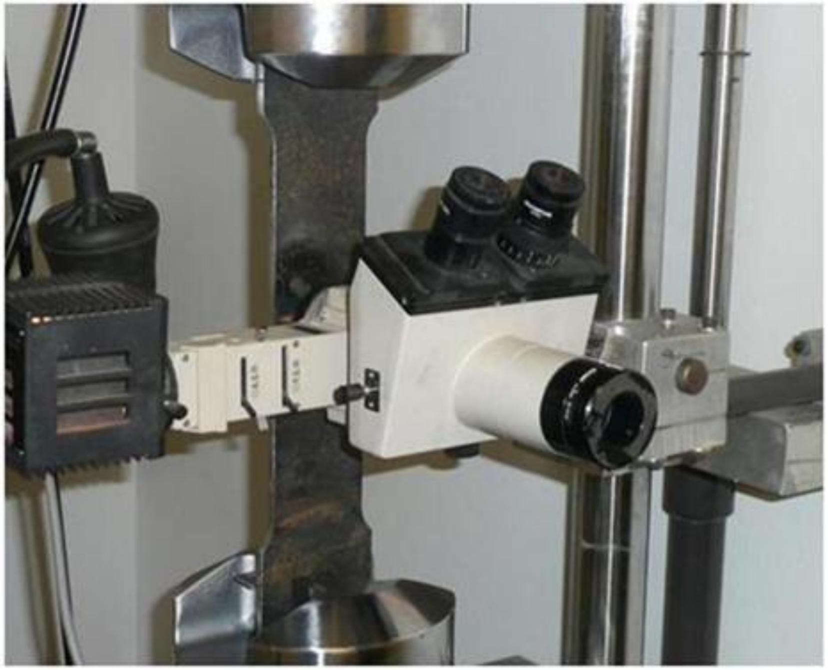
Compressive Radial Stress

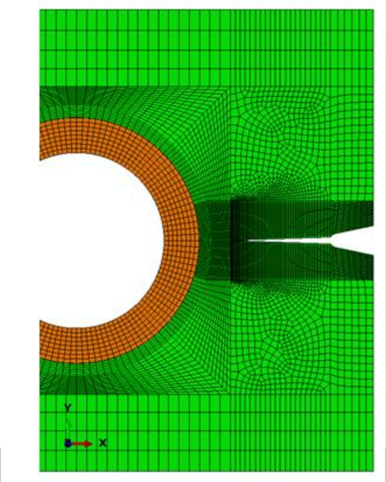
StopCrackEX Repair Kit

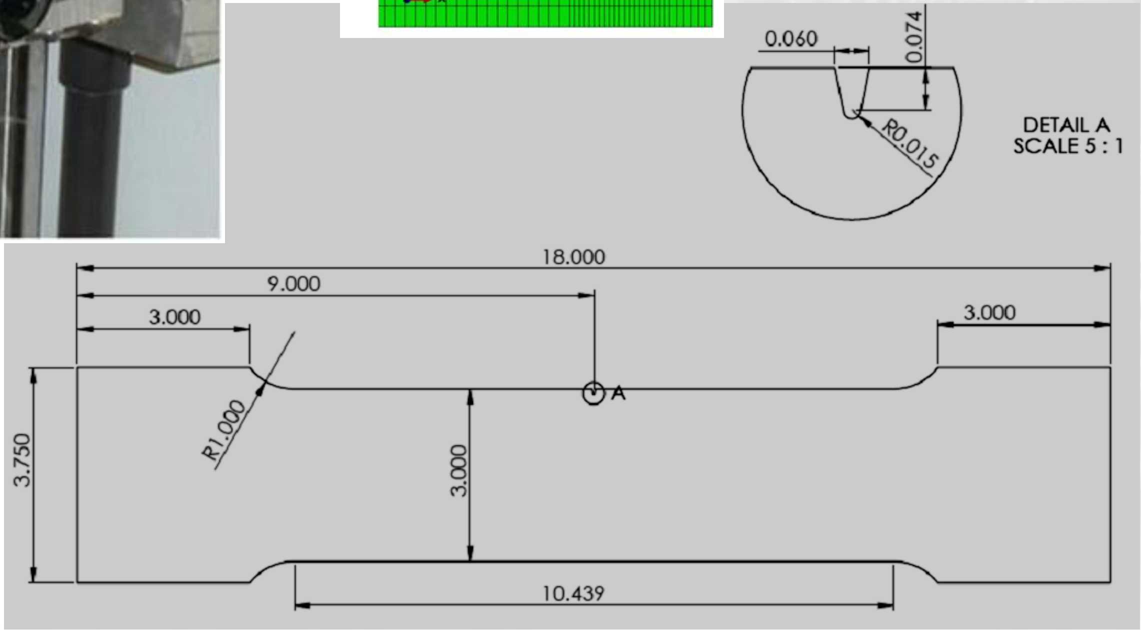


New design compact puller incorporating offset

Coupon Test Program and Validating Analysis







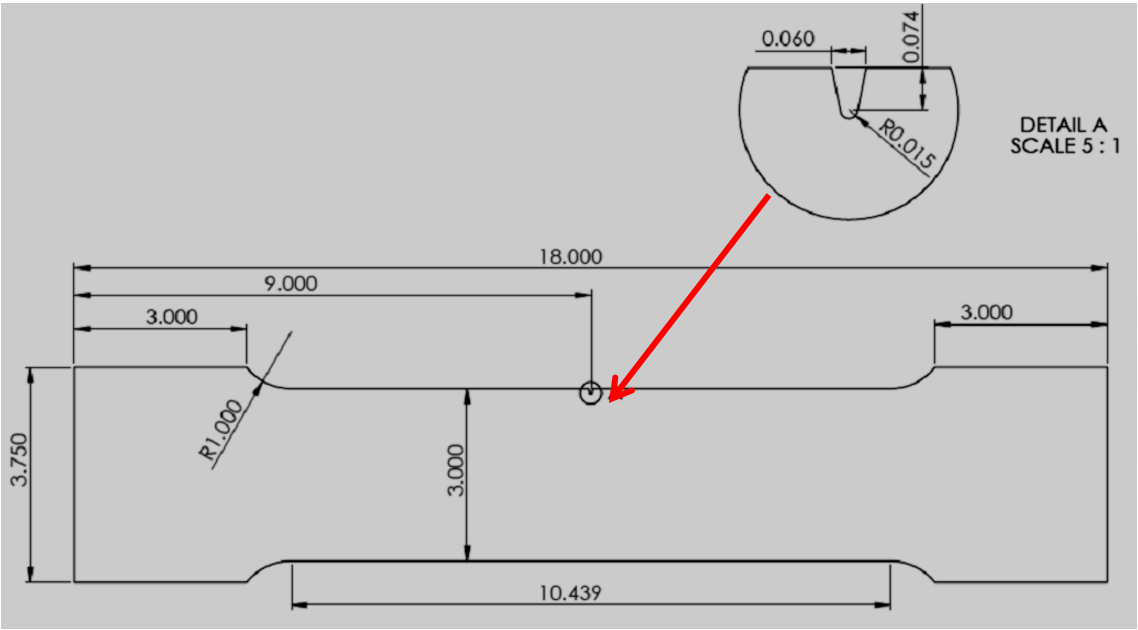
Objective of the Analysis

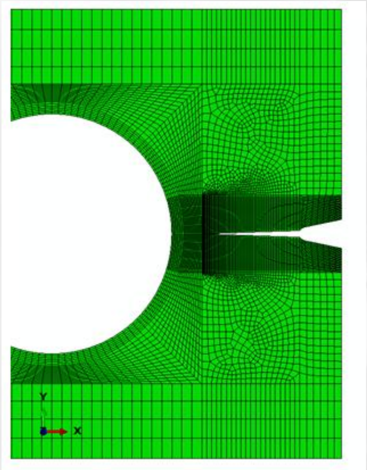
- Prior to conducting coupon test program the coupon was modeled to optimize location of StopCrackEX and the load level
- Evaluate stress state at crack tip under tensile load for
  1. Baseline plate configuration with hole drilled at crack tip to arrest crack growth.
  2. Plate with hole at the crack tip cold expanded using StopCrackEX system

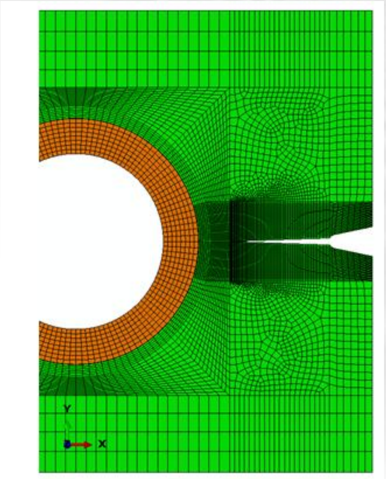
- Three different stress levels were evaluated for these two scenarios
  1. Hole is drilled 1/16 inch in front of the crack tip and the crack is stopped at this location.
  2. Hole is drilled 1/16 inch in front of the crack and the crack is allowed to grow into the hole.

FEA Model Simulation:

Compared to Coupon Test Configuration







FEA Model Simulation:

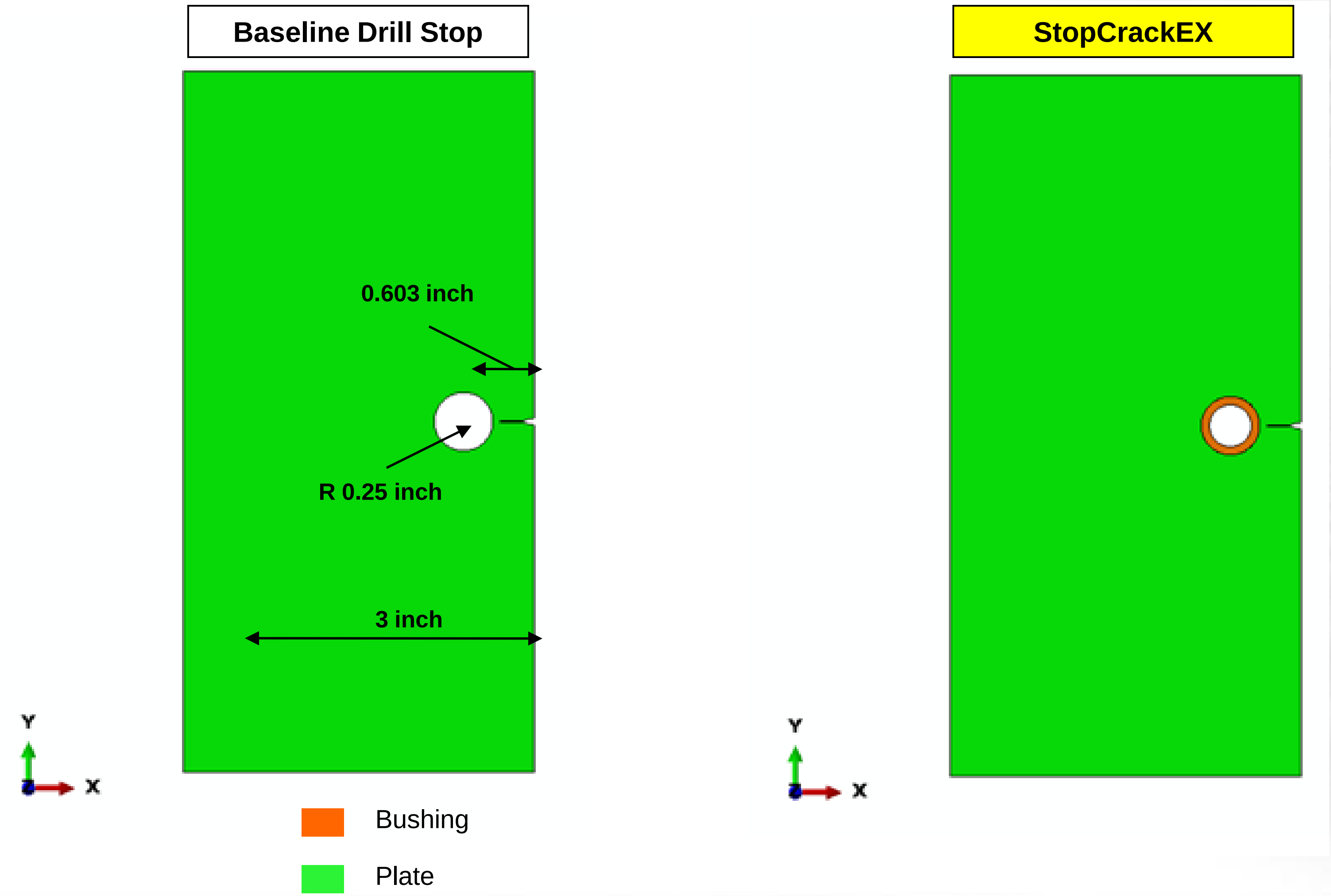
Compared to Coupon Test Configuration

- 2D plane stress models used for analysis
  - Plate width =3 inch.
  - Hole diameter = 0.5 inch, located 0.603 inch from edge of plate.
  - Notch Dimensions (from coupon drawings):
  - Crack Located 1/16 inch from hole edge. extending from pre-notch.
- Plate material = A36 steel.

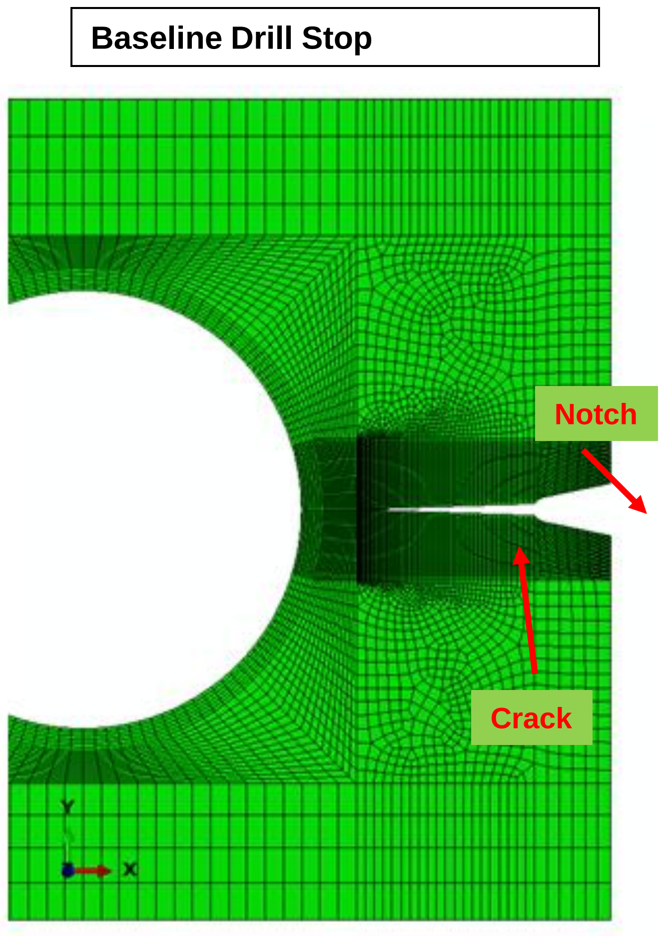
  - yield strength = 46.6 ksi.

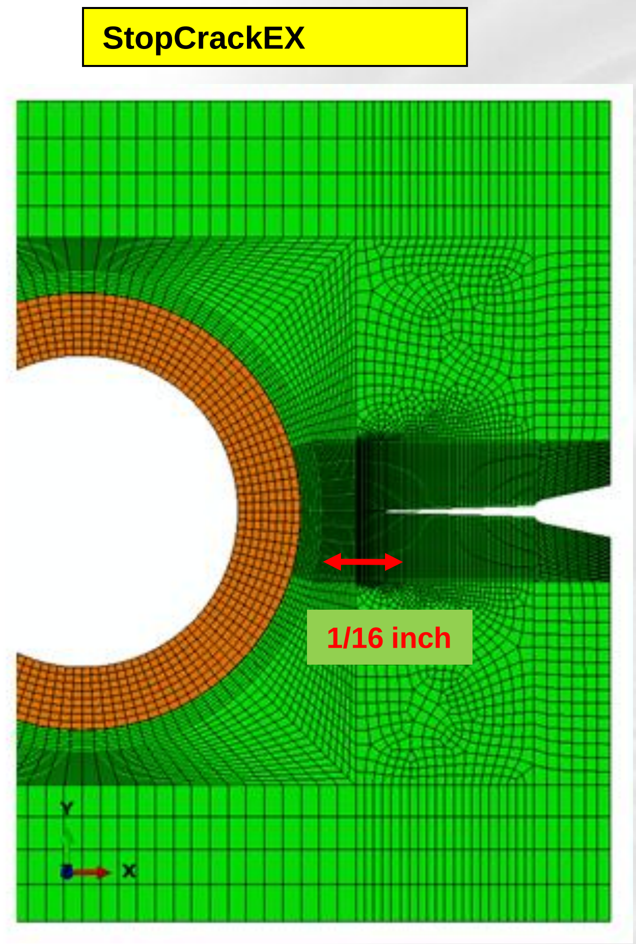
  - Ultimate strength = 70.1 ksi.
- The StopCrackEx process was simulated
- Tensile load of 10995 lbs (net stress =20.5 ksi) was applied to the plate after expansion to evaluate the stresses at the crack tip.

Finite Element Comparative Study
Drill Stop Vs StopCrackEX - Simulating Coupon Test



FEA Model: Crack Details

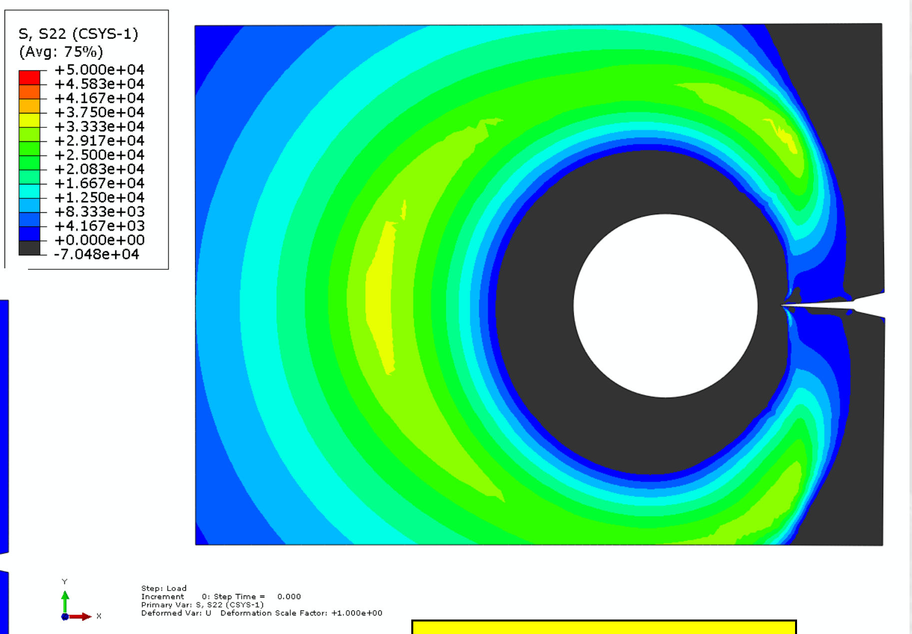




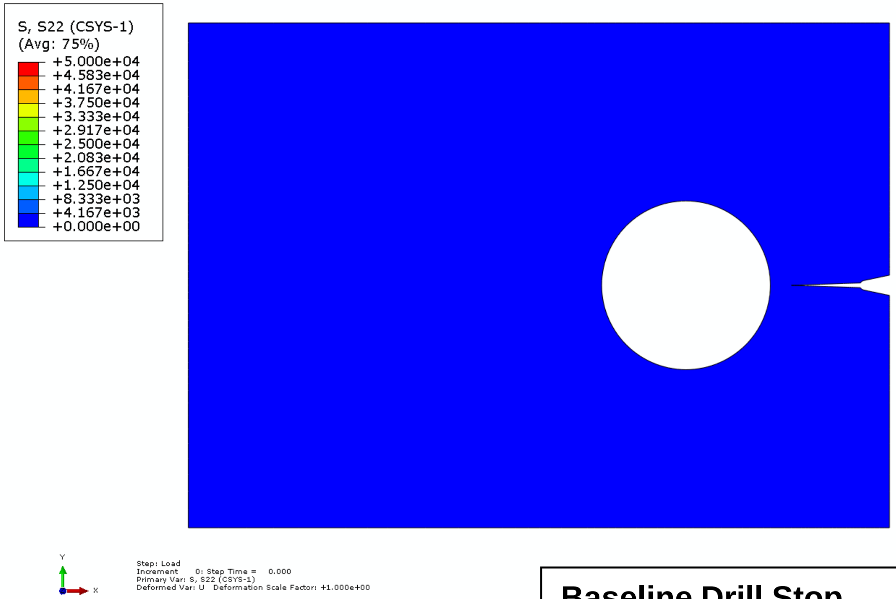
Bushing

Plate

Hoop Stress (psi) Contour Plot: Tensile Load = 0 ksi (No Applied Load)



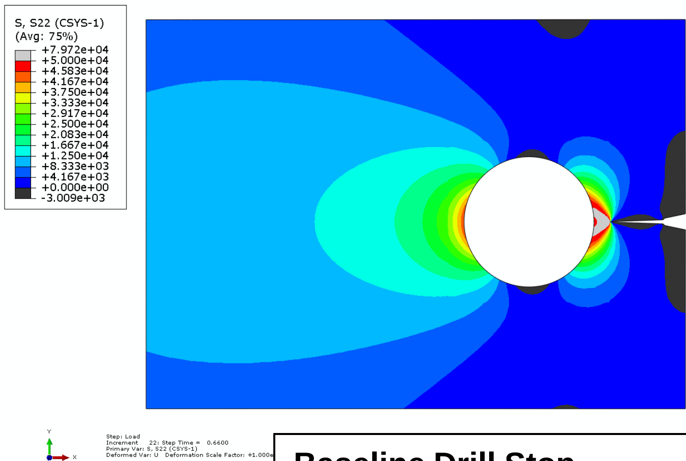
StopCrackEX



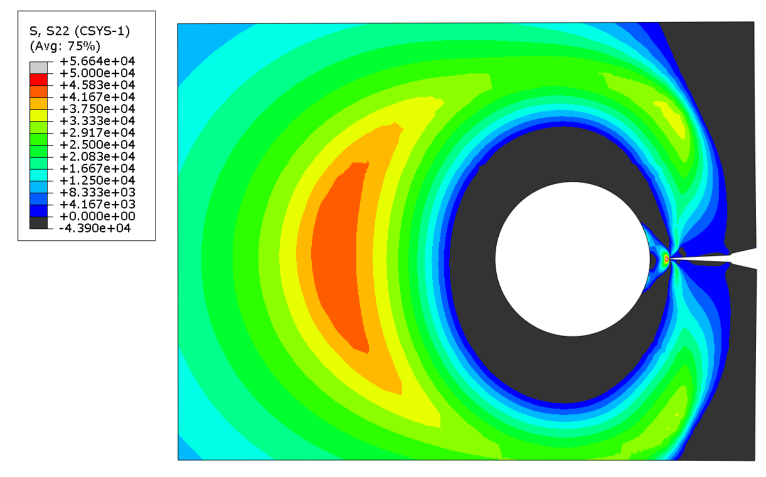
Baseline Drill Stop

Hoop Stress (psi) Contour Plot:

Tensile Load = 13.5 ksi (Net Stress)

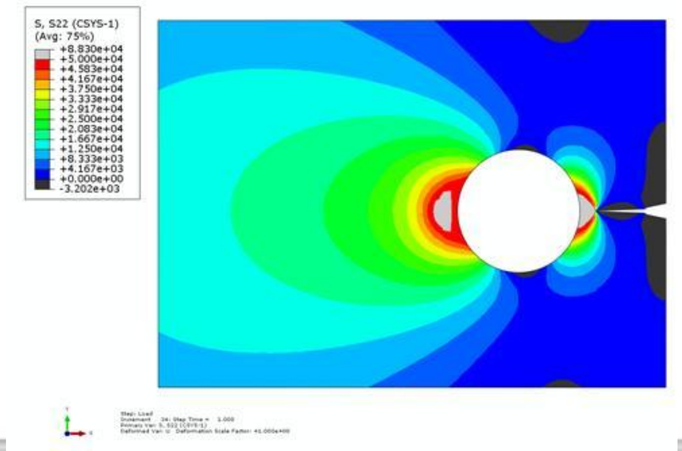


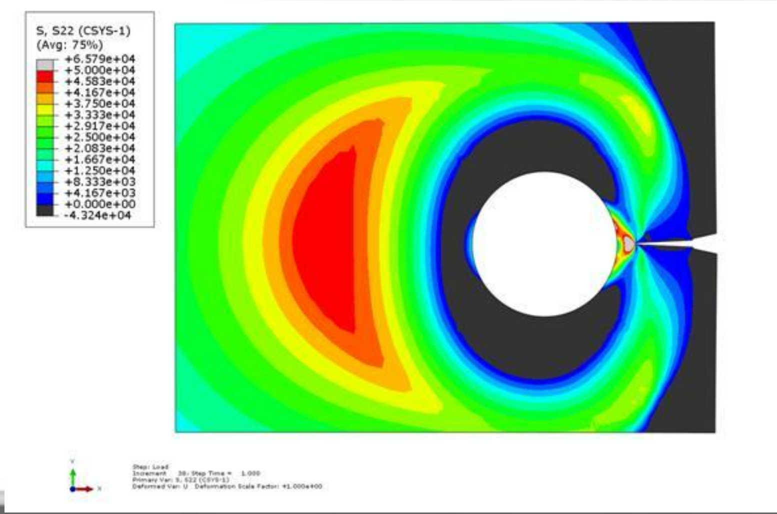
Baseline Drill Stop



StopCrackEX

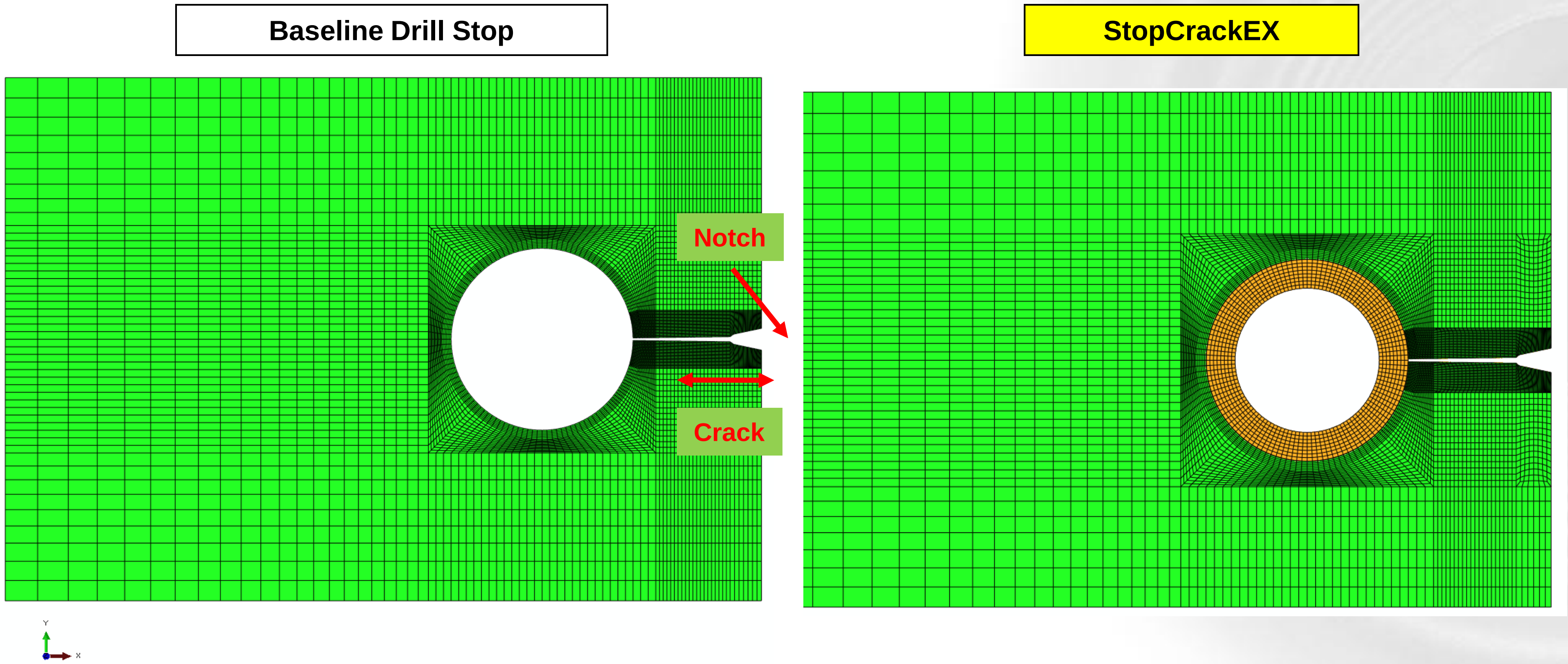
Tensile Load = 20.5.5 ksi (Net Stress)





FEA Model: Crack Details

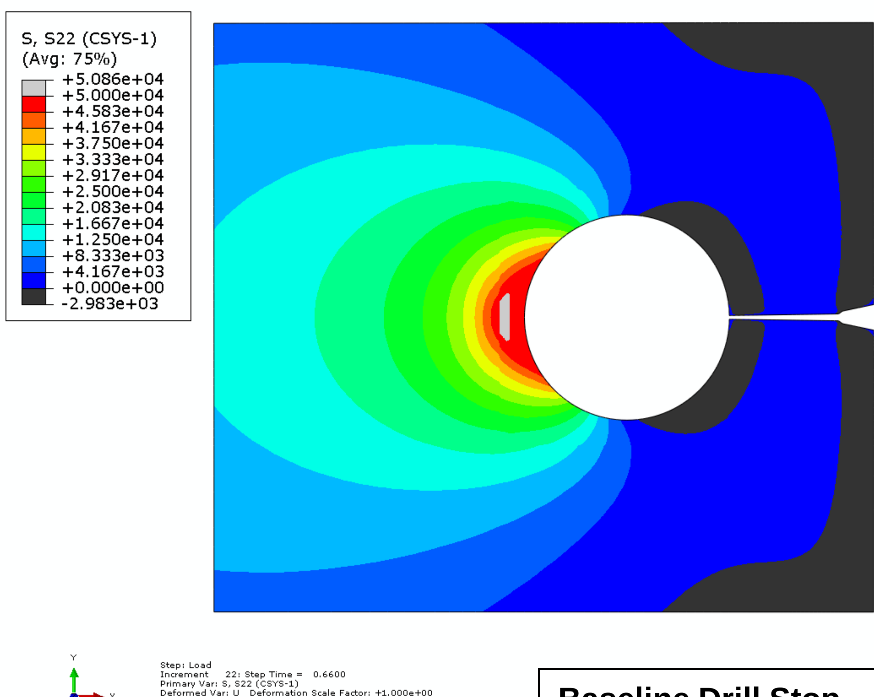
Crack at Edge of Hole



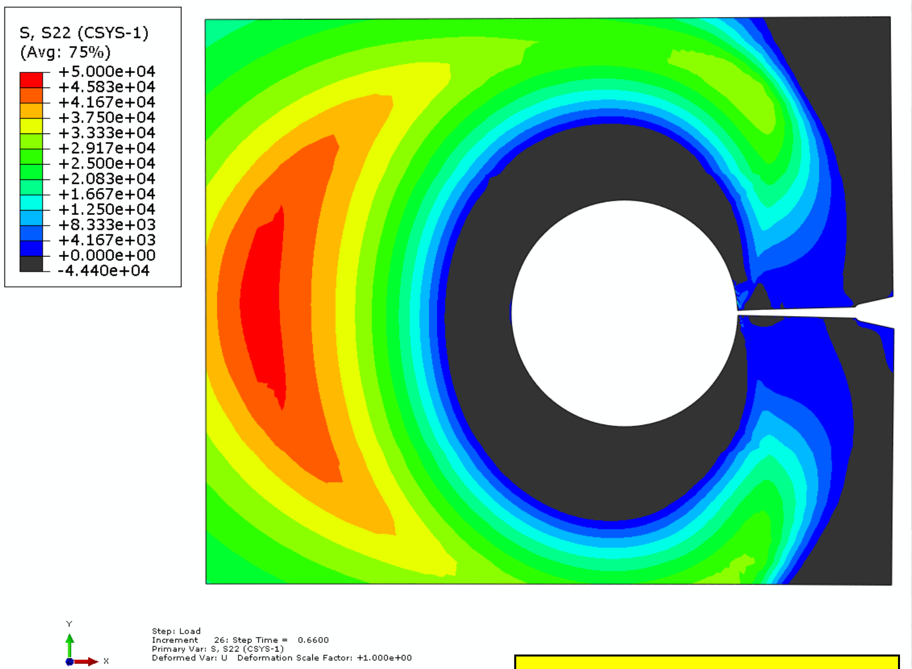
Bushing

Plate

Hoop Stress (psi) Contour Plot: Crack at Edge of Hole Tensile Load = 13.5 ksi (Net Stress)

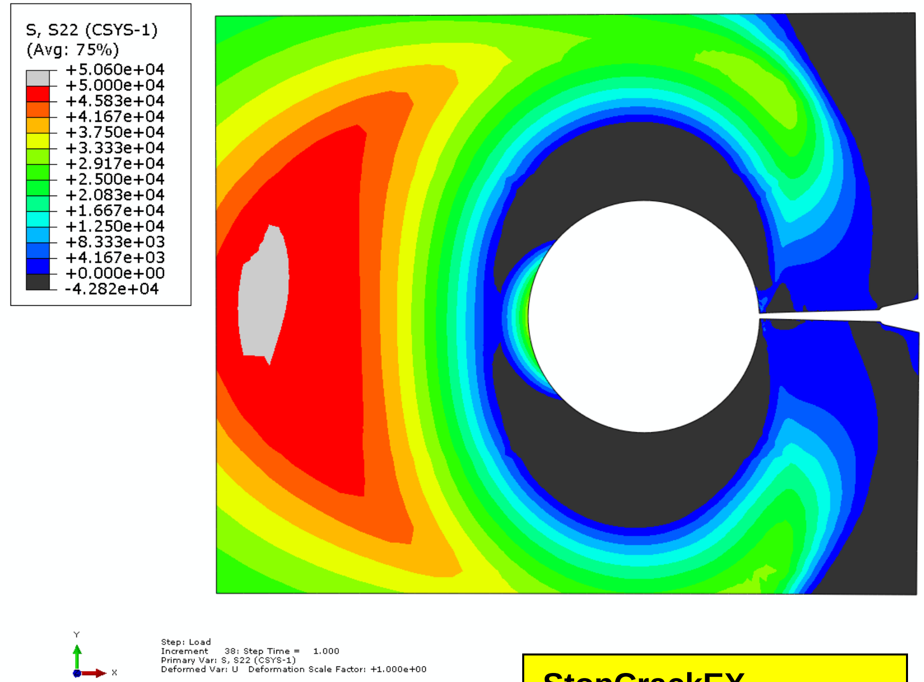


Baseline Drill Stop

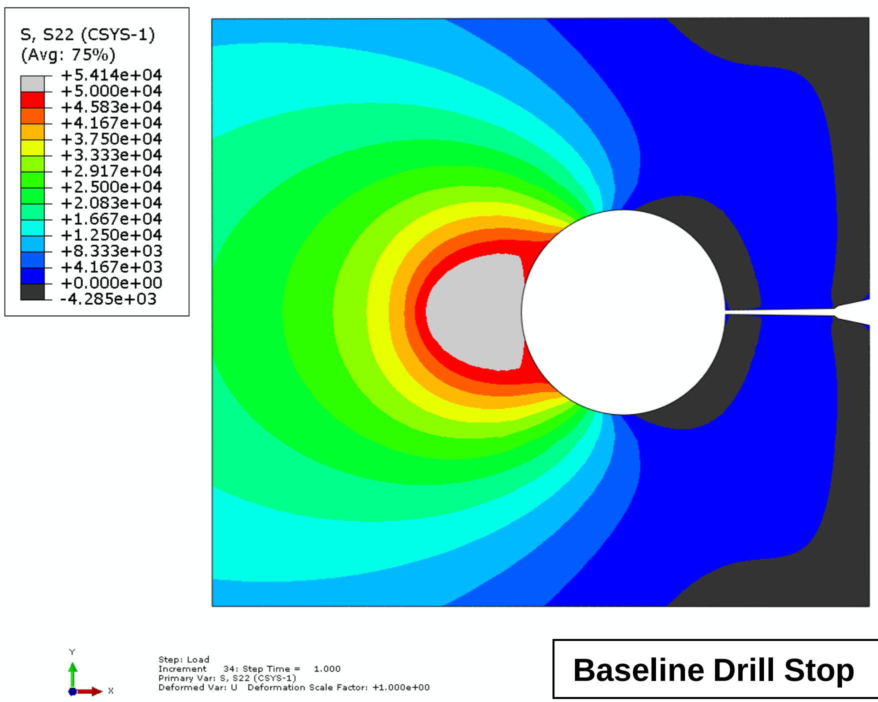


StopCrackEX

Hoop Stress (psi) Contour Plot: Crack at Edge of Hole
Tensile Load = 20.5 ksi (Net Stress)



StopCrackEX



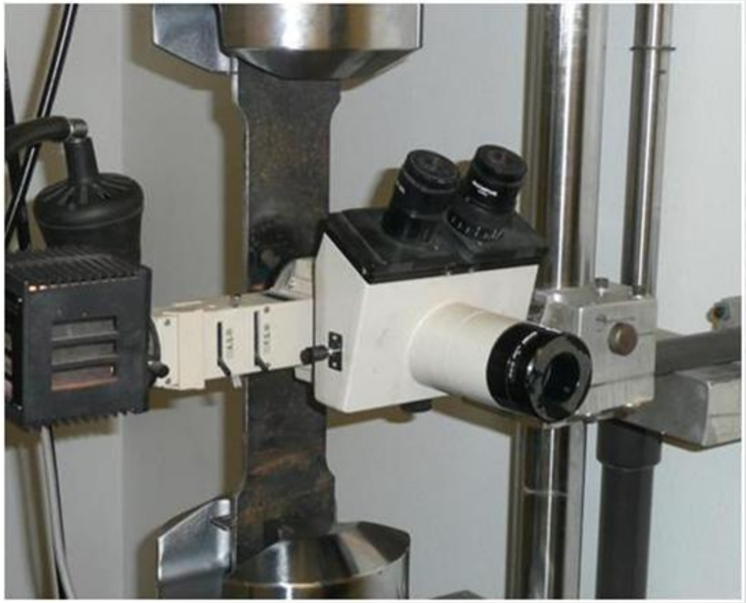
Baseline Drill Stop

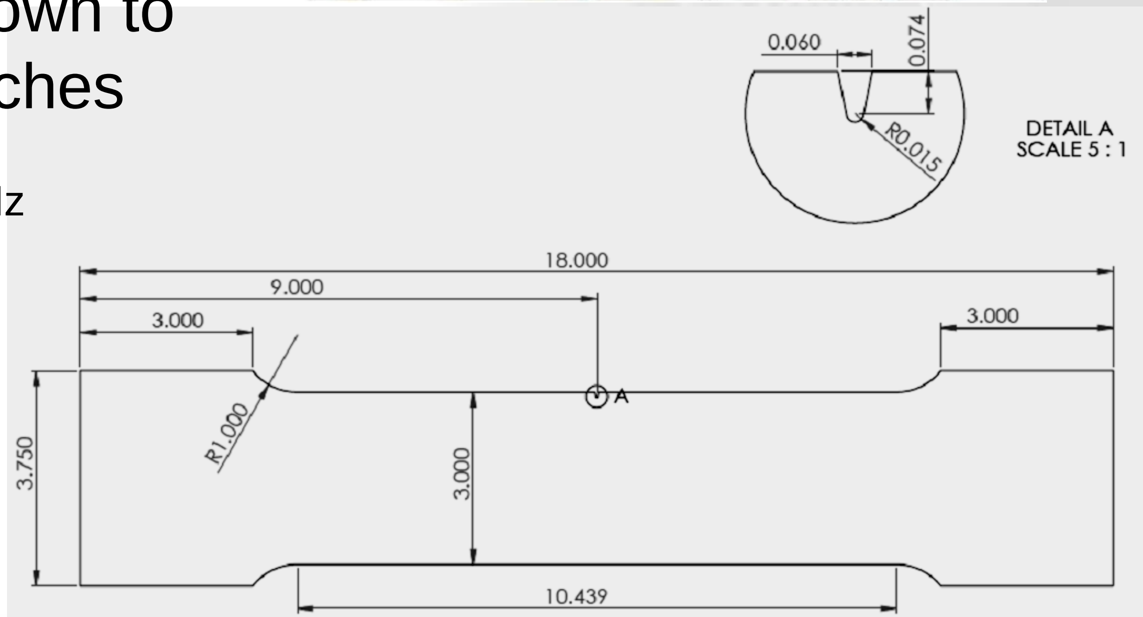
FEA Summary

- Models were run simulating test case with StopCrackEX repair with the initial crack and the crack extending into the hole bore.
  - Load of 10995 lbs (20.5 ksi net stress) was applied to the test plate with the notch, initial crack and the crack at edge of hole.
- Stress profile for StopCrackEX process shows lower stresses at the potential crack initiation site on the un-cracked side of the hole.
  - Stresses on the un-cracked side of hole for StopCrackEX process were about 20 ksi lower than for Drill Stop process (under tensile load of 10995 lbs).
- **Based on the stress profiles, StopCrackEX will provide better fatigue life compared to Drill Stop method**.
- The Drill Stop process could have crack initiation at as low as 6.7 ksi per FEA model
- FEA results under load showed good correlation to the test coupons

Fatigue Test Overview

- 7 specimens prepared – tested in 22-kip frame
- Initial starter notch to promote natural propagation of fatigue crack
- Crack initiated and grown to approximately 0.25 inches
  - 25 ksi max gross stress
  - R = 0.05, Frequency = 10 Hz

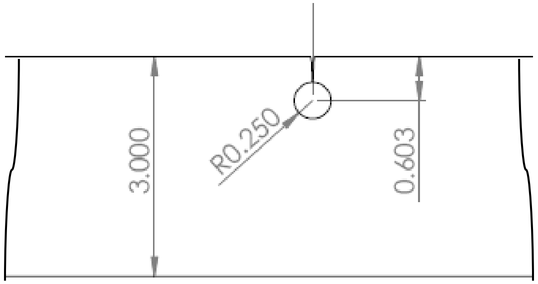


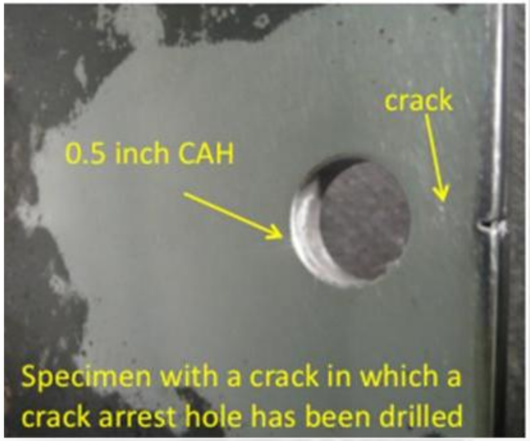


A36 Steel
Minimum yield 36 ksi
Tensile strength 58-80 ksi
Actual yield - 46.6 ksi
Actual tensile strength – 70.1 ksi

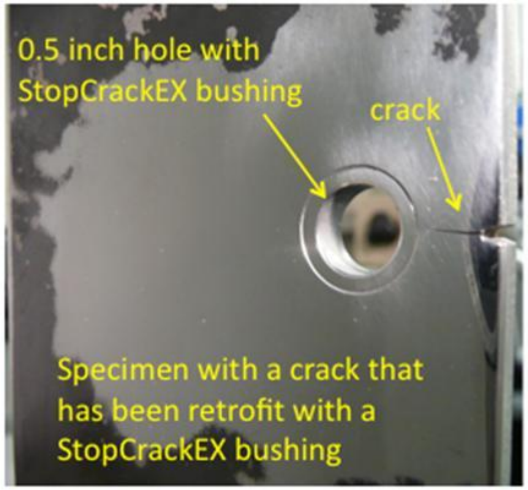
Test Setup - Pre-Cracking

- After all initial cracks were grown to approximately 0.25 inches the specimens were retrofitted with 1 of 2 methods
  - Standard 0.5 inch crack arrest hole (CAH)
  - FTI's StopCrackEX process
- CAH and StopCrackEX Bushing holes were placed in the same location for all samples
  - 0.603 inches from edge
  - 0.060 inches in front of the crack





Crack Arrest Hole

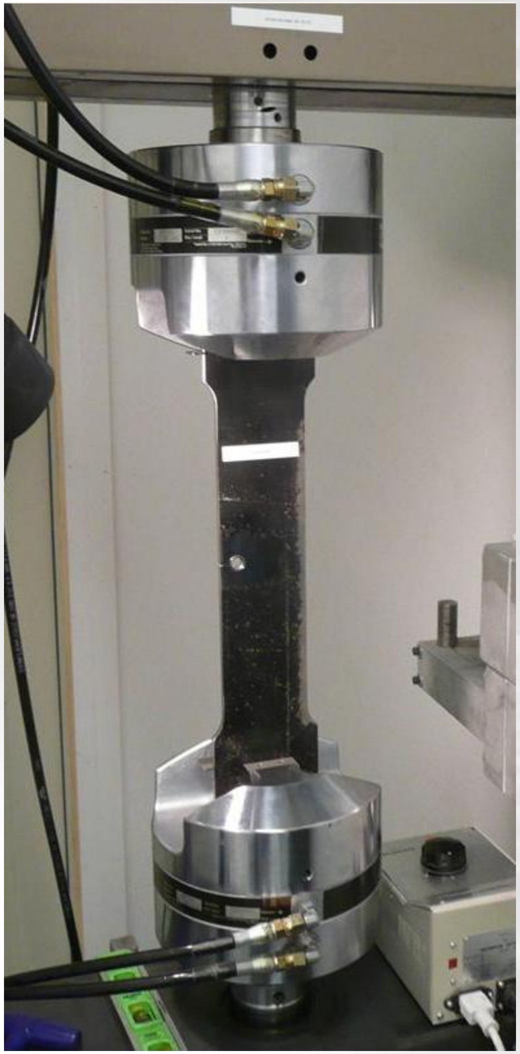


StopCrackEX Bushing in Crack Arrest Hole

Crack Arrest Method Testing

- After retrofit specimens were tested to determine the fatigue life of the retrofit
  - Max Net Stress = 20.5 ksi
  - R = 0.05, Frequency = 10 Hz

- Cycle counts measured for two events
  1. Number cycles for crack to reach the hole
  2. Number of cycles required to initiate a crack of approximately 0.150 inches on the side of the hole opposite the crack

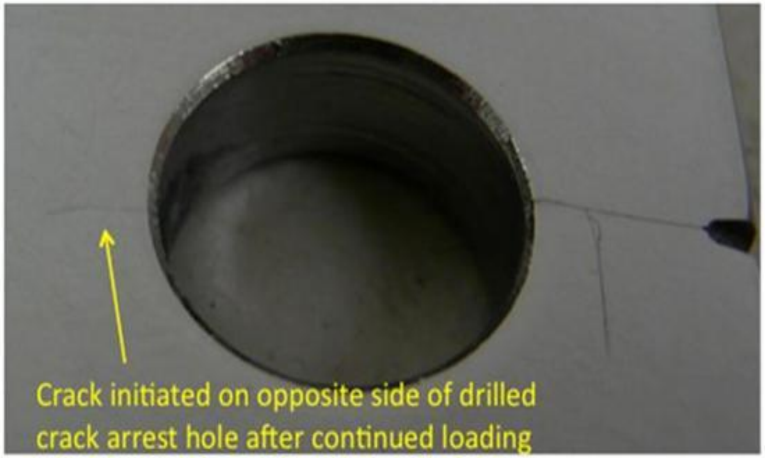


Post Repair Test Results

StopCrackEX™ Independent Fatigue Test

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	**20,000,000**	**No Crack**

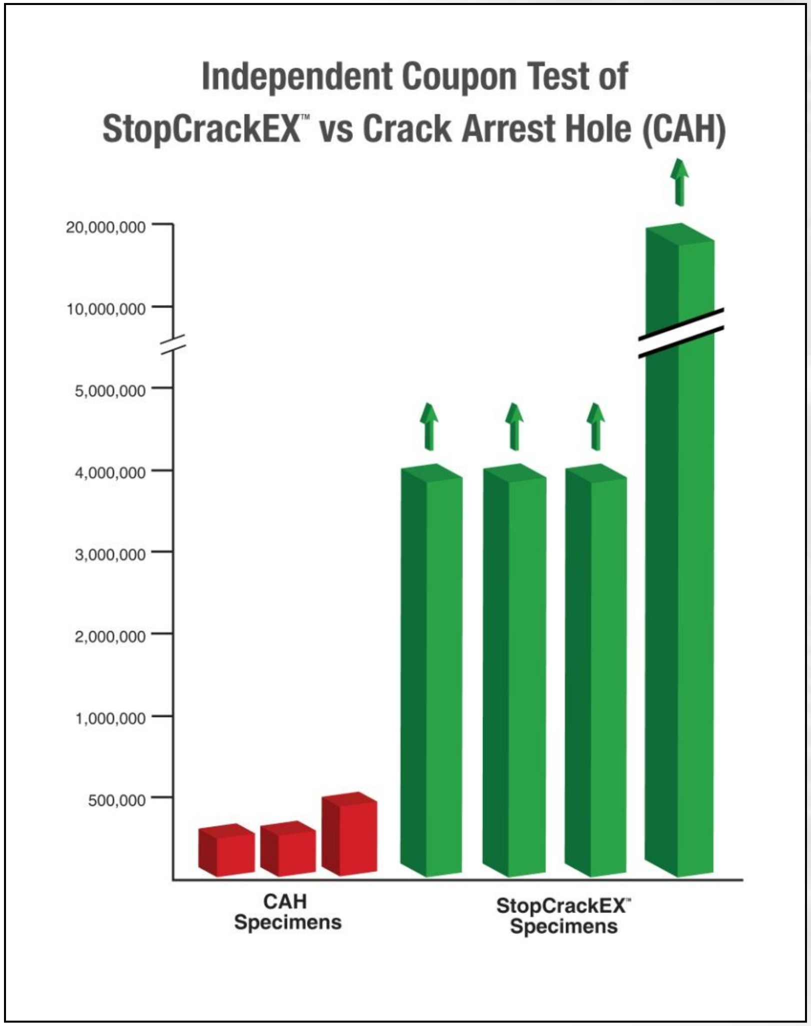
Crack Arrest Hole



StopCrackEX Repair

Summary Of Coupon Test Results

- StopCrackEX showed at least 12:1 improvement in crack growth life
- No StopCrackEX coupons cracked on other side of hole
- **One Coupon ran to 20,000,000 cycles with no evidence of crack on other side of hole**



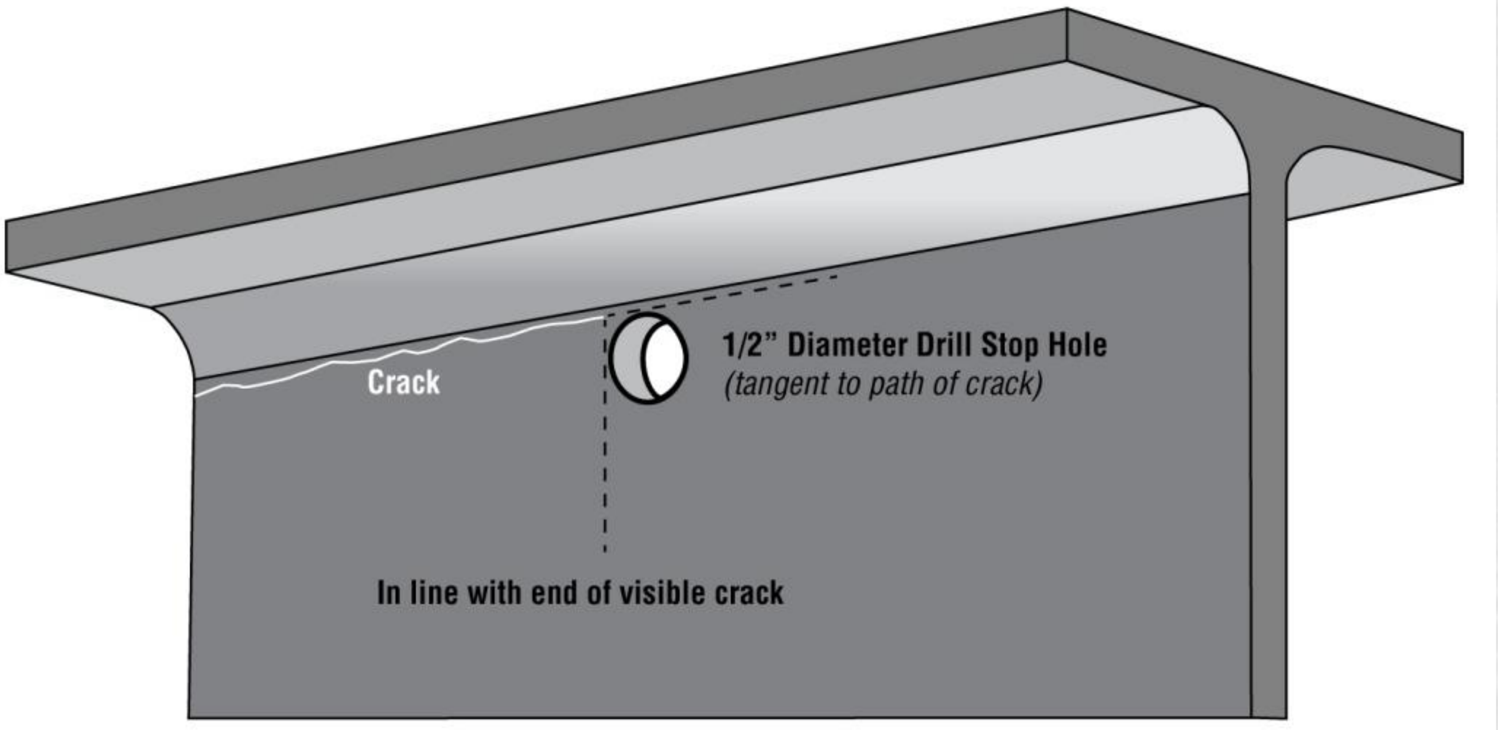
Post Test Evaluation

- One more of the StopCrackEX coupons that did not fail at 4 million cycles was put back in the test frame and tested at progressively increased load (stress level)
  - 2 ksi increase to 22.5 ksi – ran 2 million cycles
  - 2 ksi increase to 24.5 ksi – ran 2 million cycles
  - 2 ksi increase to 26.5 ksi – ran 381,835 cycles failed
- Results showed that StopCrackEX allowed operations at up to a 20% increase in load factor

Second Coupon Test Program

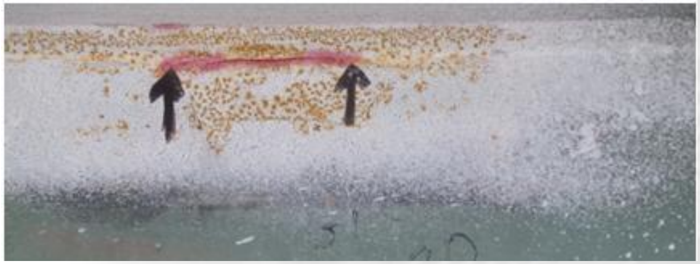
- One of the more prevalent cracks in bridges are those that run along the heat effected zone associated with welds under flanges, beams or girders
- Standard crack arrest holes are not effective in stopping cracks
- Often cut into and compromise welds

Location of Drill Stop Hole – Tangent to Crack Path



Second Test Program

- FTI has test program to evaluate effectiveness of StopCrackEX placed adjacent to tip of crack
- Authorities do not want to compromise the weld
- Currently optimizing location of StopCrackEX with respect to crack tip



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

- StopCrackEX showed a 300% improvement on life extension compared to CAH
- Relative position of StopCrackEX adjacent to crack tip being optimized
- Currently being evaluated on New Jersey Turnpike

CURRENT AND PENDING BRIDGE APPLICATIONS

New Jersey Manahawkin Bay Bridge

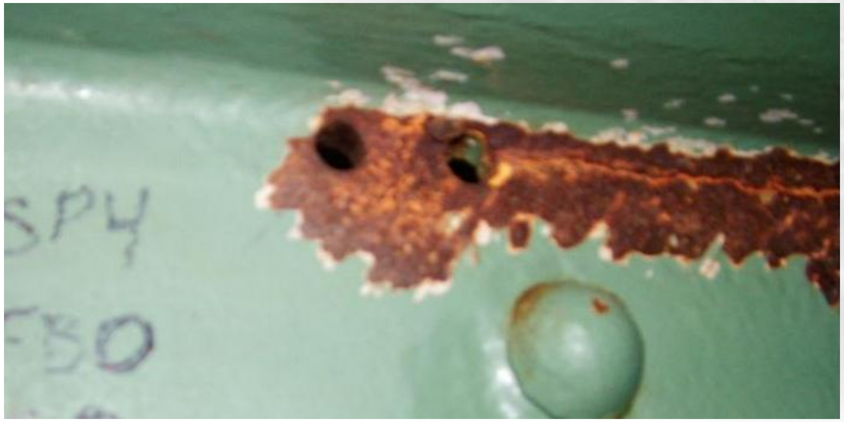
Applied StopCrackEX to several cracks on bridge October 2011
After 15 months NJDOT observed cracks had reached the bushing but were arrested

New Jersey Manahawkin Bay Bridge Observation

After 15 months NJDOT observed crack had reached the bushing but was arrested

New Jersey Turnpike

- Head to head comparison of StopCrackEX against standard CAH on flyover to Lincoln Tunnel in NY
- Cracks running along weldment under flange
- CAH cannot be drilled into weld so need to drill CAH adjacent to crack
- FEA shows StopCrackEX should be effective in retarding crack growth because of induced residual compressive stress
- Application March 2012



NJ Turnpike Authority Trial

<u>6 Cracks Identified for Trial Evaluation</u>:

Conventional 1.0 inch diameter CAH on one end of crack and StopCrackEX on the other

NJ Turnpike

Carrying out trial repair on one of the cracks

Drilling through weld for 1.0" diameter CAH proved difficult and time consuming (5 times longer)


Reaming Drill Stop Hole


Pilot drilling hole


Installing StopCrackEX

NYDOT Bridge, Marysville

- Installed StopCrack EX on hole that had been RED Flagged
- Repaired hole will be monitored
- Will save considerable time and cost over alternate doubler repair.

Alternate Doubler Repair

Post Repair

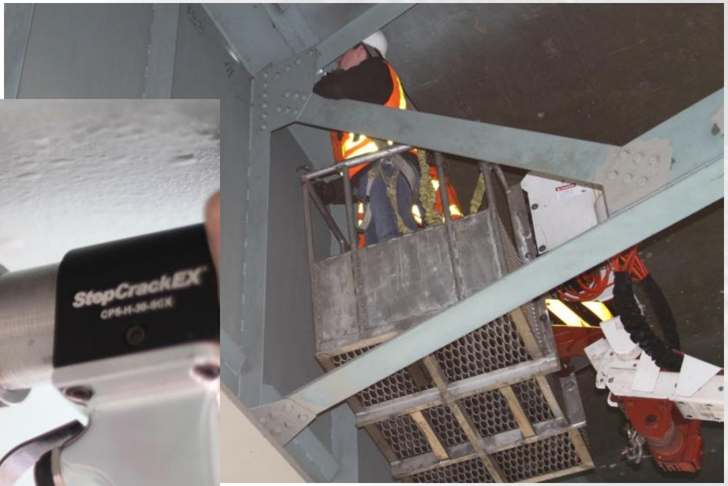
NYDOT Miller Rd Bridge
Near Albany (I-90 overpass)

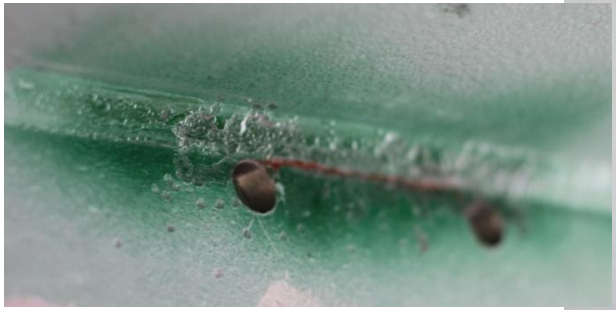
- Double ended crack either side of a structural diaphragm
- Crack occurred in previously welded patch repair
- StopCrackEX installed at each end of crack

June 25, 2012

WASDOT – I-5 Bridge over Stillaguamish River, Marysville
January 2013

- 8 locations where StopCrackEX applied
- Some with multiple cracks
- Cracking associated with out-of-plane bending from diaphragm attachment





Missouri DOT Orthotropic Bridge Deck Repair

4-28-2013 A1500 St. Louis City
WB Poplar St. Bridge
Transverse Deck Crack Repair
37' West of Bent 3 at WB Rt Shldr

4-28-2013 A1500 St. Louis City
WB Poplar St. Bridge
Wearing Surface Removal Very Difficult
Hand Grinders Worked Best

4-28-2013 A1500 St. Louis City
WB Poplar St. Bridge
Crack Extended 6" inside Vertical Plate

4-28-2013 A1500 St. Louis City
WB Poplar St. Bridge
7/16" Dia. Mag Drill Used for End of Crack Hole

Missouri DOT Orthotropic Bridge Deck Repair

Missouri DOT

- Evaluation using the expanded bushing method to resize holes in girders on a bridge to facilitate removal of corroded/cracked pin joint plates
- Plug welds removed by core drilling through plate and girder
  - Faster and easier than drilling out weld
- Plates removed
- Hole in girder resized by expanding high interference fit bushing into hole
- New plates fitted and bolted in place using original size bolts

MODOT Pin Joint Plate Replacement

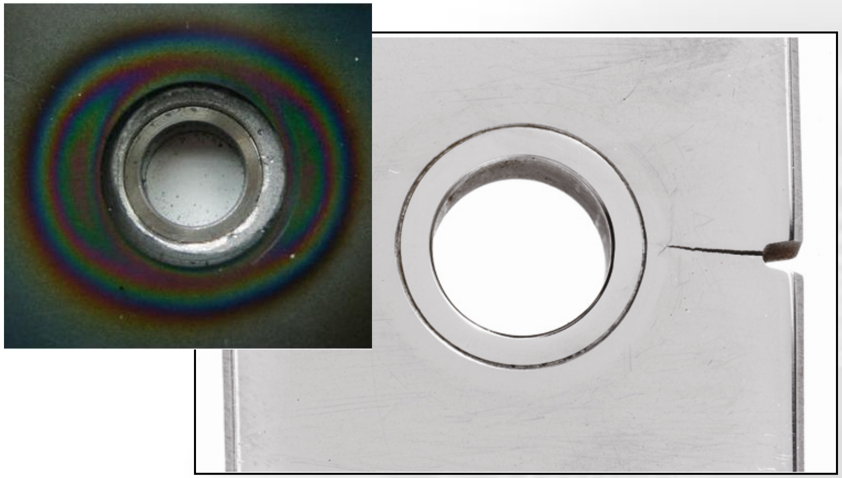
- Core drilling out the plug welds (1.25” dia)
- Expanding bushing in girder to resize hole for 1.00” dia bolt

Summary Conclusions

- There are many aging steel bridges in the USA
- A large number of these bridges have critical fatigue cracks
- Repairs are expensive and time consuming
  - Require continuous monitoring
- Catastrophic failure devastating in terms of lost infrastructure, commerce and possibly lives lost
- Current crack arrest hole is ineffective in mitigating crack growth

Conclusions

- **StopCrackEX** system based on proven aerospace technology
- Induces beneficial residual compressive stress around the bushed hole
- Shown by coupon test and FEA analysis to arrest growth of cracks
- Provides positive indication of implementation – visible bushing
- Will extend structural inspection cycle
- Can provide significant maintenance, preservation and repair cost savings
  - Extend inspection intervals
- Will enhance overall structural integrity and safety of bridge structure
- **Should be part of overall long term bridge preservation plan**



StopCrackEX showed 45 to 90 times improvement over crack arrest holes

Questions? Thank You!

Visit our website www.ft-infrastructures.com