ABS ADVISORY ON COLD EXPANSION TECHNOLOGY

ABS

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SECTION 1 - INTRODUCTION

Cyclic loading from ocean waves can cause fatigue damage and cracks in marine and offshore structures. If these cracks are left to propagate they can compromise the structural integrity and safety of the vessel/asset. To protect the vessel/asset and preserve life and the environment, class societies typically require owners to permanently repair cracks located at critical areas of structures. For cracks located at non-critical areas, when constraints such as hot work restrictions make permanent repairs impractical during normal operations, temporary repairs may be considered on a case-by-case basis.

To permanently repair a cracked structure inside the cargo tank of a Floating Production Storage and Offloading (FPSO), the operator must:

- Halt production
- Empty the affected tank
- Clean the affected tank
- Make the confined space safe for human entry
- Make the confined space safe for hot work (depending on the type of repair)

In today's sensitive economic environment, owners want a repair solution that features an expedited, reliable, and safe repair process.

A CRITICAL CRACK IS CHARACTERIZED AS EITHER:

"a visible, through thickness fracture of any length in the oiltight envelope of the outer shell where threat of pollution is a factor" or "a fracture or buckle which has weakened a main strength member to the extent that the safety of the vessel to operate within its design parameters is compromised" during normal operation conditions."

United States Coast Guard (USCG) Navigation and Vessel Inspection Circular (NVIC) 15-19

A temporary repair method with these features is desired to allow normal operations until the next scheduled inspection. Cold expanded crack arrest hole technology has been used to improve the fatigue life of crack arrest holes (i.e. stop holes) and satisfies the necessary features of repair (Reid 2014). The aerospace industry has implemented this cold expansion (CX) technology for 48 years to improve the fatigue life of fastener holes. Over the past decade, the scope of this technology has expanded to encompass improving the fatigue life of crack arrest holes in railroad rails and bridges. However, this technology has only been implemented on a limited basis in maritime applications. It would be beneficial for the maritime industry to utilize the experience of CX technologies from other industries.

In 2015, the American Bureau of Shipping conducted a feasibility study of cold expansion technology for marine structures (Lee et al., 2017, Liu et al., 2019). The cold expansion technology was implemented on an active crack. Visual inspection, as well as acoustic emission testing were used to understand crack growth conditions. Results from these studies show a promising potential for cold expanded arrest holes as a long lifetime repair solution.

1.1 OBJECTIVE

The objective of this Advisory is to provide operators and ship/asset owners with insight, best practices, and a procedure for cold expansion technology as a possible measure to slow down crack propagation. Cold expansion technology offers a simple, easily implemented, and low cost way to slow crack propagation.

1.2 SCOPE AND LIMITATIONS OF USING COLD EXPANSION TECHNOLOGY

The scope of this document covers crack repair options, the description of cold expansion technology, the installation of cold expansion technology, the experience from the feasibility study, and the ABS approval process of cold expansion technology. The typical cold expansion technology is shown in Figure 1. The cold expansion technology is used as a means to slow down the propagation of a through-thickness crack on steel structures. Depending upon the application it may be possible to apply cold expansion technology to arrest an existing crack for a defined period of operation, where usually it would have been necessary to crop and renew plating, or gouge and reweld.

The following items as a minimum must be satisfied for the implementation of cold expansion technology:

- Acceptance of the procedure by the class society.
- The overall coating condition must be good or fair and the structural condition be sound.
- In general, the cold expansion technology can be used for local and non-watertight structures.
- The thickness of steel plate is to be less than or equal to 25mm (1 inch). If the thickness of the steel plate is greater than 25mm (1 inch), a laboratory fatigue test or/and a Finite Element Analysis (FEA) is to be performed to evaluate the fatigue life for the cold expansion technology at the crack tip.

Figure 1: Typical cold expansion technology at crack tip

1.3 ABBREVIATIONS

ABS American Bureau of Shipping
AET Acoustic Emission Testing
CAH Crack Arrest Hole
CX Cold Expansion
ECA Engineering Critical Assessment
FEA Finite Element Analysis
PDA Product Design Assessment

1.4 TERMINOLOGY

Terminology	Description
Crack Arrest Hole	A process to drill a hole at or just in front of the crack tip to relieve the localized stress concentration.
Cold Expansion Technology	A technology to expand a crack arrest hole (CAH), where a radial plastic region is formed around the hole to provide an annular zone of residual compressive stress. This compressive stress could potentially extend the fatigue life of the hole and help to retard further crack propagation.
Engineering Critical Assessment	A procedure by which the safety of a welded structure with defects or flaws can be determined. An Engineering Critical Assessment (ECA) is based heavily upon fracture mechanics principles.
Manufacturing Assessment	An assessment of manufacturer who can demonstrate the ability to produce consistent products in compliance with PDA.
Product Design Assessment	A general assessment of materials, components, products or systems for a specific use in compliance with recognized standards.
Type Approval	An ABS voluntary program which provides qualified manufacturers targeting marine and offshore sectors the benefit of a more efficient product certification process.

SECTION 2 - REPAIR CRACKS ON MARINE AND OFFSHORE STRUCTURES

2.1 TRADITIONAL REPAIR OPTIONS FOR ADDRESSING CRACKS

The most common traditional crack repair methods are "gouge and re-weld" and "crop and renewal" (SSC-462, 2012). Both methods are time intensive, costly, and are hot-work processes. In the case of a cracked structure inside a cargo tank, the confined space must be prepared and approved for safe human entry, as well as hot work conditions, before repairs may commence. Additionally, for the cracked structure inside the cargo tank, the vessel/asset must stop operations during this process resulting in loss of valuable time in addition to the costs of performing the repair. As such, these types of repairs are not always feasible during normal operational periods. In these cases, alternative means may be considered.

There are two types of alternative means to slow down crack propagation — composite repair and crack arrest hole (CAH). Detailed information about composite repairs is described in the ABS *Guidance Notes on Composite Repairs of Steel Structures and Piping* (https://ww2.eagle.org/en/rules-and-resources/rules-and-guides.html). The CAH repair method is applicable to a temporary repair for a very short-term period (e.g. several months). The acceptance of a CAH by ABS is considered on a case-by-case basis. Detailed information about CAH repair is described in the next section.

2.2 WHAT IS A CRACK ARREST HOLE?

For current marine/offshore industry practice, a temporary means to slow down a crack's propagation is drilling a "stop hole" or a CAH. This CAH is a means by which a hole is drilled at or just in front of the tip of the crack to relieve the localized stress concentration. This method is relatively inexpensive and less time consuming compared to a permanent weld repair.

WHAT IF THE CRACK IS NOT CRITICAL?

A crack is deemed medium or low criticality if it "does not compromise the safety of the vessel to operate within its design parameters and does not create a threat of pollution either by location or containment."*

These cracks are generally monitored, either visually or with a fatigue sensor, for crack growth. Alternatively, an engineering critical analysis is conducted, which uses fracture mechanics principles to evaluate the crack and determine how urgent repairs are. Furthermore, vessels can redistribute the loads acting on the crack to mitigate propagation.

Follow-up inspections re-evaluate the crack's criticality and whether continued monitoring is sufficient or if repairs are needed.**

*United States Coast Guard (USCG) MOC Policy Letter No. 2-96

**United States Coast Guard (USCG) Navigation and Vessel Inspection Circular (NVIC) 15-91

While this method may require confined space preparations and precautions, the hot work restrictions associated with drilling metal with appropriate treatments are far less extensive than those required for welding. The typical treatment involves lubricating the drill bit with oil to reduce friction and sparks and to keep down the temperature of the materials with a slow drilling speed. The total time required to drill a CAH is much less than the total time needed to perform a weld repair, greatly reducing the operational cost of the repair.

However, there are some limitations for CAH repairs. From operational experience, crack re-initiation is very often seen on the opposite side of the CAH, leading to mistrust in the efficacy and reliability of CAHs. The main factors in the efficacy of CAHs in retarding further crack growth are proper execution and the selection of an appropriate crack arrest hole diameter. Common issues with the repair execution include CAH missing the crack tip, not located in front of the crack tip, and poor surface finish inside the hole. If the CAH misses the crack tip and the stress concentration is not properly relieved, the crack will quickly propagate. Additionally, if the CAH is not reamed to a smooth finish, localized stress concentrations can form on the rough edges of the hole and re-initiate cracks.

The hole diameter of the CAH must be sized correctly for the given loading, crack dimensions, and the structure's geometry. An undersized CAH may temporarily retard crack growth, but the crack will eventually re-initiate on the other side of the CAH and continue to propagate. Determination of the minimum hole diameter considers the crack length, material strength, and applied stress range (SSC-425, 2003). As shown in the example below, a crack in AH32 steel under a moderate stress range requires a CAH diameter that is larger than the crack itself. Since drilling large holes in a plate is impractical, a rule of thumb has been developed that states "for steel plates 12.7–25.4 mm in thickness, the diameter of a stop drilling hole is 0.5–2.0 times the plate thickness" (SSC-425, 2003).

Consider an AH32 steel plate of thickness 25 mm subject to a stress range of 94.5 MPa (30% of its tensile yield strength, 315 MPa). A 50 mm long crack is discovered, and a crack arrest hole is to be drilled at the crack tip. The minimum CAH diameter,D, (mm) given by (SSC-425, 2003)

$$D \geq \frac{S_R^2 a}{18\sigma_y}$$

where S_R is the stress range (MPa), a is the crack length (mm), and σ_y is the yield strength (MPa). This equation yields a minimum diameter of 78.75 mm, while the "Rule of Thumb" gives a diameter range of 12.5-50 mm. The resulting diameters are shown in Figure 2 relative to the original crack.

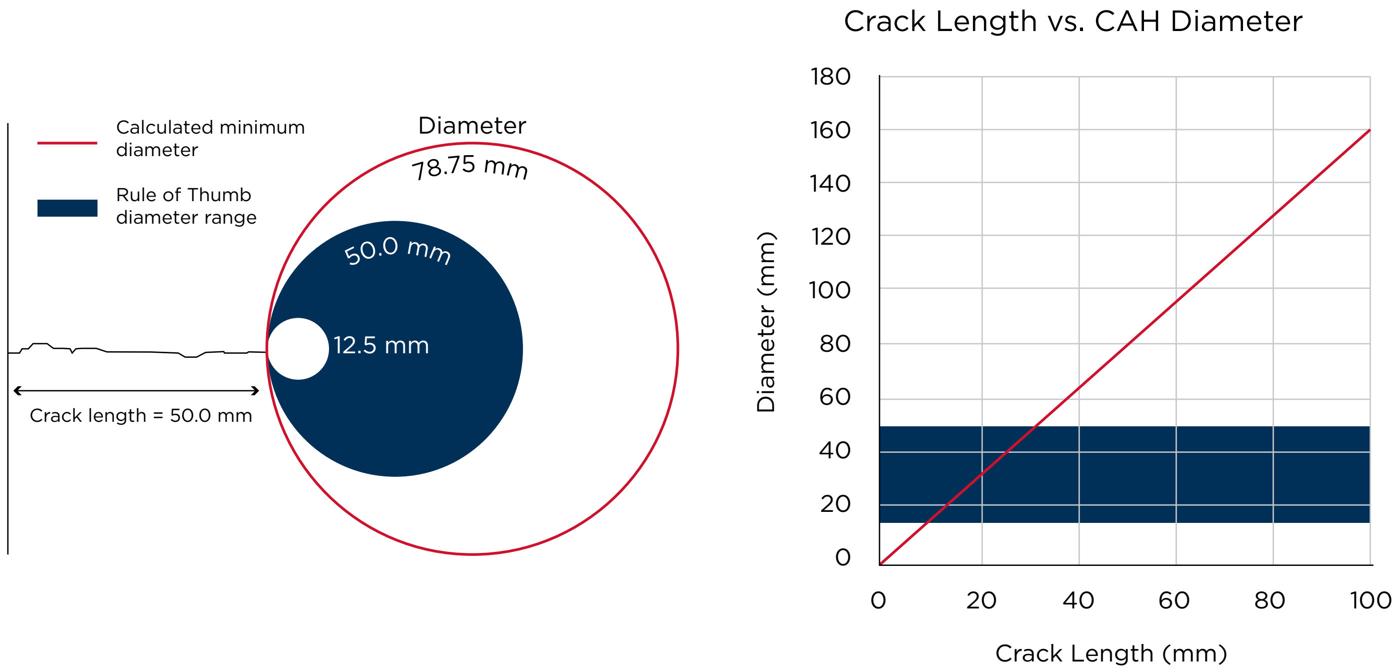


Figure 2: Calculated minimum diameter of hole and "Rule of Thumb" diameter range shown relative to given crack length.

Figure 3 (left): Crack re-initiation of CAH.

This required minimum hole size is impractically large. This calculated diameter is seldom used in maritime applications. The "Rule of Thumb" diameter is more often adopted for hole size. However, the crack re-initiation is frequently seen on the opposite side of the CAH (see Figure 3), leading to mistrust in the efficacy and reliability of CAHs. Due to the variation of the effectiveness of the CAH approach, it often requires more frequent inspection, which could be costly in both time and money. A simple, easily implemented, more reliable, and ABS-accepted method is Cold Expansion Technology, which may be used to slow down a crack's propagation.

SECTION 3 - COLD EXPANSION TECHNOLOGY

3.1 WHAT IS COLD EXPANSION TECHNOLOGY?

Cold Expansion is a technology that expands a CAH at ambient temperature. First developed for the aerospace industry by the Boeing Corporation in the late 1960s, the process uses a tapered mandrel pre-fitted with a lubricated split sleeve. The mandrel and sleeve are pulled through a hole drilled to a close tolerance, typically a 0.076mm (0.003 inch) range. Drawing the mandrel through the hole causes a radial plastic flow of material that results in plastic deformation. The material just beyond the plastically deformed hole constrains the plastic region and provides an annular zone of residual compressive stress. Later, an advanced cold expansion was developed and produced for multiple applications in aviation, rail, medicine, bridges, and other structural industries.

In the early 1980s a metal manufacturer evaluated combining the split sleeve cold expansion process with the stop-drill process (called enhanced stop-drill repair) to provide additional life to the temporary repair (Landy, et al. 1986). A parametric study was performed to evaluate the variables that may affect the use of the enhanced stop-drill repair process, including applied expansion level to the hole, fastener fit (interference), size of stop-drill hole, material differences, fastener head type, thin materials, different aluminum materials, and if the crack tip was missed with the repair. In all tests, the enhanced stop-drill repair was superior to the standard stop-drill process.

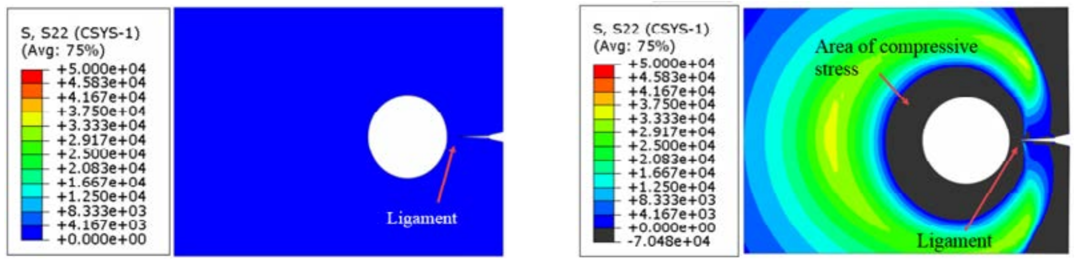
An aircraft manufacturer performed testing to compare stop-drill holes and cold expanded stop-drill holes. The aircraft manufacturer concluded that cold expanded stop-drill holes should be incorporated into their Structural Repair Manual for aluminum material. In their conclusions, they also recommended stop-drill holes should not be used in high stress areas (Worden and Miller 1993). A report produced by the Defense Science and Technology Organization (DTSO) in Australia concluded that the combination of an interference fit pin and cold expansion of hole extended the fatigue life of stop-drill holes. It was further stated that this process was promising to extend the structure life of Royal Australian Air Force (RAAF) aircraft (Callinan, et al. 1998). For bridge steel, the process of open cold expanded hole was developed in the 1990s (Reid, 2014) with testing performed on A36 steel. The results of this testing showed, at the forces tested, an open cold expanded hole provided a 12 to 1 improvement of fatigue life compared to just machining the hole (i.e. CAH).

The previous process was only to open and cold expand the hole. A plug or other interference fit fastener on aircraft was recommended in several research tests previously cited (Landy, et al. 1986; Worden and Miller, 1993; Callinan, et al. 1998). As a result, the previous process was modified for the bridge industry to include the installation of an interference fit bushing. The addition of the bushing allows for the hole to remain propped open with more interference than a typical interference fit fastener.

Cold expansion technology on a CAH was placed ahead of the visible crack tip, or adjacent to it, with the installation of a clearance fit specially designed stainless steel bushing (Reid, 2014). The bushing was expanded radially into the hole using an expansion mandrel. Equipped with a tool and a few minutes of instruction, an operator can quickly install a CAH at the end of the crack and cold expand the appropriate length bushing into the hole. The length of the bushing was determined by the thickness of the web or member into which the bushing was inserted.

As an example for the bridge industry (A36 steel), a Finite Element Analysis (FEA) was conducted with a 17-4 steel bushing. The yield stress of the A36 bridge steel is 321.3 N/mm2 (46.6 ksi) and the ultimate strength is 483.3 N/mm2 (70.1 ksi). The FEA showed that the installation of the bushing provided a residual stress field around the hole in Figure 4 (Reid, 2013).

When the FE model was loaded to 141 N/mm2 (20.5 ksi) in the vertical direction, the area around the cold expanded hole remained in compression as shown in Figure 5 before the crack reached the hole. The compressive zone on the cold expanded hole shielded the hole from the applied cyclic stress to slow or prevent crack growth. The depth of compression for this example was approximately 5 mm (0.2 inch) (Reid, 2013).



(a) Crack Arrest Hole (b) Cold Expansion

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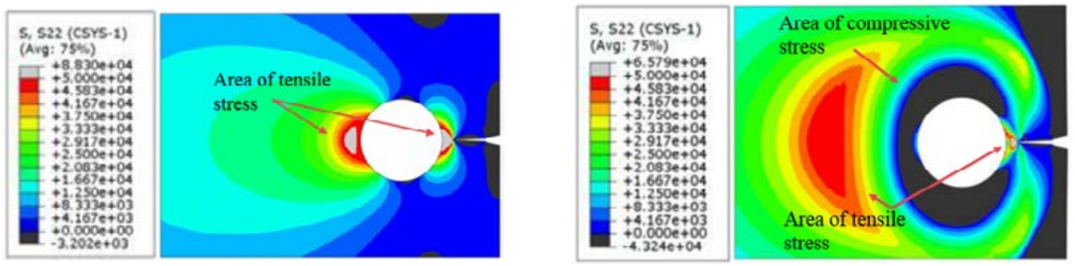
Figure 4: Hoop stress (psi) contour plot without applied load.



(a) Crack Arrest Hole (b) Cold Expansion

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Figure 5: Hoop stress (psi) contour plot with net stress 20.5 ksi applied.

A laboratory fatigue test was performed (Reid, 2013) using seven specimens of A36 bridge steel. For this test, 17-4 steel bushings were installed with the cold expansion technology as well as CAH as a baseline. The type of this 17-4 steel bushing was used for base material with yield strength lower than 413.7 N/mm2 (60 ksi). The fatigue test results indicated that the time to re-initiate the crack in the CAH was between 230,000 and 440,000 cycles (testing at 141 N/mm2 (20.5 ksi) net stress and load ratio of +0.05). After 4,000,000 cycles there was no crack re-initiation for the specimen with cold expansion technology. . Another specimen with cold expansion technology was tested to 20,000,000 cycles without crack re-initiation. From these laboratory fatigue test results, the ratio of the fatigue life of cold expansion technology to that of CAH was greater than 10.

3.2 INSTALLATION OF COLD EXPANSION TECHNOLOGY

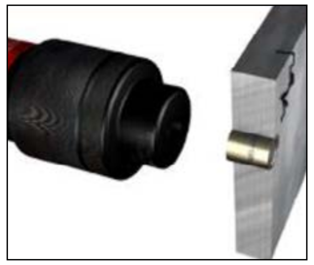
The accurate identification of the crack tip is the most important factor during the installation of cold expansion (CX) technology. The crack tips on both sides of steel plate are to be carefully examined to choose the longest crack tip. After the crack tip is identified, the next CX installation process involves drilling a crack arrest hole (CAH) in front of the crack tip and then cold expanding the hole by a tapered mandrel while simultaneously installing a bushing inside the hole. A typical installation process is shown in Figure 6.

1. Locate crack tip and drill/ream 0.5" diameter hole 1/16" ahead of tip

2. Place bushing on mandrel and insert into puller

3. Place bushing in hole

4. Pull mandrel through bushing



5. Cold expanded bushing installed

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Figure 6: Installation of Cold Expanded Crack Arrest Hole (CAH).

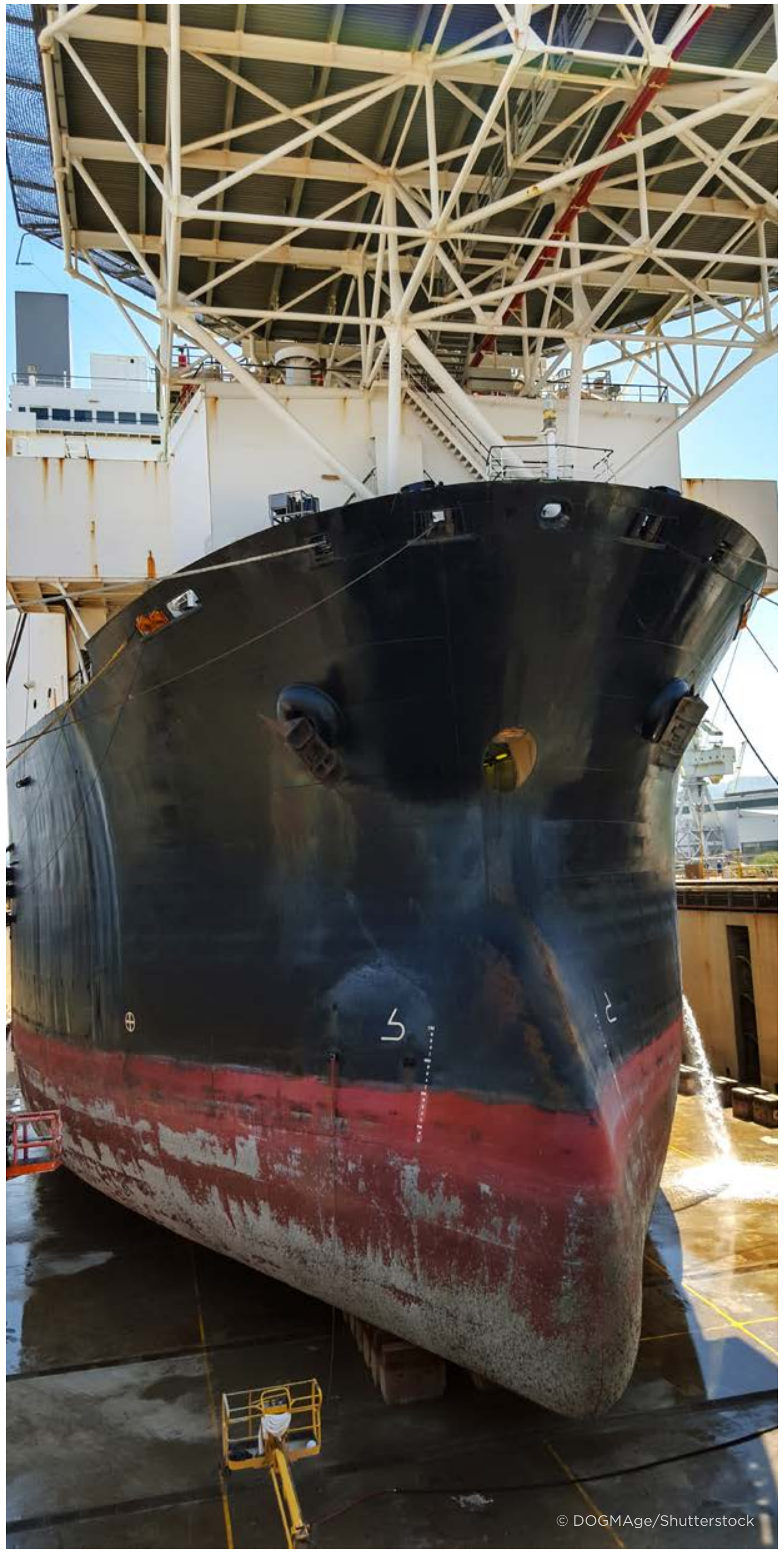
For the cold expansion technology to work effectively, there are several key points during installation to be noted:

1. Location of hole: The location of the hole is to be drilled in front of the crack tip. Sometimes the crack front is not uniform through the crack cross section. The machined hole is be drilled to the longest crack tip. In order to get the maximum effectiveness of arresting or slowing a crack's re-initiation on the other side of the hole, the ligament length between hole and the longest crack tip is to be 1/16 inch (1.5875 mm).

2. Tolerance of hole diameter: Three tools are used to machine the hole (pilot drill, drill, and a reamer). During drilling, lubricants are to be applied to avoid sparks. These tools will provide the correct hole diameter 12.700 +.0508/-.000 mm (0.500 +0.002/-0.000 inch). A hole gauge is used to check that the hole is within the correct tolerance range for the installation of bushing. If the hole is out of tolerance or oversize, an oversized contingency kit (hole diameter 13.119 +0.0508/-0.000 mm (0.5156 +.002/-.000 inch) diameter) is to be used. After the completion of drilling, the surface finish inside the hole is to be smooth and free of debris. Also, the hole needs to be free of lubricants. The use of sealants with the bushing installation is not recommended. Low viscosity primers may be used.

3. Tolerance of the mandrel's diameter: Mandrels must be manufactured to fine tolerances. There is a mandrel gauge to check for wear of the mandrel's diameter. If the mandrel fits into the gauge, the mandrel has excessive wear and is not be used and is to be replaced with a new mandrel.

4. Bushing geometry: The bushing is to be manufactured to tight tolerances. Bushings come in different lengths. Bushings are selected so that the length of bushing is greater than the thickness of plate to avoid sinking into plate. The bushings can protrude up to 6.35 mm (0.250 inch) above the steel surface for standard H40 steel material (390 N/mm2 (57 ksi) yield strength).



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SECTION 4 - FEASIBILITY STUDY – LESSONS LEARNED

In order to consider this CX technology in the marine and offshore industries, ABS has investigated this technology through field and laboratory tests. Beginning in 2015, ABS conducted a feasibility study of cold expansion technology for marine structures. The cold expansion technology was implemented on an active crack in a steel structure. A visual inspection and a monitoring method (i.e. acoustic emission testing (AET)) were used to monitor and understand crack propagation conditions. A laboratory fatigue test was also performed to study the fatigue life of cold expanded CAH. The effect of cold expansion was evaluated by the ratio of fatigue life of cold expanded CAH to that of the CAH alone. The detailed description of this feasibility study is shown in Appendix A – Feasibility Study of Cold Expansion Technology. The lessons learned from the feasibility study include:

- The field test results demonstrated that cold expansion technology can retard the crack growth.
- From visual inspections and AET results, the fatigue life from field testing was about four months for the ligament between the initial crack tip and the edge of crack arrest hole.
- The fatigue life of the cold expanded crack arrest hole was more than two and half years and no crack re-initiation was observed on the other side of crack tip.
- In the Engineering Critical Assessment (ECA), the predicted crack growth lengths without repair were calculated by two approaches (i.e. simplified fatigue loads and measured loads from strain gauge).
- From the ECA result, the risk of crack was elevated due to a higher rate of crack growth without a repair.
- From the laboratory test results, the fatigue life of the ligament for cold expanded crack arrest hole was about 17 times higher than that for the CAH.
- The laboratory test result also showed that the fatigue life of failure for cold expanded crack arrest hole was more than 13 times greater than that for the CAH.

SECTION 5 - APPROVAL OF COLD EXPANSION TECHNOLOGY

5.1 CONDITIONS FOR USING COLD EXPANSION TECHNOLOGY

Cold expansion technology can be used as a means to slow down the propagation of a through-thickness crack on steel structures. The overall coating condition on a structure needs to be good or fair and the structural condition be sound. Depending upon the application, it may be possible to apply cold expansion technology to arrest an existing crack for a defined period of operation, where usually it would have been necessary to crop and renew plating, or gouge and reweld.

The following items need to be addressed for the application of cold expansion technology:

- The ABS local office is to be contacted by ship/asset owner prior to the use of cold expansion technology as a measure to slow down the crack propagation.
- In general, cold expansion technology can be used for local and non-watertight structures.
- A repair plan is to be submitted by ship/asset owner for approval by ABS. At a minimum, this plan needs to include details related to the crack's location, dimensions, repair materials (including bushing), installation procedure for the repair, and repair lifetime category (temporary, short lifetime, or long lifetime repair).
- The thickness of the steel plate is to be less than or equal to 25mm. If the thickness of the steel plate is greater than 25mm, a laboratory fatigue test or/and an FEA is to be performed to evaluate the fatigue life of the cold expansion technology at a crack tip.
- If previous repairs were performed in the same crack location, or more than one repair is required at the same crack location, the details and reasons for the existing repairs or additional repairs are to be examined by ABS in order to evaluate that multiple repairs on a crack are a viable option.

5.2 PROCESS OF COLD EXPANSION TECHNOLOGY

The process to implement cold expansion technology is shown in Figure 7 below.

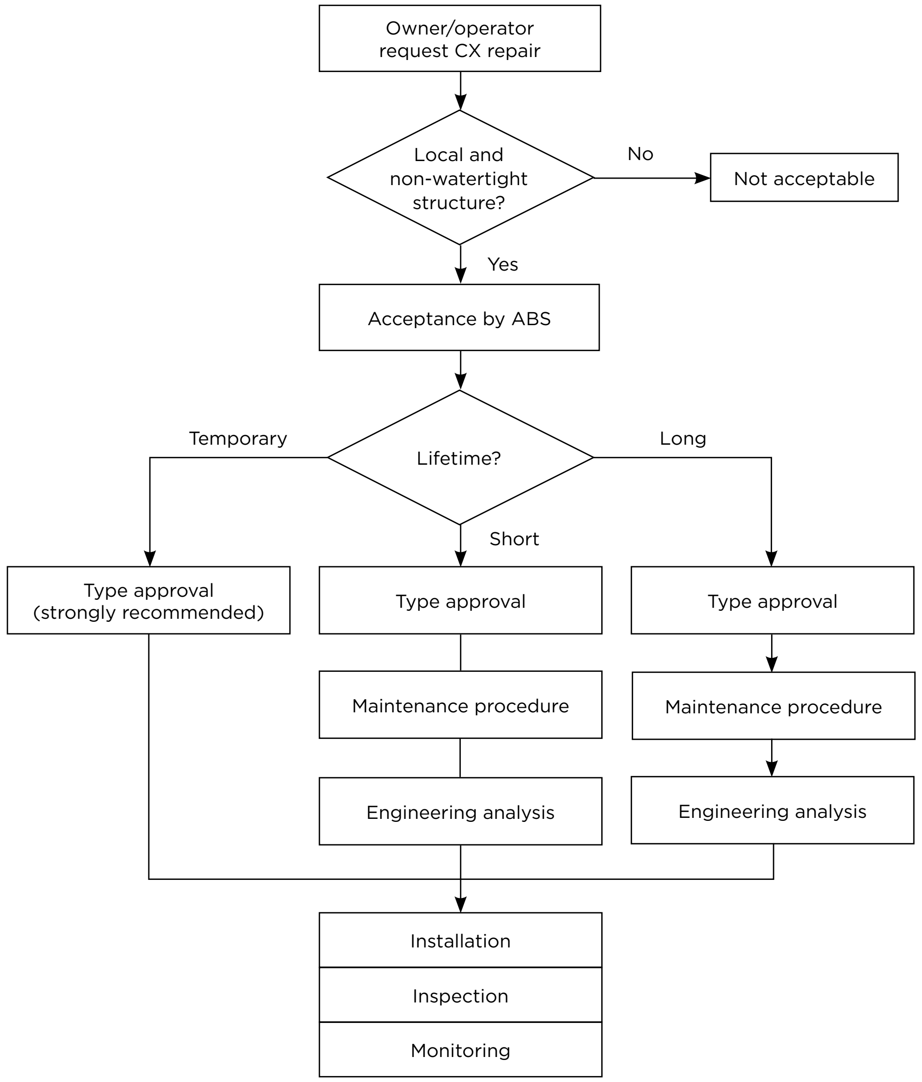

Figure 7: Flowchart for the process to implement cold expansion technology.

5.3 REPAIR LIFETIME CATEGORY AND QUALIFICATION

The qualification and lifetime for each repair lifetime category are summarized in Table 1.

Table 1: Repair lifetime category and qualification for cold expansion technology.

Repair Lifetime Category	Type Approval	Maintenance Procedure	Engineering Analysis	Lifetime	Inspection Period
Temporary	Strongly recommended that the manufacturer requests ABS for Type Approval	-	-	Up to 1 year	Every 3 months
Short Lifetime	Manufacturer requests ABS for Type Approval	Owner submits for ABS review	Owner submits for ABS review	Up to 2 years	1st year (every 3 months) 2nd year (every 6 months)
Long Lifetime	Manufacturer requests ABS for Type Approval	Owner submits for ABS review	Owner submits for ABS review	Up to 20 years	1st year (every 3 months) 2nd year (every 6 months) 3rd-20th years (every 12 months)

The detailed description of application and qualification is described as follows:

5.3.1 APPLICATIONS FOR EACH REPAIR LIFETIME CATEGORY

1. A temporary repair is usually applied for emergency repairs where the quick action of the crew is required to avoid operational downtime or a shutdown. This type of repair is normally intended for very short periods of time (up to 1 year). For example, when waiting for ship drydocking to perform a traditional permanent repair or preparing for a short/long lifetime cold expansion technology repair, a temporary repair can be performed. The type approval of cold expansion repair system is strongly recommended.
2. A short lifetime repair (up to 2 years) is applicable to those situations where the repair is required to last until the next drydocking. The type approval of the cold expansion repair system is required. The maintenance procedure and engineering analysis reports are to be submitted for review by ABS.
3. A long lifetime repair (up to 20 years) is applicable to those situations where the repair is required to last the asset's/ship's design life for a specific period with visual inspection on-site by the ABS Surveyor during the annual survey or through the owner's post-installation inspection/monitoring report. The type approval of a cold expansion repair system is required. The maintenance procedure and engineering analysis reports are to be submitted for review by ABS.
4. In the decision of lifetime repair category of the repair, the crack length and service conditions (e.g., internal corrosion, applied loads) are to be addressed.
5. Once the lifetime of the repair category has expired, the ship/asset owner must either remove or revalidate the repair system.

5.4 TYPE APPROVAL

The products of cold expansion repair system can be certified by ABS with an ABS Type Approval certificate. The Type Approval certificate is issued by ABS after the successful completion of the Production Design Assessment (PDA) and Manufacturing Assessment (MA).

5.4.1 PRODUCTION DESIGN ASSESSMENT (PDA)

Data and specifications for the cold expansion technology repair system are to be created by the manufacturer and approved by ABS. Submittals are to include, as a minimum:

- ISO 9001 certificate or equivalent quality system
- Design data sheet
- Mechanical properties of bushing
- Proposed hole size and requirements
- Structural thickness and bushing length
- Geometry dimensions between the crack tip and hole edge
- Mandrel dimensions
- Installation tool
- Installation procedure, requirements, and guidance

Test reports and information are also required to be submitted for the PDA review. These include:

- Laboratory fatigue test – specimen preparation (yield strength, tensile strength, thickness, applied stress range), crack initiation, CAH repair with and without cold expansion technology, and a summary report of the laboratory fatigue test. The fatigue life of the cold expanded CAH is to be at least 10 times of that of CAH.
- Also, the finite-element analysis (FEA) method is to be used to demonstrate adequate fatigue life of cold expanded CAH (i.e. at least 10 times of that of CAH).
- The manufacturer is to have a quality system and be certified in accordance with ISO 9001 (or comparable quality system). The quality system is to consist of elements necessary to produce bushings with consistent and uniform physical properties.

5.4.2 MANUFACTURING ASSESSMENT (MA)

When Type Approval is requested by the manufacturer, a manufacturing assessment (MA) is required to be submitted by the manufacturer and reviewed by ABS. A valid PDA, along with the satisfactory demonstration that the product can be consistently manufactured, also needs to be submitted for review. The manufacturing process must be witnessed by an ABS Surveyor. A separate certificate is to be issued for each manufacturing facility and for each product.

5.5 MAINTENANCE PROCEDURE

The maintenance procedure includes a list of repair and inspection activities regarding the identification, location, control, and management of those repairs. This procedure is to be submitted by the ship/asset owner and reviewed by ABS for short or long lifetime repairs.

In general, the ship/asset owner is responsible for the submission and verification of data regarding how the repair system will be implemented within the ship/asset. This procedure also identifies the following roles and responsibilities relating to the repair system process.

5.5.1 MANAGEMENT OF CHANGE (MOC)

A MOC order is to be issued for any type of repair that is proposed to be performed, according to the company's MOC quality procedures. No repair is to be performed before the appropriate personnel sign/approve the MOC order.

After expiration of the determined period for the repair (i.e. repair lifetime category) of a through thickness crack, the repair is to be removed. If a new repair is proposed, a new MOC order is to be issued, and a new repair qualification is to be done.

5.5.2 KEY PERSONNEL

Ship/asset owner defines Key Personnel (function and responsibility) or designated qualified professional who will participate in the repair system process.

5.6 ENGINEERING ANALYSIS

For a short or long lifetime repair, the engineering analysis report is to be submitted by the ship/asset owner and reviewed by ABS. This engineering analysis report includes predicted repair service lifetime, acquired data from field test reports, risk assessment, and Engineering Critical Assessment (ECA) results.

Whether a cold expansion (CX) repair is performed for either a short or a long lifetime repair, a data book is to be maintained for a period of at least one (1) year. The following subsection "Data Book from Field Test" outlines the required information to be documented for each CX repair.

During the approval of a PDA, the fatigue life of the cold expanded CAH has been provided. Using the data from the field test, the measured service loads are also acquired, and an average measured stress range is estimated. With the information of the fatigue life of the cold expanded CAH from PDA and the average measured stress range, the predicted lifetime can be calculated and described in the repair plan. This predicted lifetime should be greater than the lifetime of the repair category (e.g. 20 years for long lifetime repair category) times a safety factor associated with the importance (critical or non-critical) of the structure.

The ship/asset owner is responsible to perform a risk assessment and an Engineering Critical Assessment (ECA) for the crack's propagation rate without any repair. These two assessments are to be submitted by the ship/asset owner and reviewed by ABS.

5.6.1 DATA BOOK FROM FIELD TEST

A complete data book from the field test results, comprising at least one year measurements of the strain gauge, is to be submitted by the ship/asset owner and reviewed by ABS for the CX technology. The data book is to include, as a minimum, the following:

- Dimensions and location of through-thickness crack
- Material properties of steel structure
- Methodology for the cold expansion technology to slow down the propagation of a through-thickness crack
- Installation procedure of the repair system
- Measured service loads (e.g. strain gauge)
- Monitoring methods for re-initiation of crack (e.g. periodic visual inspection, acoustic emission testing, or other alternative methods)
- Summary of field test results

5.6.2 RISK ASSESSMENT

The following items are to be addressed and submitted for review for each specific repair in the long lifetime repair category:

1. Assessment of the location of the cracks
2. Design and operating conditions for the structures (including stress, ship/asset design fatigue life)
3. Hazards associated with the structure's service
4. Performance under major incident situations including, impact, fire, explosion, collision, and environmental loading
5. Failure modes
6. Inspectability

5.6.3 ENGINEERING CRITICAL ASSESSMENT

An Engineering Critical Assessment (ECA) is to be performed by the ship/asset owner to calculate the crack propagation rate following BS7910 (or an equivalent approach). In the ECA, the applied fatigue loads for stress range calculation are to be calculated from the design's wave induced bending moments with a long-term distribution or from FEA results.

5.7 INSPECTION AND MONITORING

The ship/asset owner is responsible for repair inspections and monitoring during the lifetime of the repair.

5.7.1 REPAIR INSPECTION

The repair inspections include the installation and post-installation inspections for temporary, short lifetime, and long lifetime repairs. Any non-compliance / crack propagation found is to be immediately reported to the Key Personnel or the designated qualified professional and ABS, then recorded in the inspection report and a recommendation made for the correction. If the Key Personnel or the qualified professional confirms the non-compliance / crack propagation, a means is to be defined to provide a repair solution. This could include requiring removal of the existing repair. Replacing the steel structure or performing a new repair could resolve the problem.

5.7.2 POST-INSTALLATION MONITORING

For post-installation monitoring, the repair system can be monitored by a continuous monitoring method (e.g., acoustic emission testing) or a periodic visual/NDT inspection for crack re-initiation. The periodicity of inspection of repairs (see Table 1) is to be performed at as listed below (as a minimum):

1. Temporary repair: Post installation up to 1 year – quarterly (every 3 months)
2. Short lifetime: 1st year – quarterly (every 3 months) and 2nd year – semi-annually (every 6 months)
3. Long lifetime: 1st year – quarterly (every 3 months), 2nd year – semi-annually (every 6 months), and 3rd – 20th years – annually (every 12 months)

For tracking purposes, all relevant documentation relating to any repair is to be stored according to the owner's internal quality control system.

SECTION 6 - REFERENCES

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APPENDIX A - FEASIBILITY STUDY OF COLD EXPANSION TECHNOLOGY

In order to approve cold expansion technology, ABS has investigated this technology through field and laboratory tests. Beginning in 2015, ABS has conducted a feasibility study of cold expansion technology for marine structures. The cold expansion technology was implemented on an active crack in a steel structure. A visual inspection and a monitoring method (i.e. acoustic emission testing) were used to monitor and understand crack propagation conditions. Also, a laboratory fatigue test was performed to study the fatigue life of cold expanded CAH.

A.1 FIELD TEST – CASE STUDY OF A CONTAINER CARRIER IN OPERATION

A joint development project between ABS, a service provider for cold expansion technology, and a global container transportation company was performed on a containership. This container carrier's geographical area of operation was the trading route between the Far East and the West Coast of the United States. The vessel would take about 42 days for a round trip. An onboard Acoustic Emission Testing (AET) system was used to monitor the area of interest during the voyage. The principal dimensions of this container carrier are listed in Table A.1.

Table A.1: Principal dimensions of the container carrier

Length of vessel		262 m
Scantling length	L	258.83 m
Molded breadth	B	40 m
Depth	D	24.3 m
Design draught	d	13.98 m
Service speed		24.6 knots
Block coefficient	C_b	0.6102

A.1.1 PRELIMINARY INFORMATION

In this case study, the area of interest for monitoring and inspection was located at 1A deck (deck between the main and second decks) in Figure A.1. A crack was identified on a stiffener above the rat hole next to a weld line (Figure A.2). The type of stiffener is a flat bar with width of 250 mm and the grade of steel is AH36. The weld line is used to connect two stiffeners with two thicknesses, 15 mm and 40 mm, respectively.

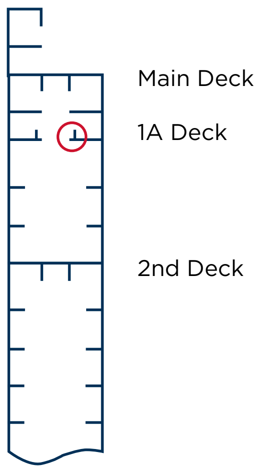

Figure A.1: Monitored area on 1A deck

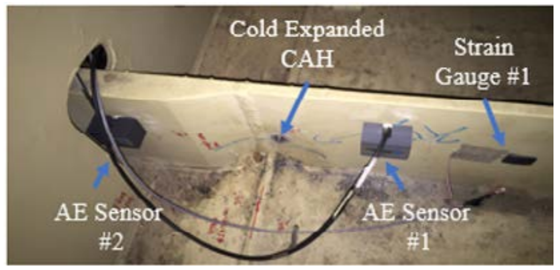

Figure A.2: Monitored repair area

The transverse cross section information with the identified crack is shown in Table A.2. A schematic diagram of the crack, the location of crack, acoustic emission sensors, and strain gauges are shown in Figure A.3. The strain gauge is a 350 ohm general purpose linear gauge.

Table A.2: Characteristics of transverse cross section and identified crack location parameters.

The moment of inertia of cross section for gross scantlings with respect to horizontal neutral axis	I_Y	440.727 m4
The vertical distance of horizontal neutral axis from baseline	z_{NA}	1055 cm
The vertical distance from baseline to considered crack location	z	2271 cm

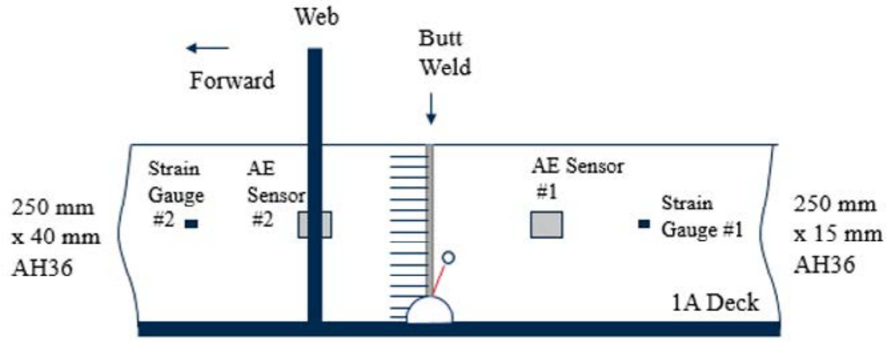

Figure A.3: Schematic diagram of the crack.

After the preliminary information was collected, an Engineering Critical Assessment was performed to estimate the crack propagation rate.

A.1.2 ENGINEERING CRITICAL ASSESSMENT (ECA)

Cracks within a marine/offshore structure increases structural health risk during vessel/asset operation. To help reduce this risk, it is necessary to predict a crack's propagation rate and estimate the consequence of the crack to avoid a possible catastrophic failure. An Engineering Critical Assessment (ECA) needs to be performed to calculate the crack propagation rate following BS7910 (2019).

The fracture mechanics approach has seen great improvement during the last decade. At present, it is widely used to predict the crack propagation and the remaining service life prediction in many industries. Paris' law has been widely accepted as a practical engineering tool for predicting crack propagation. The formulae given by industry standards and guidelines, such as BS 7910 (2019), can be used for the calculation of the stress intensity factor range (ΔK). The crack growth is predicted by Paris' law as

$$\frac{da}{dN} = C(\Delta K)^m$$

where:
a is crack length for edge crack
N is the number of stress cycles
C and m are the constants in the law
ΔK is the stress intensity factor range in a stress cycle.

The general form of the stress intensity factor is given by

$$K = Y\sigma\sqrt{\pi a}$$

where:
Y is the stress intensity factor correction
σ is the applied stress perpendicular to the plane of the crack.

The material is high tensile AH36 steel, the minimum yield strength is 355 MPa (51.487 ksi) and the tensile strength range is 490 - 620 MPa (71.066 - 89.920 ksi) (ABS 2019). The mechanical and fracture mechanics properties of AH36 are given in Table

A.3. It is assumed that the initial edge crack size is around 30 mm (1.2 inch) when the crack was identified. The constants C and m in Paris' law depend on the material and the applied conditions, including environment and cyclic frequency. For this case study of the containership with AH 36 steel, the recommended values for C and m are 5.21×10^{-13} $mm^{-1/2}/MPa^3$/cycle and 3, respectively.

Table A.3: Mechanical and fracture mechanics properties of AH36 steel.

Yield strength (minimum)	σ_y	355 MPa
Tensile strength	σ_u	490-620 MPa
Initial crack length as observed	a_o	30 mm
Fracture toughness	ΔK_{IC}	73.36 MPa √m
Static membrane stress	P_m	80 MPa
Paris Law's coefficients	m	3.0
	C	5.21E-13 $mm^{-1/2}/MPa^3$/cycle

A.1.2.1 Fatigue Loads And Stress Ranges Calculation

In order to perform the ECA, it is necessary to acquire the stress range around the crack. Two approaches could be used to estimate the stress ranges in the ECA: 1) Simplified fatigue loads and 2) Measured strain on structures around crack.

It is difficult to generate a load spectrum which can simulate the actual encountered loading history accurately. In order to perform a conservative assessment of the fatigue, the maximum stress range (named as the dominant stress range) among all loading conditions is recommended for stress range calculation in ship structures. This simplified fatigue loads approach provides a simple method to evaluate the fatigue loads without field data at the design stage.

However, the simplified fatigue loads approach may provide a very conservative evaluation and lose the accuracy comparing with the field test results. The measured strain approach may provide a more realistic result for fatigue loads.

A.1.2.2 Simplified Fatigue Loads Approach

In order to describe the simplified fatigue loads approach, a sample calculation is described as follows for a container carrier. As a starting point in this feasibility study, only vertical hull girder loads were considered for stiffeners on the upper decks. In this application, the simplified fatigue loads and the vertical wave induced bending moments amidships, were calculated from ABS *Rules for Building and Classing Marine Vessels* (ABS 2019):

The hull girder bending stress due to vertical hogging and sagging bending moments in N/cm2 for gross scantlings was calculated as follows.

$$\sigma_{w\,Hog} = M_{w\text{-}Hog}\,(z - z_{NA}) \times 10^5 / I_Y$$

$$\sigma_{w\,Sag} = M_{w\text{-}Sag}\,(z - z_{NA}) \times 10^5 / I_Y$$

where:
I_Y = The moment of inertia, in cm4, of cross section for gross scantlings with respect to horizontal neutral axis, z_{NA}
z_{NA} = The vertical distance of horizontal neutral axis from baseline, in cm
z = vertical distance, in cm, from baseline to considered location

Hull girder stress range, in N/cm², for net scantlings was computed as follows:
$$\Delta\sigma_w = c_f\,|\sigma_{w\,Hog} - \sigma_{w\,Sag}|$$

where:
c_f = adjustment factor to reflect a mean wasted condition, taken as 0.95.

It was assumed that the long term distribution of the hull girder stress range follows the two-parameter Weibull distribution. The probability density function of Δσ is given by:

$$f(\Delta\sigma) = \frac{\gamma}{A}\left(\frac{\Delta\sigma}{A}\right)^{\gamma-1} \exp\left[-\left(\frac{\Delta\sigma}{A}\right)^{\gamma}\right]$$

where:
A and γ are the scale and shape parameters of the Weibull distribution, respectively.

The shape parameter of the Weibull distribution γ was obtained from ABS *Rules for Building and Classing Steel Vessels* (ABS 2019). The scale parameter was determined by:

$$A = \Delta\sigma_w (8\ln 10)^{-1/\gamma}$$

For the simplified fatigue loads approach, the applied fatigue stress range can be acquired by histogram of annual stress range. Following the Weibull distribution in the previous equation, the histogram of annual stress range was created using number of cycles in one year is as follows:

$$N_r = \frac{f_0 D_L}{4 \log L}$$

f_0 = 0.85, factor for net time at sea
D_L = design life in seconds, 3.15×10^7 for one year
L = Scantling length of vessel, in m

From preliminary data of ship, the generated histogram of annual stress range from previous equation is shown in Figure A.4.

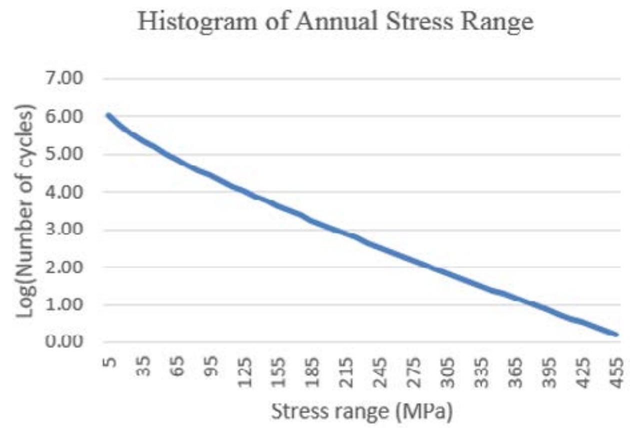

Figure A.4: Histogram of annual stress range from simplified fatigue loads approach.

A.1.2.3 Stress Range from Measured Strain

The strain gauges were installed around the crack area to acquire strain levels for the local structures. These strain gauges were calibrated by the initial strain values using calculated levels in a calm sea condition. Since the initial strain values are roughly estimated, it is difficult to get the absolute values of strain. However, the relative values of strain are still trustworthy. The derived stress range was calculated through strain value time history. The histogram of annual stress range was created from one year's worth of collected data.

Figure A.5 denotes example records of the two strain gauges taken during the voyage from Long Beach, California to Yokohama, Japan. Two lines in this figure represent two measured strains by two strain gauges. Both strains provided similar trend data. However, the value of Strain Gauge #1 (green line) was greater than the value of Strain Gauge #2 (red line). This is because the thickness 15 mm (0.59 inch) of the stiffener for the Strain Gauge #1 is less than the stiffener 40 mm (1.575 inch) for the Strain Gauge #2.

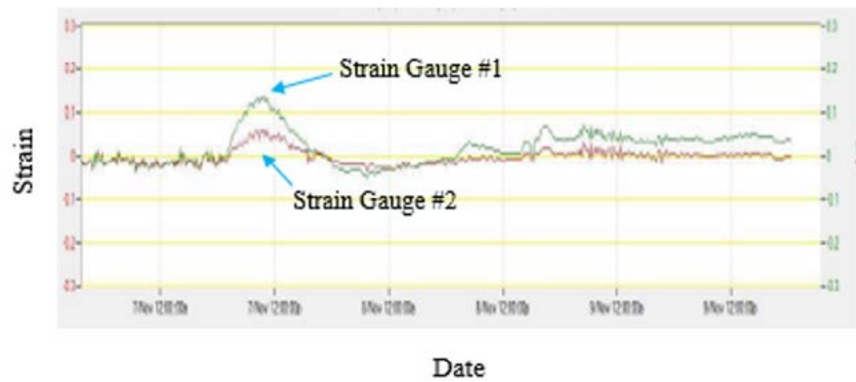

Figure A.5: Time history of measured strain.

The stress range from measured strain was calculated using strain values in time history. The histogram of the stress range from Strain Gauge #1 was calculated and shown in Figure A.6. It was observed that there is a pronounced drop in the number of cycles from the stress range 45 MPa to the stress range 55 MPa. This may be due to the smart route planning of the ship to avoid severe weather during voyages.

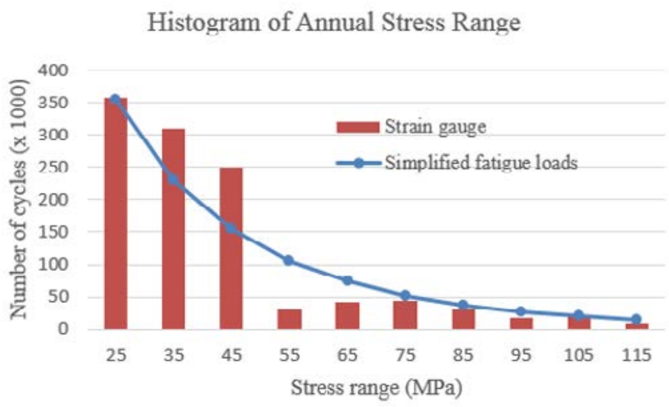

Figure A.6: Histogram of stress range from measured strain (Strain Gauge #1)

Figure A.6 also compares the histogram of stress range from measured strain and the one from simplified fatigue loads. It was observed that the number of cycles from the simplified fatigue loads are larger than the ones from the measured strain, especially for the stress range greater than 45 MPa. This may be due to the conservative considerations of the simplified fatigue loads which were used at the design stage. While the measured strain histogram shows the actual data obtained during the voyage, the value may be lower than those originally designed for.

A.1.2.4 Crack Propagation Calculation

The previously generated histograms of annual stress range for Strain Gauge #1 were used to predict the crack propagation rate model following the approach from British Standard *Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures* (BS7910, 2019). The SIF (stress intensity factor) calculation formulas for an edge crack on a flat plate crack at a butt weld toe in BS7910 (2019) were utilized. Since the high stress area was located at the butt weld, it is necessary to consider the weld's residual stress and the static membrane stress (as a mean stress) in determining static membrane stress (Pm). In this case study, the static membrane stress was assumed to be 80 MPa. The stress concentration due to the structure's geometry was assumed to be 1.3 for the tapering plate thickness and the rat hole. The residual stress is assumed to be uniformly distributed and equal to 30% of the material's yield stress.

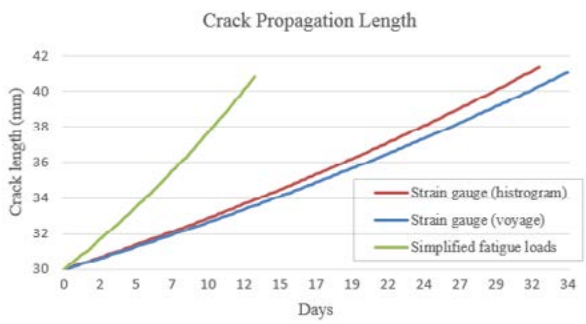

Figure A.7: Predicted crack propagation length.

CrackWISE software (CrackWISE, 2013), developed following the publication of BS7910, was used to the calculate crack propagation. The predicted crack growth lengths are plotted in Figure A.7 for the three load cases (simplified fatigue, measured strain level in histogram, and measured strain level following voyage). It can be observed from the diagram that the fatigue life (in days) for the predicted crack growth for the measured strain is about 2.5 times that of the simplified fatigue loads approach. These fatigue lives reflect the consequence of the loads depicted in Figure A.6. The simplified fatigue loads at design stage are higher than the actual data of loads obtained from strain gauge.

Because the consequence of a failed 1A deck stiffener is high, the risk of the identified crack was elevated considering the high rate of crack growth as shown in Figure A.7 without any repairs. The frequency of inspection should be high and the inspection areas are not only at this stiffener of interest, but also the adjacent plates and stiffeners.

In order to reduce the frequency of inspection, a cold expanded CAH was installed in accordance with the discussions in the previous sections. After installation, the cold expanded CAH was monitored by Acoustic Emission Testing as well as inspected periodically by a surveyor and the onboard crew. This case study lasted about two and half years.

A.1.3 ACOUSTIC EMISSION TESTING (AET) FOR MONITORING

AET is a passive nondestructive testing method that has been used by the petrochemical industry since the early 1980s with more than 22 fully accepted codes and standard practices published in ASTM, BS, and ABS (ASTM E 976-2010, BS EN 13554, 2011, and ABS, 2016). Acoustic emission is very effective at identifying crack growth and propagation. As a result, it has been observed that different acoustic emission signal properties, such as cumulative count or energy, increase as the crack growth rate increases.

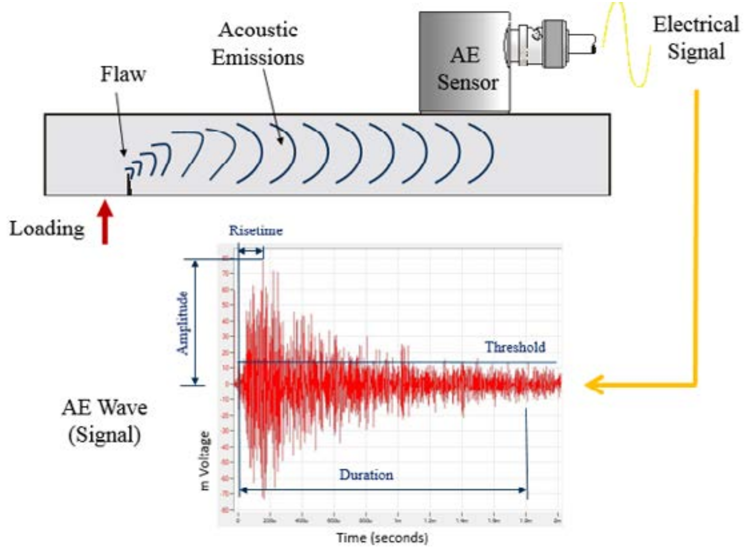

Figure A.8: Overview of Acoustic Emission Testing.

In Acoustic Emission Testing (Figure A.8), piezoelectric transducers are attached to a structure. These sensors convert mechanical energy such as elastic waves into an electric impulse that is transmitted by wired cables or wireless communication to the AET computer.

As the structure is stressed, the AET computer collects data. Parameters from each emission are measured and then stored within the system data logger. Data from each sensor is stored on separate channels along with the exact time that the acoustic emission events occurred. These data are analyzed during and after testing. In order to attain a reliable level of structural defect detection, signature recognition, noise filtering, and identification of high acoustic emission activity need to be performed.

When filtering noise, the relevant indications are separated from non-relevant indications using the known signatures for structural defects. It has been postulated for many years that different defects would leave unique characteristic signatures (Figure A.9) of acoustic emission signals (i.e., wave form). These unique signatures became a standard tool for Acoustic Emission data interpretation and noise filtering in the 1980s.

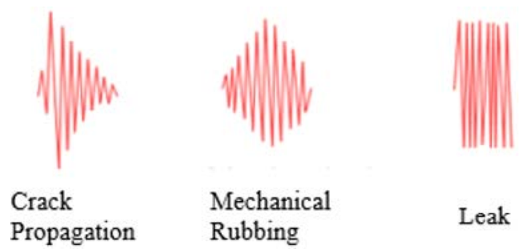

Figure A.9: Unique wave form (signature) for each defect.

After the acoustic emission data was acquired, acoustic emission signal discrimination was executed to identify the target defects (crack propagation). Past experience in the field (Lee, et al. 2014) and laboratory tests (Lee, et al. 2013) have established warning criteria of acoustic emission parameters to detect the active crack propagation activities.

The energy of each high acoustic emission activity was calculated and identified. In the time history of the energy of acoustic emission events, the crack propagation activities can be classified and monitored.

A.1.3.1 Crack Propagation Activities

In order to understand crack propagation activities, the time history of acoustic emission energy activity in Figure A. 10 was studied during the period between December 2015 and March 2016. There were no or limited acoustic emission activities after March 8, 2016. In Figure A.10, it was noted that there was an increase in acoustic emission activity during the period of 2 to 4 months after the bushing's installation. During this period, high acoustic emission activities were observed in three periods of December 16 – 22, 2015, January 20, 2016, and February 24 – March 8, 2016. These three high acoustic emission activities indicated crack propagation activities.

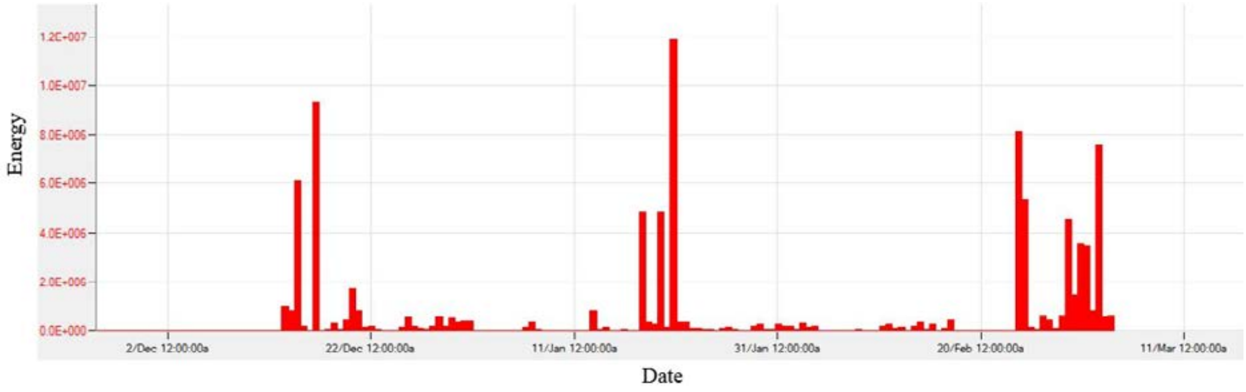

Figure A.10: Time history of acoustic emission energy activity.

A.1.4 EFFECT OF COLD EXPANDED CRACK ARREST HOLE ON FIELD TEST

In order to study the crack retarding effect of cold expanded crack arrest holes, crack propagation activities in field tests were monitored by acoustic emission testing and visual inspections. During the first four months of the Trans-Pacific voyages, it was observed that the crack propagation occurred through the ligament between the initial crack tip and the edge of CAH. The ligament length is about 1.5875 mm (1/16 inch) corresponding to the crack length between 30 mm and 31.5875 mm. The time history of ligament crack activities is shown in Figure A.11. From Acoustic Emission Testing (AET) results, three high acoustic emission activities (i.e. crack propagation activities) were observed in 2nd - 4th months after bushing installation. The visual inspections were performed approximately 5.5 months, 12 months, and 24 months after the installation of the bushing. From these results, the ligament between the crack tip and CAH was penetrated through in approximately 5.5 months (164 days) after the installation of the bushing. The AET results were consistent with the visual inspection results. The fatigue life of the ligament in this field test was about four months.

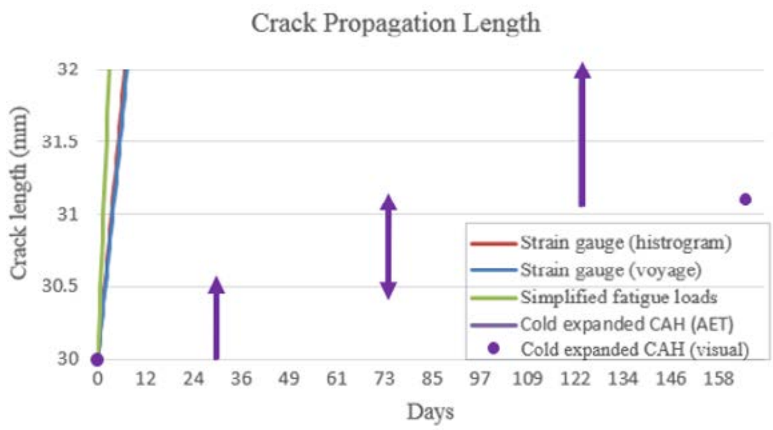

Figure A.11: Crack propagation of ligament between crack tip and hole.

The time history of the first year's Trans-Pacific crack activities is shown in Figure A.12. Key observations were:

- From visual inspection at 5.5 months after bushing installation, the crack propagated through the ligament – crack length increased from 30 mm to 31.5 mm.
- The crack reached the bushing – crack length increased from 31.5 mm to 44.3 mm (i.e. effective crack length includes crack and hole size 12.7 mm).
- From visual inspection at 12 months after bushing installation, crack growth ceased for 6.5 months – crack length was at the same level of 44.3 mm (i.e. crack has not re-initiated on the other side of CAH).
- No significant acoustic emission activities were observed during the 4th – 12th months after bushing installation.

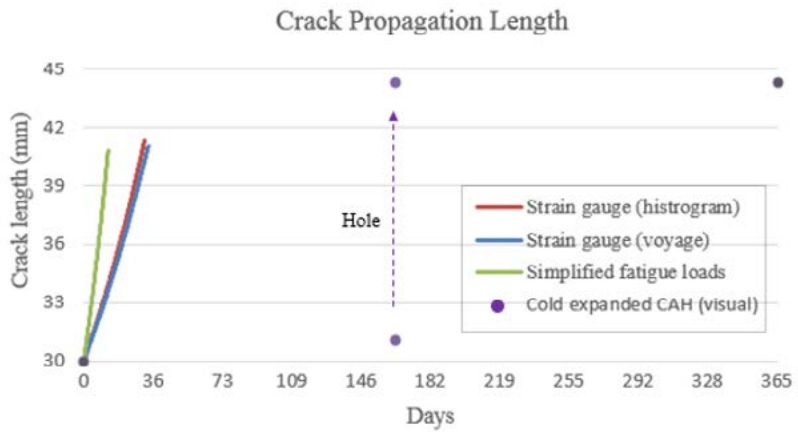

Figure A.12: Effect of cold expanded crack arrest holes on field test.

In order to acquire the fatigue life of cold expanded CAHs in field test, this test was continued for another one and half years. At the end of 30 months after bushing installation, a visual inspection was performed, and no crack re-initiation was observed on the other side of the hole. From these observations, the fatigue life of cold expanded CAH in this field test is at least two and half years (30 months).

A.2 LABORATORY FATIGUE TEST

The outline of a laboratory test procedure is described below for evaluating the effectiveness of the cold expansion of CAH repair for marine and offshore steels.

A.2.1 SPECIMENS

The material properties of the selected specimen and its associated thickness are listed in Table A.4.

Table A.4: Material properties and specimen thickness.

Steel Grade	Yield Strength σy (MPa)	Tensile Strength (MPa)	Specimen Thickness (mm)	Force of 45% σy kN (kips)
AH32	315	440 – 590	15	162 (36.4)

There are two stages applied for crack initiation. At stage 1, the initial crack length of 0.15 in (3.81 mm) was created. At stage 2, the initial crack length of 0.25 inch (6.35mm) was reached using the gross stress of 45% of the material yield stress or 20.7 ksi (142 MPa).

Table A.5: Initial Crack testing.

Initial Crack Stages	Specimen Width (W)	Specimen Thickness (t)	Gross Area (A_g)	Test Stress (σ_g)	Max Test Force (P_{max})	Min Test Force (P_{min})	Expected Crack Length
1	3.000 inch 76.2 mm	0.500 inch 12.7 mm	1.5 inch^2 968 mm^2	25 ksi 172 MPa	37.50 kip 167 kN	1.88 kip 8.4 kN	0.150 inch 3.81 mm
2				20.7 ksi 142.7 MPa	31.05 kip 138 kN	1.55 kip 6.9 kN	0.250 inch 6.35 mm

Table A.5 shows the initial crack testing information. The position of the crack arrest hole is shown in Figure A.13. Its position is based on the observed initial crack length. Two specimens were created with standard arrest holes and one specimen was created with cold expansion.

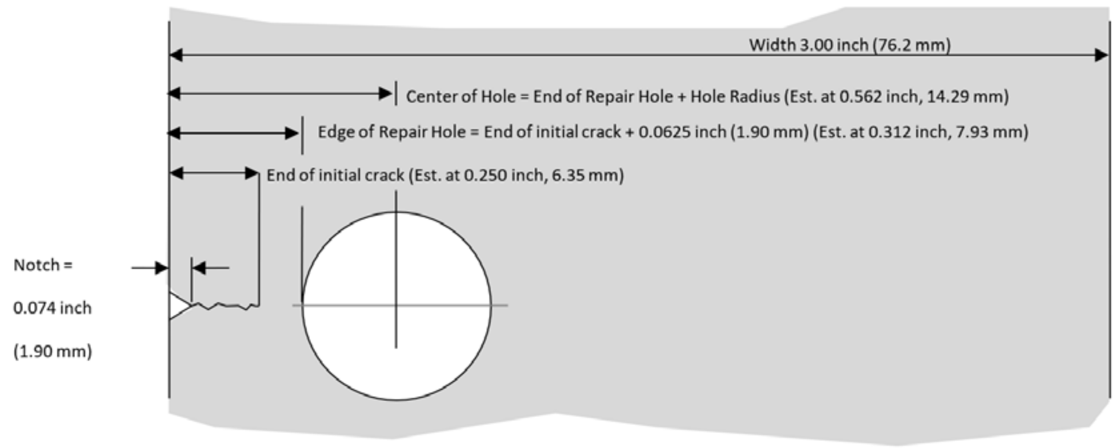

Figure A.13: Determination of crack arrest hole position.

A.2.2 LABORATORY FATIGUE TEST

After the specimens were prepared, a constant amplitude fatigue load was applied. The applied load is a net stress range of 45% of the yield strength with a stress ratio of +0.05, as shown in Table A.6. The test frequency was 5 Hz. Testing was complete when the crack reached 0.150 inch (3.81mm) on the side of the hole opposite the initial-crack (estimated total crack length of 1.121 inch (28.47mm) from edge of part) or a maximum of 5,000,000 cycles.

Table A.6: Applied stress of laboratory fatigue test.

Specimen Width (W)	Specimen Thickness (t)	Gross Area (A_g)	Est. Net Area (A_n)	Test Stress (σ_n)	Max Test Force (P_{max})	Min Test Force (P_{min})
3.000 inch 76.2 mm	0.500 inch 12.7 mm	1.5 inch^2 968 mm^2	0.406 inch 262 mm	20.7 ksi 142.7 MPa	22.64 kip 101kN	1.13 kip 5.0 kN

Note: Net area is calculated as the Thickness times the surface length of the Width, minus the distance from the edge of the specimen to the end of the far end of the hole, and is estimated as (0.25 inch crack + 0.0625 inch uncracked ligament to hole + 0.500 inch hole, or 0.812 inch, 20.6 mm). The actual net area will be calculated for each specimen. The actual test specimen dimensions will be used to calculate the area for calculations of the test force.

A.2.3 EFFECT OF COLD EXPANSION TECHNOLOGY

Following the procedure described in the previous section, three specimens (two for crack arrest hole and one for cold expansion technology) were prepared with crack initiation (initial crack) and crack arrest hole/cold expansion. Then, these specimens were applied by constant amplitude fatigue loads with the load ratio of +0.05. The results of failure cycles are shown in Table A.7. Here the failure cycle is defined as the crack reached 0.15 inch on the other side of the hole or a maximum of 5,000,000 cycles. Figure A.14 shows the cracks of specimens after completion of fatigue tests.

Table A.7: Laboratory fatigue test results.

Specimens	Hole Config.	Uncracked Ligament Length	Cycles to Ligament Failure	Final Crack Length	Cycles at Tet Completion
SO156138-1	CAH	0.0477 inch 1.2116 mm	500	0.170 inch 4.318 mm	323,000
SO126238-2	Cold Expansion	0.1053 inch 2.6746 mm	70,709	0.000	5,000,000
SO156138-3	CAH	0.1089 inch 2.7661 mm	4,000	0.151 inch 3.8354 mm	385,000

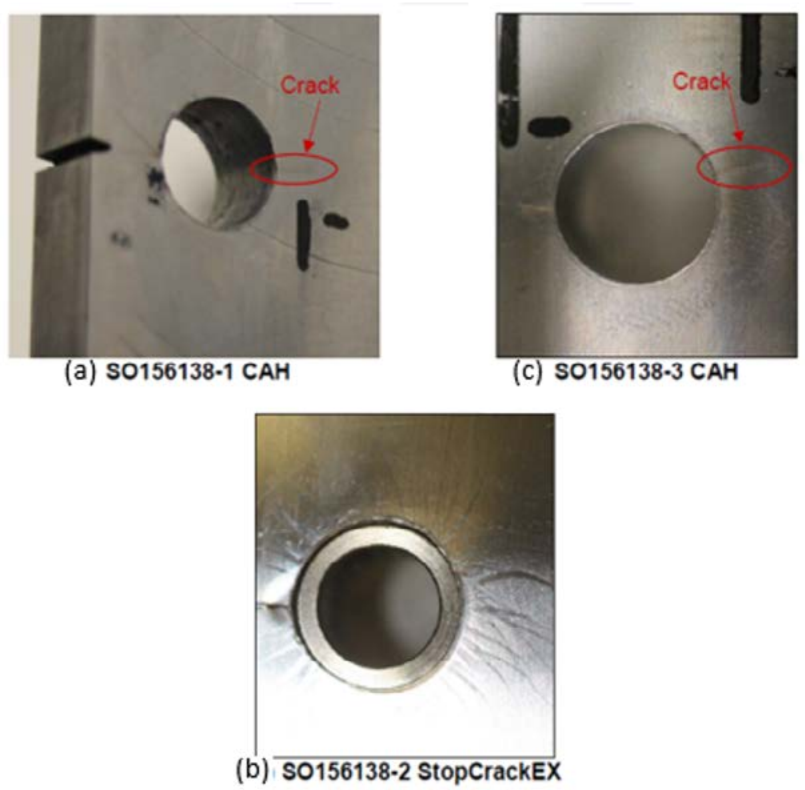

Figure A.14: Cracks of completed laboratory fatigue tests

The results of fatigue life (i.e. failure cycles) are shown in Figure A.15. Comparing the results from specimens 2 and 3, the fatigue life of the ligament for cold expansion is about 17 times higher than that for the CAH. If the period of each cycle is assumed to be 10 seconds as a wave period, the fatigue life of the ligament for cold expansion is about 8 days. The fatigue life of failure for cold expansion is about 13 times greater than that for CAH. Due to time and budget constraints, the fatigue life of failure for cold expansion only reached 5,000,000 cycles. The actual fatigue life could be greater than 5,000,000 cycles. If the period of each cycle is assumed to be 10 seconds as a wave period, the fatigue life of failure for cold expansion is more than 19 months. This laboratory test showed that cold expansion technology is a promising solution for a short lifetime repair (19 months or longer).

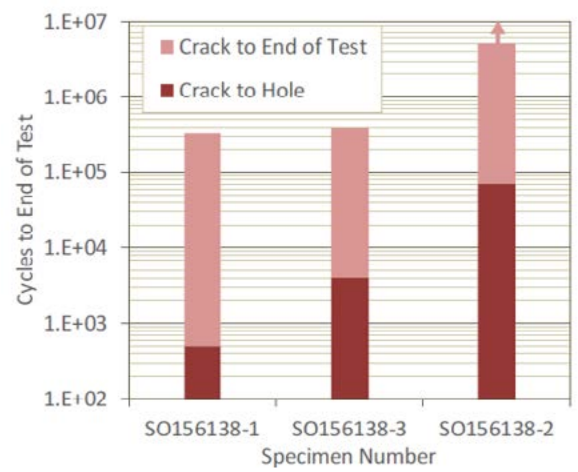

Figure A.15: Fatigue life (i.e. failure cycles) of ligament and final crack length.

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