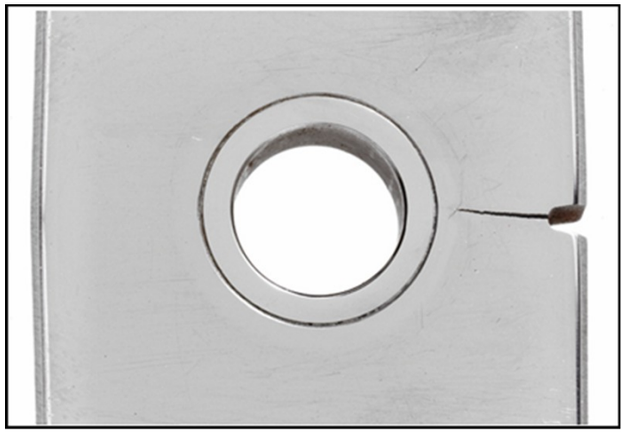
Fatigue Technology
World Leaders in Cold Expanded Products

Residual Compressive Stress as a Crack Arrest Method

Agenda

- Fatigue Technology
- Introduction
- Cold Expansion
  - Crack Arrest
  - Development and Testing
  - Current Applications
- New Applications
  - New configuration for lime kilns
  - Lab Testing
  - Field Testing
- Conclusions



An Aerospace Company??

A little bit about FTI

- FTI is a wholly-owned subsidiary of Precision Castparts Corp (PCC) and Berkshire Hathaway
- Recognized as industry experts on Residual Stress Field technology relative to fastened joints and holes
- FTI uses finite element analysis (FEA) together with static and dynamic testing to validate solutions prior to implementation
- FTI repeatedly provides solutions that lower manufacturing and maintenance costs while enhancing structural performance

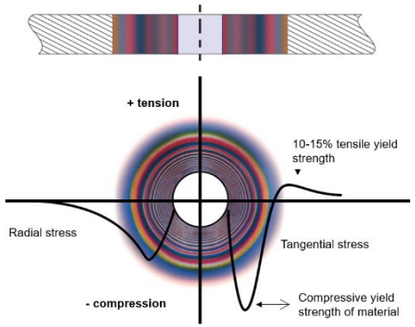
FTI is committed to internal and collaborative research programs that enable continual improvements to the fidelity and accessibility of RS data for customer use

Introduction

- Cracks from cyclic loading can be mitigated and even prevented through compressive residual stress (RS)
- Boeing developed the cold expansion process to impart RS in metallic structures
- Used as a crack repair in aviation starting in the 1980s
  - Crack Arrest Hole (CAH) paired with an interference pin
  - Longer life than traditional CAH
- Now used in infrastructure, primarily bridges
- Marketed as StopCrackEX™
- Evolved the process to include heavy industry, kilns, and maritime structures

Cold Expansion (Cx)

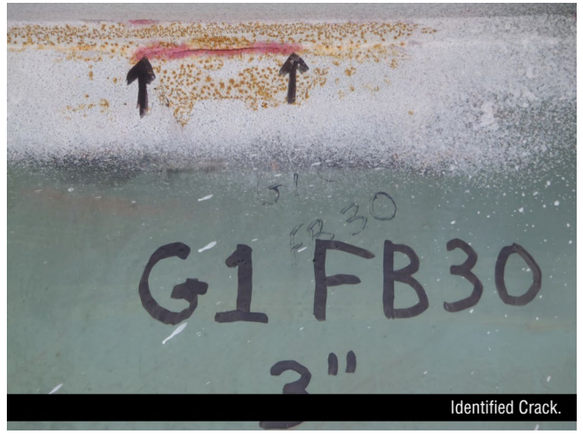
- Radial displacement of material around a hole
- Creates a zone of residual compressive stress



- Used in aviation for 49 years to protect fastener holes and joints from cyclic fatigue

Cold Expansion continued

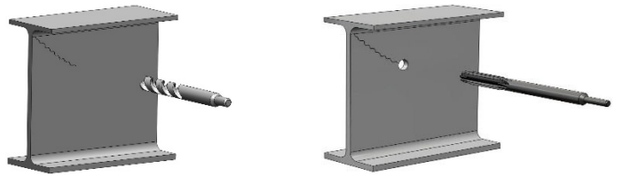
- RS from Cx is used for more than just aviation
  - Adapted as an enhanced aviation CAH repair
  - Further evolved for use in structural steels
  - Combines imparted RS with propping action of a bushing



Identified Crack.

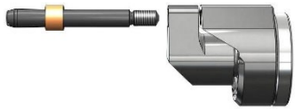
Repair Complete: ‘Crack Arrest Hole’ (left), ‘StopCrackEX Hole’ (right).

Crack Arrest Process

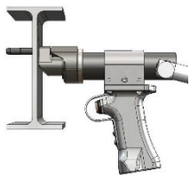


CAH located, drilled, reamed

Hole quality and mandrel wear check



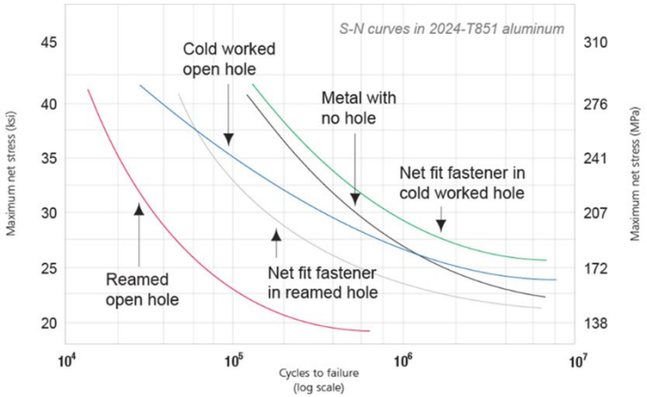
Load bushing and thread mandrel



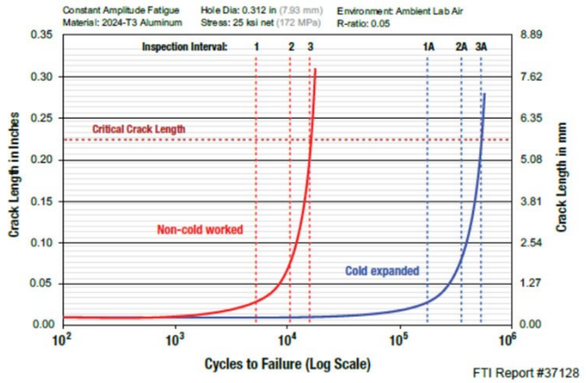
Hydraulically retract mandrel, install bushing, impart RS

Process Animation

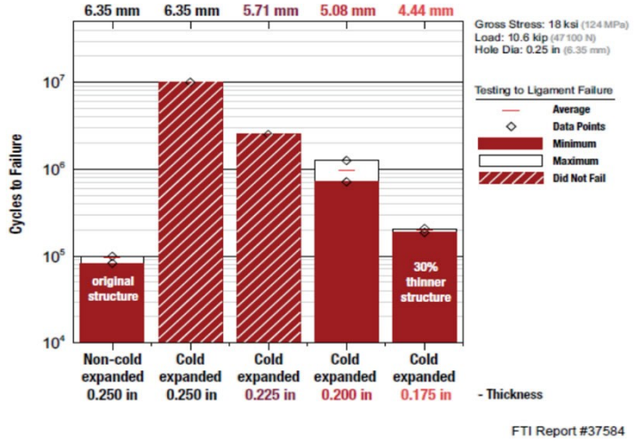
Development & Testing of RS from Basic Cx



A: Fatigue Life Improvement due to SsCx



C: Extending Inspection Intervals due to SsCx



B: Weight Savings due to SsCX

Numerous studies showing benefit of RS

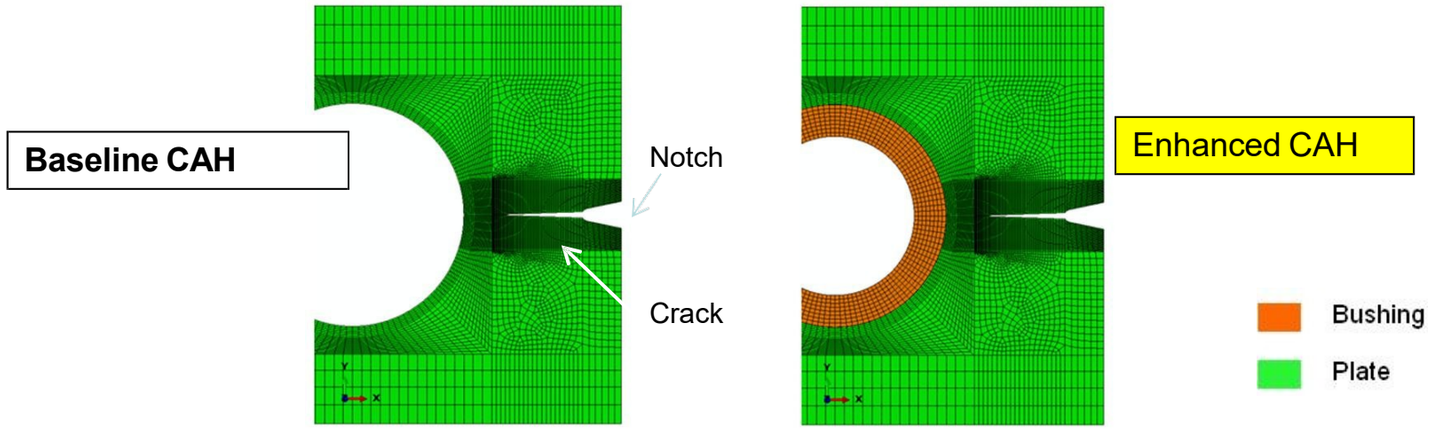
- A Cx hole with a net fit fastener demonstrated better fatigue performance than no hole at certain stress levels (Fig A)
- Shown to reduce weight by allowing for thinner structures (Fig B)
- Allows for increased inspection intervals (Fic C)

Development & Testing of RS as Crack Mitigation

- Introduced for use in aviation in early ‘80s
  - Confirmed in lab and field studies
  - Adopted as a standard repair
  - Additional testing showed increased efficacy with interference fit pin
- Developed for use in infrastructure late ‘00s
  - RS are compressive at the hole bore, reducing mean stress during in service cycling
  - Bushing props hole, altering the effective stress amplitude at the bore

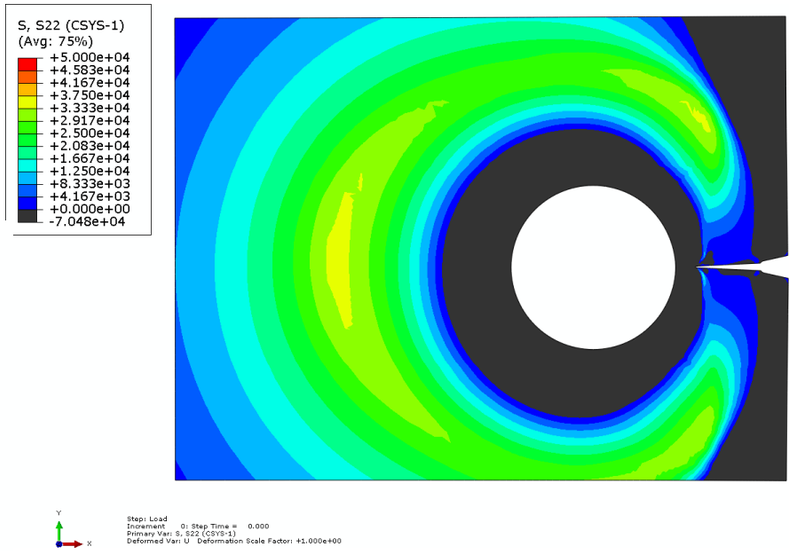
Finite Element Analysis

- Simulate CAH and enhanced CAH at time of repair
- Applied stress to test plate after repair

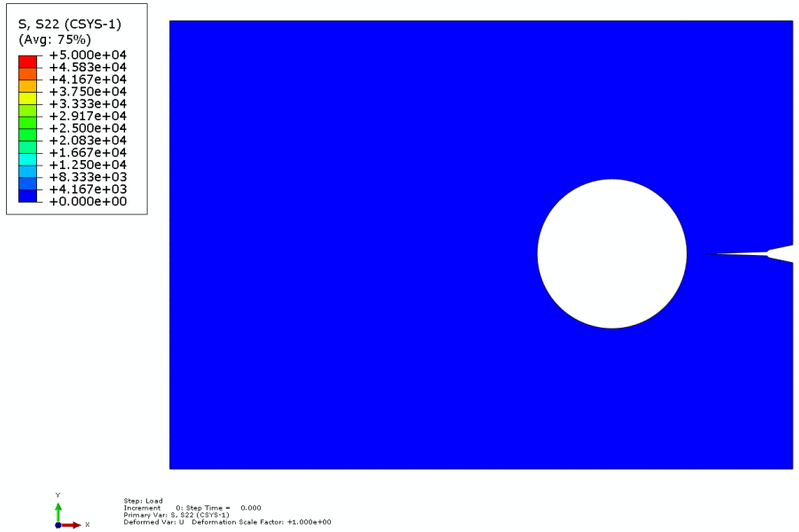


Residual Hoop Stress (psi) Contour Plot

Enhanced CAH



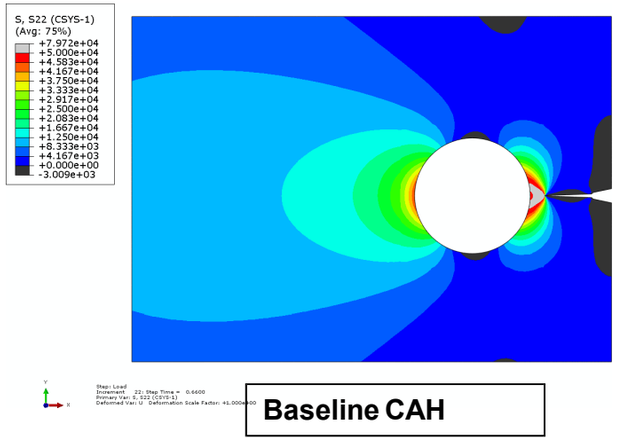
Baseline CAH



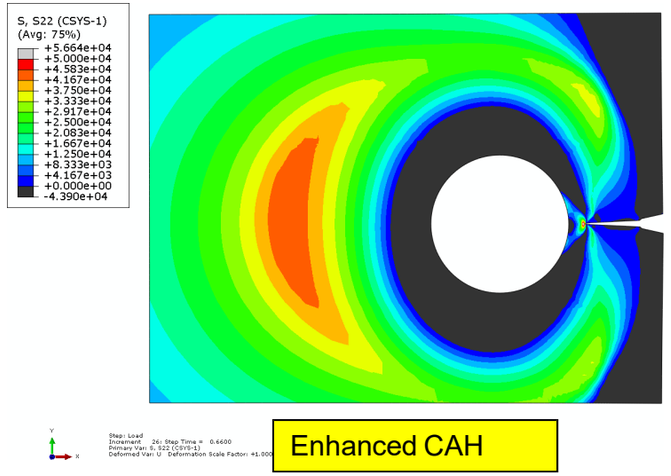
No Load

Hoop Stress (psi) Contour Plot:

Tensile Load = 13.5 ksi (Net Stress)

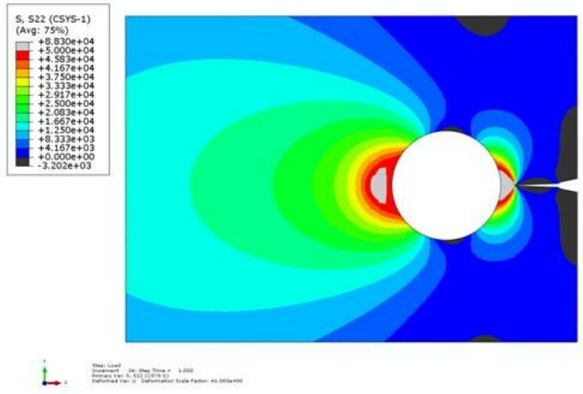


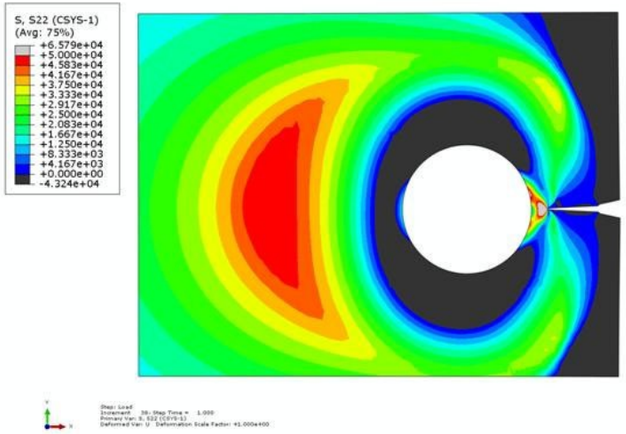
Baseline CAH



Enhanced CAH

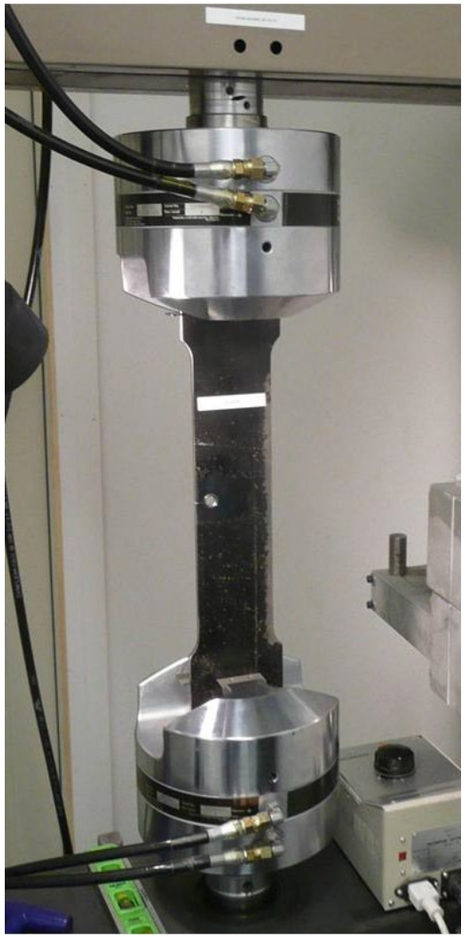
Tensile Load = 20.5 ksi (Net Stress)





Independent Crack Arrest Testing

- Southern Utah Engineering
- 6 coupons and a spare
- Notched and grew crack to 0.25 inch
- Test conditions
  - Max Net Stress = 20.5 ksi
  - R = 0.05, Frequency = 10 Hz
- Cycle counts were measured for two events
  - Number of cycles for crack to reach the hole and break the first edge
  - Number of cycles required to initiate a crack of approximately 0.150 inches on the side of the hole opposite the crack



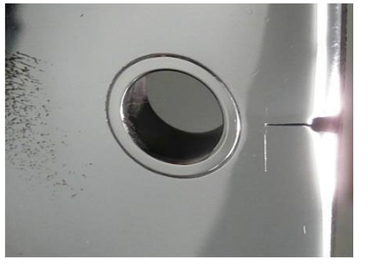
Post Repair Test Results

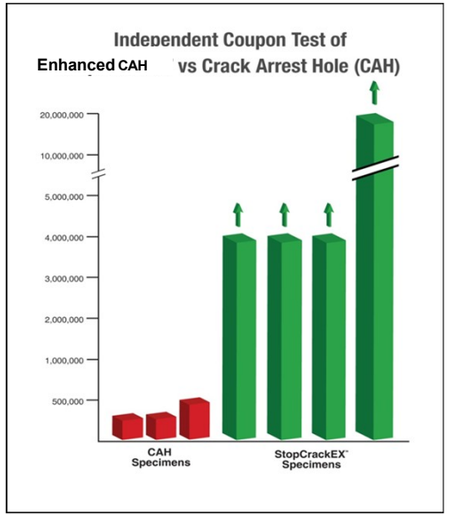
StopCrackEX™ Independent Fatigue Test

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	Enhanced CAH	0.29	20.5	0.05	580,000	1,700,000	**4,000,000**	**No Crack**
2	Enhanced CAH	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	Enhanced CAH	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	Enhanced CAH	0.262	20.5	0.05	210,000	3,700,000	**20,000,000**	**No Crack**

Baseline CAH

Enhanced CAH





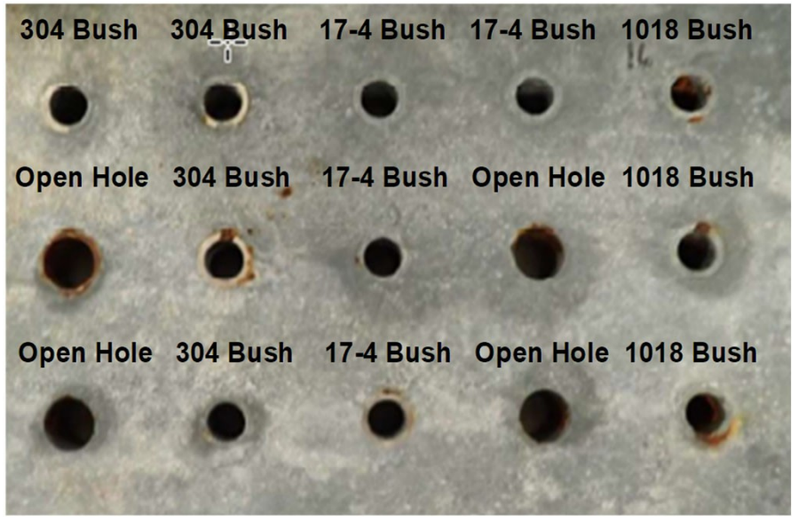
Welded Coupon Test Program

- One of the more prevalent cracks in steel structure are those that run along the heat effected zone associated with welds under flanges in beams or girders
- Standard crack arrest holes are not effective in stopping cracks
- CAH cut into weld can compromise weld
- Test program performed to evaluate effectiveness of enhanced CAH placed adjacent to tip of crack
- In place since 2012 on New Jersey Turnpike - no reported propagation to date

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

Corrosion Testing

- 1000 hour salt spray corrosion test
- Tested three different bushing materials
  - 304 SS
  - 17-4 SS
  - 1018 SS
- No difference in corrosion in non bushed holes
- Paint after processing



Monitored Field Trials

Manahawkin Bay Bridge, NJDOT (Oct 2011)

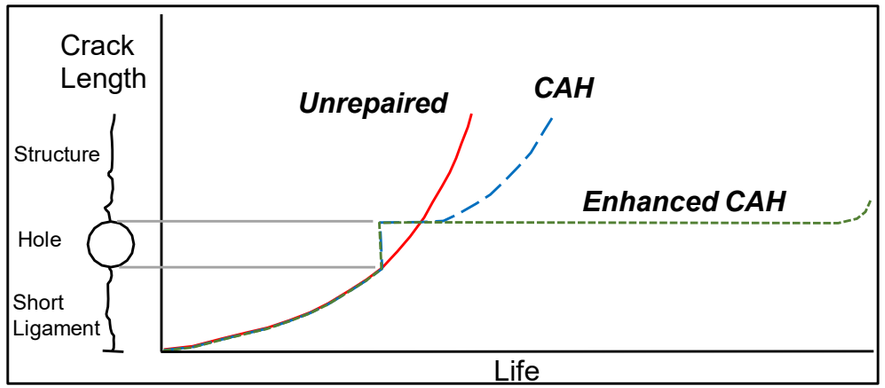
Lincoln Tunnel Interchange, NJTA (Mar 2012)

Bridge over Delaware River, NYSDOT (Apr 2012)

No reported failure or further crack propagation

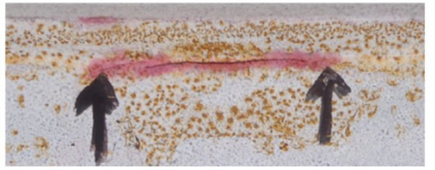
Developmental Conclusions

- Foundation from aerospace practical applications
- FEA supported assumptions of performance in mild steel
- Lab testing confirmed performance
- Ready for field use



Current Applications

- Multiple transportation agencies at the state, county and city level
  - Recent survey for issues
  - None reported
- Other misc
  - Amusement park
  - Port material handling equipment
  - North Sea oil rig



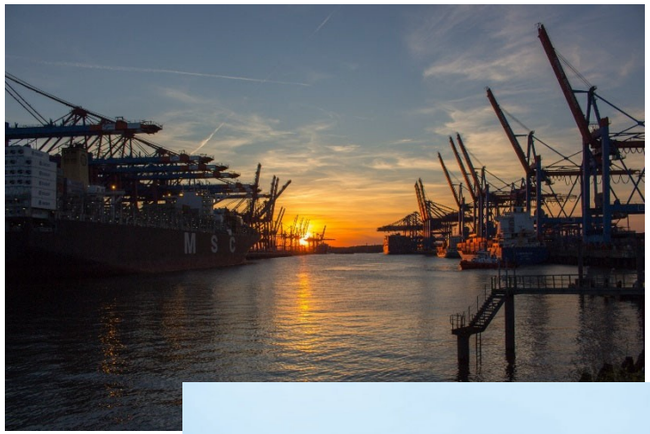
Before: Typical Weld Line Crack

After: StopCrackEX installed

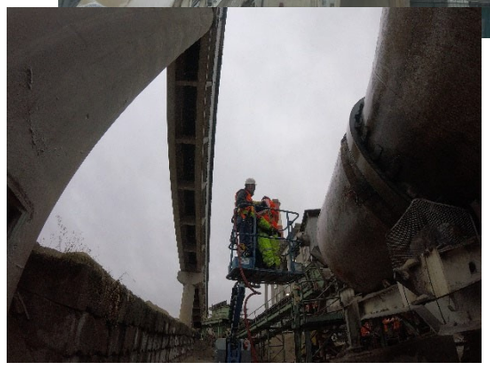
Lincoln Tunnel Interchange, NJTA

New Applications

- Maritime

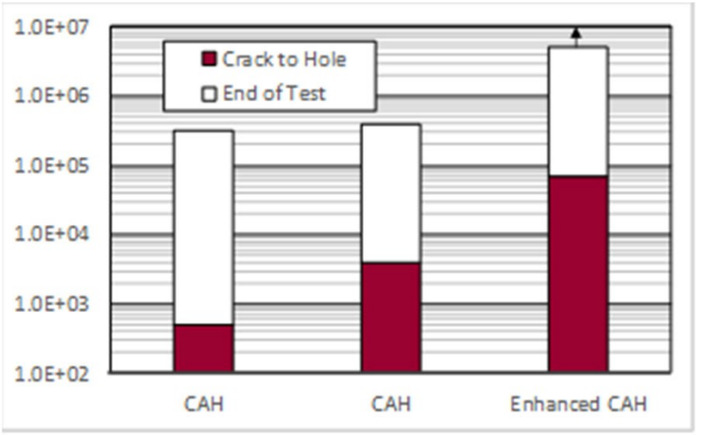


- Lime Kilns



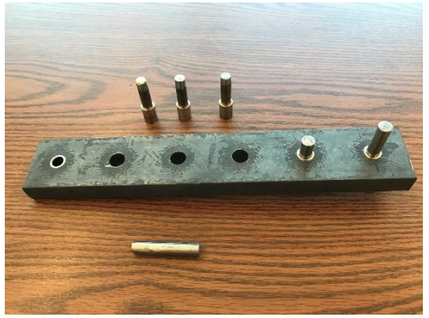
Maritime Applications

- Partnered with a Classification Society for lab and field testing
- 13:1 improvement in the lab
- Container ship field test
  - Crack on a stiffener weld line
  - Multiple North Pacific crossings in heavy sea conditions
  - No propagation beyond the repair after 30 months of monitoring



AH32 Marine Steel Fatigue Test Results

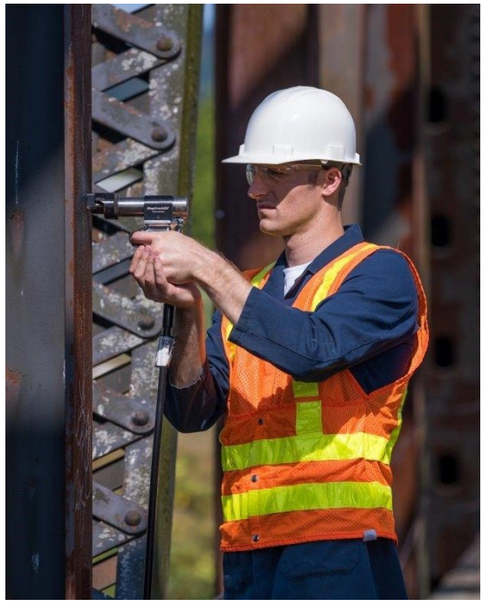
Kilns



- Tooling adapted to kiln use via discussions with multiple operators
  - Longer widths
  - Flanged bushings
  - Interference Pins
- Monitored repair
  - Operating lime kiln
  - No propagation at 12 month inspection

Conclusions

- Enhanced CAH reduces stress intensity at crack tip
- Delays crack propagation
- Refined through years of development, lab and field testing
- No reports of crack propagation from the field
- Lab testing demonstrated up to a 13:1 improvement over traditional method
- Successful 30-month field trial on container ship in the North Pacific and 12 months on operating kiln
- Simple and easy to use
- Ready to be deployed



Questions?