



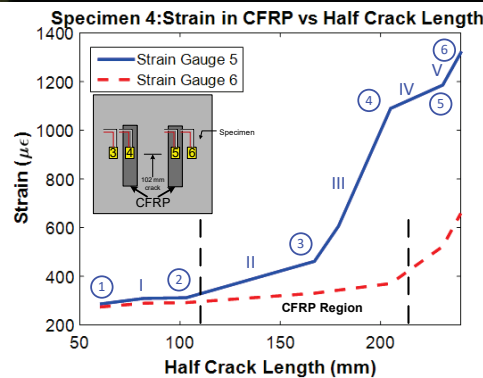
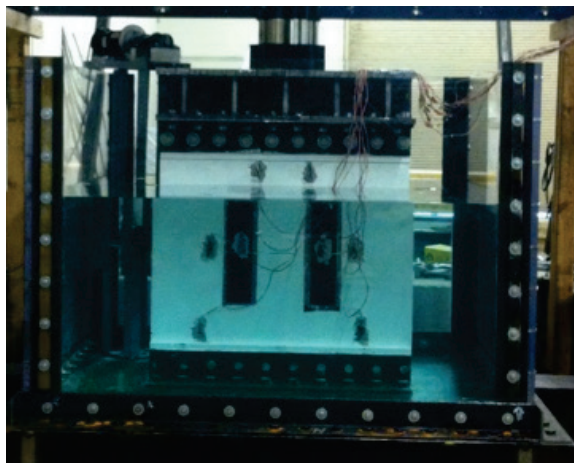
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Underwater Fatigue Repair of Steel Panels Using Carbon Fiber Reinforced Polymers

Guillermo A. Riveros, Hussam Mahmoud, Mehrdad Memari,
Christine Lozano, Anuj Valsangkar, and Bashir Ahmadi

May 2019



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Underwater Fatigue Repair of Steel Panels Using Carbon Fiber Reinforced Polymers

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Abstract

Steel hydraulic structures (SHS) are deteriorating day by day whether it is from corrosion due to harsh environmental conditions or because of the fatigue cracks developed in the components due to daily wear. Repairing these fatigue cracks is not only time consuming but also expensive with available repair methods. Recent advances with the use of carbon fiber reinforced polymers (CFRP) to retrofit structures has proven helpful to increase the fatigue life of structures made of different types of metals. Although a large number of studies have been conducted for structures retrofitted with CFRP, very few have been conducted for underwater metal structures.

The purpose of this experimental study is to evaluate the fatigue crack growth in SHS retrofitted with CFRP. Four specimens were tested with different types of CFRP and adhesive with different environmental conditions. The main focus is on the crack growth rate. As the river waters contain fluvial sediments as well as salt, the effect of both of these factors are taken into account. The results showed the increase in fatigue life with the use of CFRP but the effect of fluvial sediments and salts showed accelerated fatigue crack growth.

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Preface

This study was conducted for U.S. Army Corps of Engineers Headquarters under the Navigation System Research Program, U.S. Army Engineer Research and Development Center (ERDC), Project HB52B1, “Methods to Repair Fatigue-Induced Cracks Using Fiber-Reinforced Polymers”. The Technical Monitor was Mr. Charles E. Wiggins, Associate Technical Director, Coastal Hydraulics Laboratory, ERDC.

At the time of publication, Dr. Jeffrey Hensley was Chief of the Computational Analysis Branch, ERDC-Information Technology Laboratory (ITL); Dr. Jerrell R. Ballard, Jr. was Chief of the Computational Science and Engineering Division, ERDC-ITL; and Mr. David Richards was the Technical Director for ERDC-ITL. The Deputy Director of ERDC-ITL was Ms. Patti Duett and the Director was Dr. David A. Horner.

The Commander of ERDC was COL Ivan P. Beckman and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
foot-pounds force	1.355818	joules
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
kilopounds (force)	4.4482216	kilonewtons
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
tons (force)	8,896.443	newtons
tons (force) per square foot	95.76052	kilopascals

1 Introduction

1.1 Problem statement

Hydraulic steel structures (HSS) operating in harsh corrosive environments such as miter gates, ships, oil rigs, and pipes, among others, experience fluctuations in loading due to normal operation (e.g., loading and unloading of cargo ships) or their interaction with the surrounding water (e.g., wave loading). Due to load fluctuations, fatigue cracks can develop at various locations in the structures, and become a nuisance because they require extensive inspection and continuous repair. Although fatigue crack propagation is typically stable, if left unrepaired, these cracks can propagate and threaten the integrity of the structure. This study evaluates the fatigue repair of underwater structures through a newly devised experimental platform.

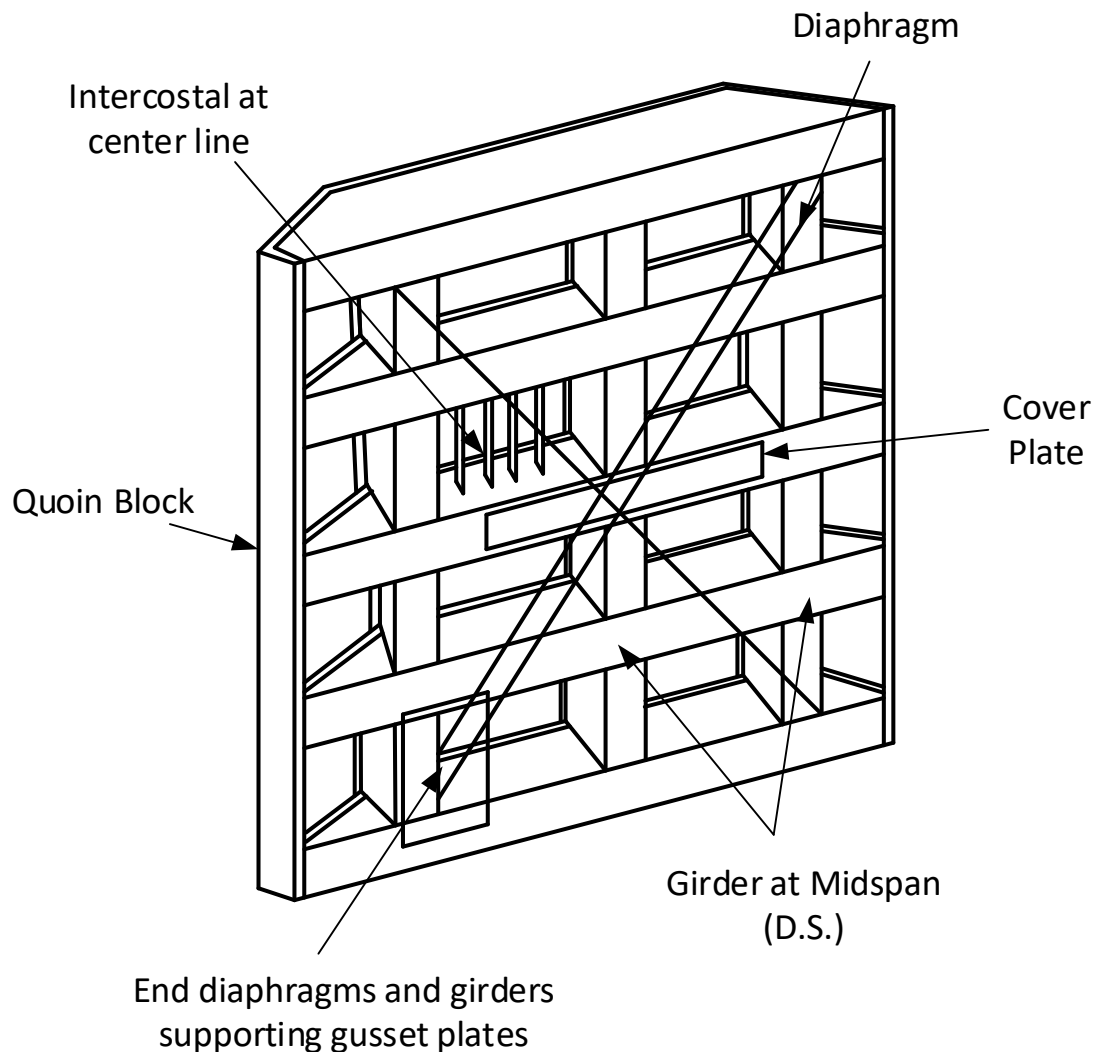
Navigational river locks employ miter gates to allow vessels passage within the different levels of a river system by opening and closing the lock. Miter gates are fabricated by welding steel sections together in a horizontally or vertically framed configuration. The horizontally framed miter gate, shown in Figure 1, is a very typical design (USACE 2010), and Figure 2 shows the main components of miter gates. Horizontal girders are framed together with vertical diaphragms and the skin plates are welded to the upstream flanges. The miter gates experience cyclic loading as the gates are opened and closed; while in the closed position, the horizontal girders in bending transfer the hydrostatic loads to the lock walls. During operation, the gates experience opposing eccentric loading due to strut arm forces at the top of the gate and the water resistive forces to the gates movement through the water at the bottom of the gates submerged section. The eccentric loading causes twisting and warping to develop in various parts of the gates including the intersection of welded vertical and horizontal flanges, cutouts, attachments to the skin plate, and pintle socket connections. With continuous operation, these components develop fatigue cracking.

Figure 1. Typical horizontally framed miter gate (USACE 2010).



Fatigue life of structures is defined as the total life required the crack to initiate and propagate to a critical length. Fatigue cracks generally originate from a flaw in the weld and extend to the base metal connected to the weld. This cracking occurs mostly in the submerged surfaces and may require unscheduled outage for repairs (USACE 2010). Examples of miter gates in which fatigue cracking was observed include the Snell Locks (built in 1959) on the St. Lawrence Seaway, Greenup (built in 1959), Meldahl (built in 1959), Markland (built in 1960), McAlpine Locks (built in 1961), Upper St. Anthony's Falls (built in 1963), Poe locks at the Soo (built in 1968), and Bankhead Lock (built in 1975). In all of these examples, the most common fatigue cracking is observed at welded details and is due to the presence of tensile residual stresses coupled with geometric concentration and weld geometry (USACE 2010).

Figure 2. Components of common miter gates (Riveros 1997).



1.2 Objective and scope

As previously stated, fatigue cracks in miter gates occur typically in the submerged portion of the gate. To repair these cracks, the whole catchment near the gates needs to be dewatered, requiring a scheduled or unscheduled outage. The dewatering process is expensive, time consuming, and has a negative impact on the economy as it influences traffic flow through the river. Therefore, it is important to develop and evaluate new fatigue repair methods that are easy to implement and effective in mitigating crack growth; thus, limiting the disruption of normal gate operations. An attractive alternative for the repair of fatigue cracks is carbon fiber reinforced polymers (CFRP), because it is effective for mitigating crack propagation and easy to implement. A study

conducted by Mahmoud and Riveros (2013) provides an in-depth overview of existing experimental and analytical studies on the use of CFRP for the repair of metallic structures and on the potential of using CFRP for the repair of hydraulic steel structures. Their study indicated that several experimental methods were performed to evaluate the use of CFRP for extending the in-air fatigue life of aircraft stiffened aluminum panels and steel bridge girders. However, no research has been conducted for repairing fatigue cracks in underwater metallic structures. Mahmoud et al. (2014) to evaluate crack growth in underwater CFRP-repaired steel panels conducted a recent numerical study. The study showed that CFRP-repaired plates have significant improvement in fatigue life over non-repaired plates.

Previously conducted studies show reduction in crack propagation rate when CFRP strips are either covering the crack fully or when placed ahead of the crack tips (Wu et al. 2012; Alemdar et al. 2012; Tavakkolizadeh and Saadatmanesh 2003). When CFRP is attached at the crack front, where the local stresses are higher than the nominal stresses, it reduces the effect of higher local stresses by providing additional stiffness, locally, which limits the crack mouth opening. Although this might not stop the propagating crack fully, it slows down the rate of propagation. This research deals with the application of CFRP and its effects on crack propagation rate in underwater steel panels. The objectives of this study are as follows:

- To develop a new, experimental device that allows for the assessment of underwater crack growth in CFRP-repaired steel panels.
- To determine if bonded CFRPs have any effect on the rate of fatigue crack propagation in underwater steel plates.
- To determine the effect of using different underwater epoxies on CFRP debonding.
- To determine the effect of using different types of CFRPs on fatigue crack propagation rate.
- To determine the effect of corrosion formed at the CFRP-steel interface on the behavior of bonded CFRP.
- To determine the effect of fluvial sediments on the behavior of the bonded CFRP.

1.3 Overview

This technical report is comprised of five chapters. Chapter 1 introduces the problem statement and research objectives. Chapter 2 discusses the background and literature review in relation to the use of CFRP for mitigating fatigue crack propagation. Chapter 3 discusses the experimental setup developed and the specimen topology employed in this research. Chapter 4 focuses on the experimental results regarding application of the CFRP near the crack tip, the effect of salt and fluvial sediments on the CFRP, and fatigue crack growth. Chapter 5 discusses the conclusion, field implications, and outlines future research requirements.

2 Background and Literature Review

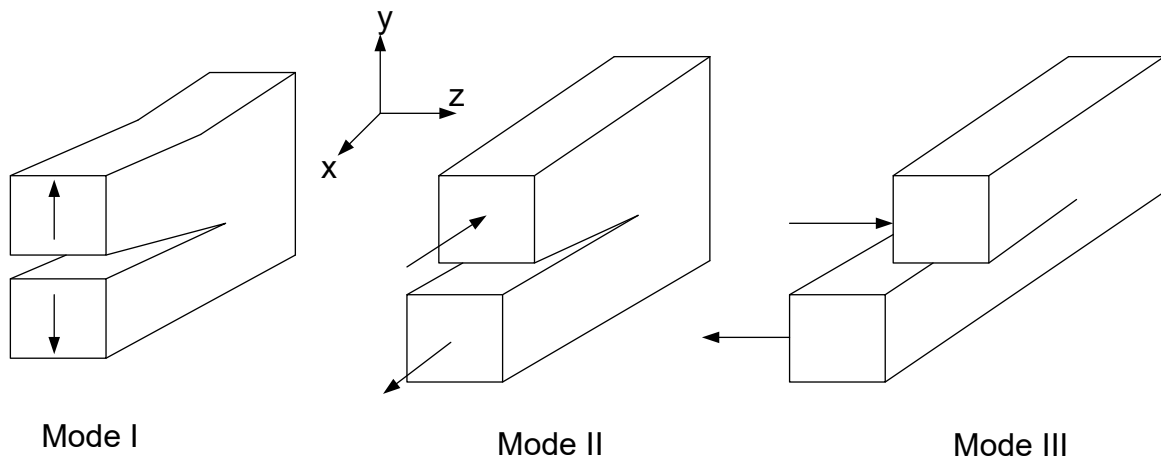
2.1 Fracture mechanics

The well established theory of fracture mechanics for predicting fatigue and fracture strength of various materials is comprised of two main fundamental approaches: Linear Elastic Fracture Mechanics (LEFM), and Elasto-Plastic Fracture Mechanics (EPFM). Both approaches analyze the stress field at the crack tip, using either limited plasticity or large plasticity. LEFM is adequate for analyses concerning fatigue crack growth where the propagation is governed by cyclic stresses that are of relatively small magnitude; fatigue analysis under service loads is known to be governed by the live-load stress range, which is typically much less than the yield stress of the material.

In Fracture mechanics, the modes of loading under which crack extension would occur fall into three different types: Modes I, II, and III, as illustrated in Figure 3 (Irwin 1958). Under Mode I, or opening mode, tensile forces load the body, such that the crack surfaces are pulled apart in the y -direction (Figure 3). The deformations are then symmetric with respect to the planes (perpendicular to the y -axis and the z -axis). Under Mode II, or sliding mode, shear forces parallel to the crack surfaces, which slide over each other in the x -direction (Figure 3), load the body. The deformations are then symmetric with respect to the plane perpendicular to the z -axis and skew symmetric with respect to the plane perpendicular to the y -axis. Finally, under Mode III, or tearing mode, shear forces parallel to the crack front, and the crack surfaces slide load the body over each other in the z -direction. The deformations are then skew-symmetric with respect to the plane perpendicular to the z - and y -axes (Figure 3).

Most civil engineering structures are geometrically symmetric and the primary stresses are typically perpendicular to the details in question. Therefore, the details are primarily under Mode I loading. It is important to recognize that hydraulic steel structures are subjected to complex loading conditions, through which multiple modes might drive the initiation and propagation of cracks. In this study, however, the focus is on Mode I loading only and is intended to provide a base for further studies, which may include Mixed-Mode loading conditions.

Figure 3. Different modes of loading in fracture mechanics (Irwin 1958).



2.2 Linear elastic fracture mechanics (LEFM)

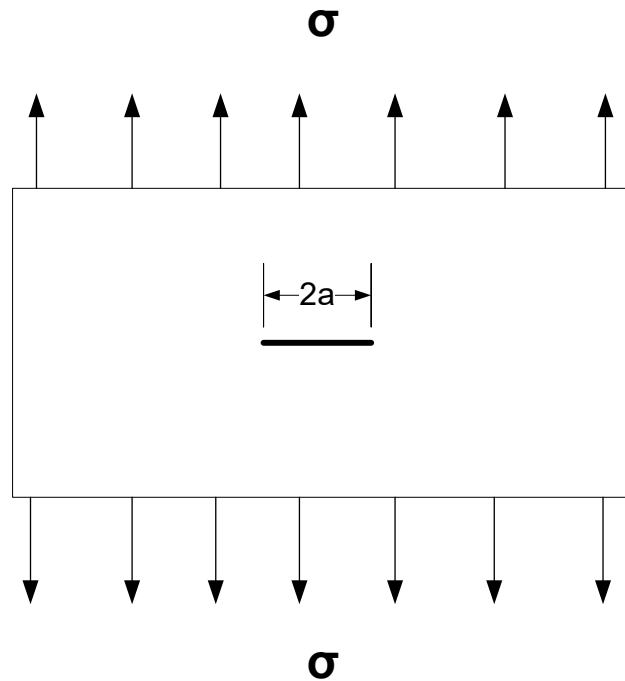
The stress intensity factor (K), which defines the demand associated with the state of stress at the crack tip, is the main parameter in LEFM. It is a measure of magnitude of the stress and strain fields at the crack tip, which can be described by

$$K = F_c F_s F_w F_g \sigma \sqrt{\pi a} \quad (1)$$

where,

- K = Stress intensity factor
- F_c = Crack shape factor
- F_s = Crack surface factor
- F_w = Finite width factor
- F_g = Non-uniform stress factor
- σ = Nominal stress
- a = Half the crack length.

Figure 4. Infinite plate under tension with through-thickness crack.



The crack length (a) is taken as half the crack length for a center crack and as the total crack length for an edge crack. The stress intensity factor has units of $\text{MPa}\cdot\text{m}^{1/2}$ or $\text{ksi}\cdot\text{in.}^{1/2}$. The resistance of material against brittle fracture depends on the relation $K < K_c$ (Anderson 1991), where K_c is the critical stress intensity factor, also known as the fracture toughness of a material, which simply can be viewed as the capacity of the particular material to resist crack formation. Primary parameters affecting fracture toughness are temperature, loading rate, and material thickness, as seen in Figure 4.

2.3 Strain energy release rate

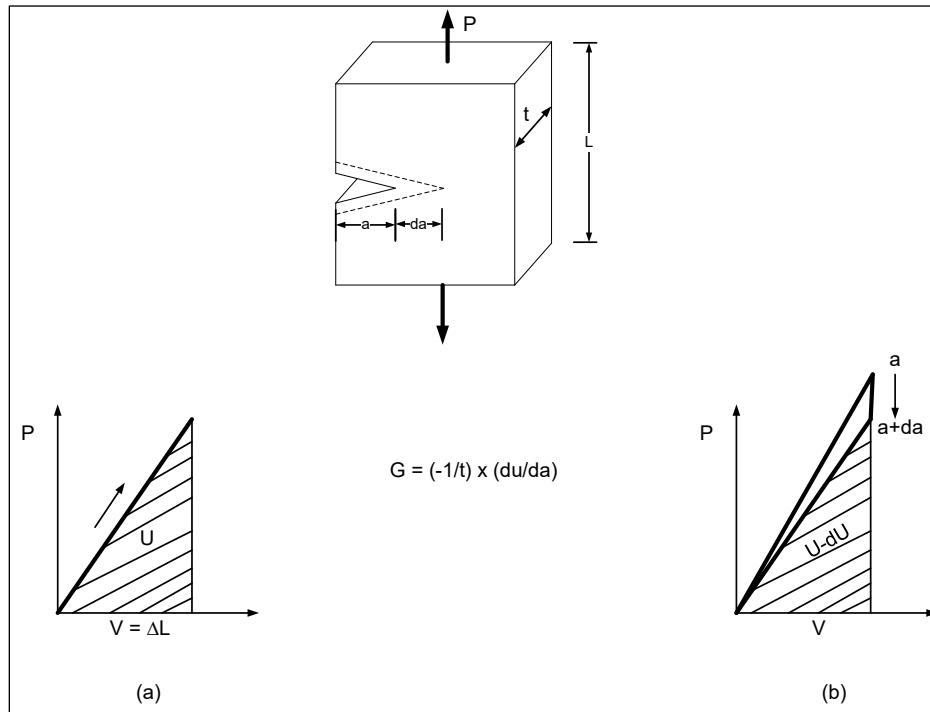
The energy release rate (G) for a crack growing under Mode I is a function of material thickness (t) and the change in energy stored (dU) for crack extension (da). When the energy available for crack growth is higher than the resistance provided by the material, the crack will grow. Figure 5 (a) describes the energy stored in the material when loaded with force (P). As the crack extends by da , the stored energy (U) in the material is released and used to form a new crack of length $(a+da)$ as shown in Figure 5 (b). The stored energy is decreased by dU . Hence, the total energy remaining in the body is $U-dU$. The stress intensity factor (K) and energy release rate (G) for the plane stress condition can be related by formula

$$G^2 = \frac{K^2}{E} \quad (2)$$

where

E = Modulus of elasticity for given material.

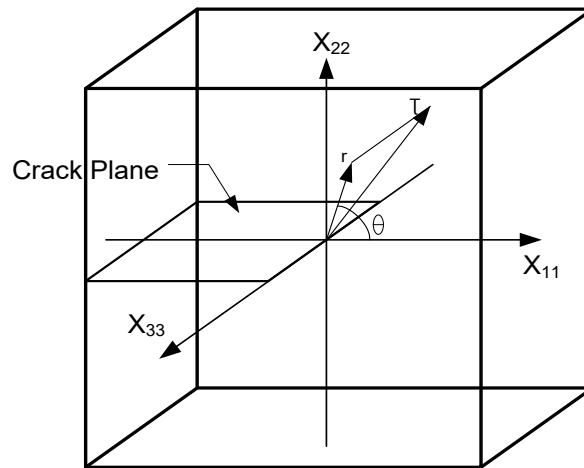
Figure 5. Energy release rate for crack of length a and da (Anderson 1991).



2.4 Stress intensity factor

As previously indicated, the stress intensity factor (K) describes the state of stress near the crack tip. Equation 3 gives the formula for the stresses surrounding the crack tip with the coordinate system shown in Figure 6.

Figure 6. Coordinate system at the crack tip
(François et al. 2013).



$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = \frac{K_I}{\sqrt{2\pi r}} \cos(\theta/2) \begin{Bmatrix} 1 - \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right) \\ 1 + \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right) \\ \sin\left(\frac{\theta}{2}\right) \cos\left(\frac{3\theta}{2}\right) \end{Bmatrix} \quad (3)$$

Under plane strain conditions, $\sigma_{33} = \nu (\sigma_{11} + \sigma_{22})$ and plane stress $\sigma_{33} = 0$.

Applying this equation at the crack tip shows that the stresses, mathematically, approach infinity. The singularity at the crack tip needs to be considered carefully when evaluating K . Therefore, it is customary to evaluate K near the crack tip. In this case, the stress intensity factor for Mode I can be calculated as the limit definition shown as

$$K_I = \lim_{r, \theta \rightarrow 0} \sigma_{22} \sqrt{2\pi r} \quad (4)$$

2.5 Fatigue category details

As previously noted, fatigue life is comprised of an initiation phase and a propagation phase. The American Association of State Highway and Transportation Officials' (AASHTO) provisions provide different fatigue detail categories and their corresponding S-N curves to determine the initiation life (AASHTO-LRFD 2010). The S-N curves are a log-log plot of the stress range versus number of cycles (Figure 7). For a particular fatigue detail, if the stress range is below its constant amplitude fatigue limit, cracking is postulated not to occur. The dotted lines in Figure 7 show the constant amplitude range for the different details. Constant amplitude

fatigue limits for the corresponding fatigue categories are provided in Table 1 and indicate that if a stress is below the given stress ranges for the given category a crack will not initiate, and it is expected that the connection will have infinite fatigue life.

Figure 7. AASHTO fatigue detail categories (AASHTOLRFD 2010).

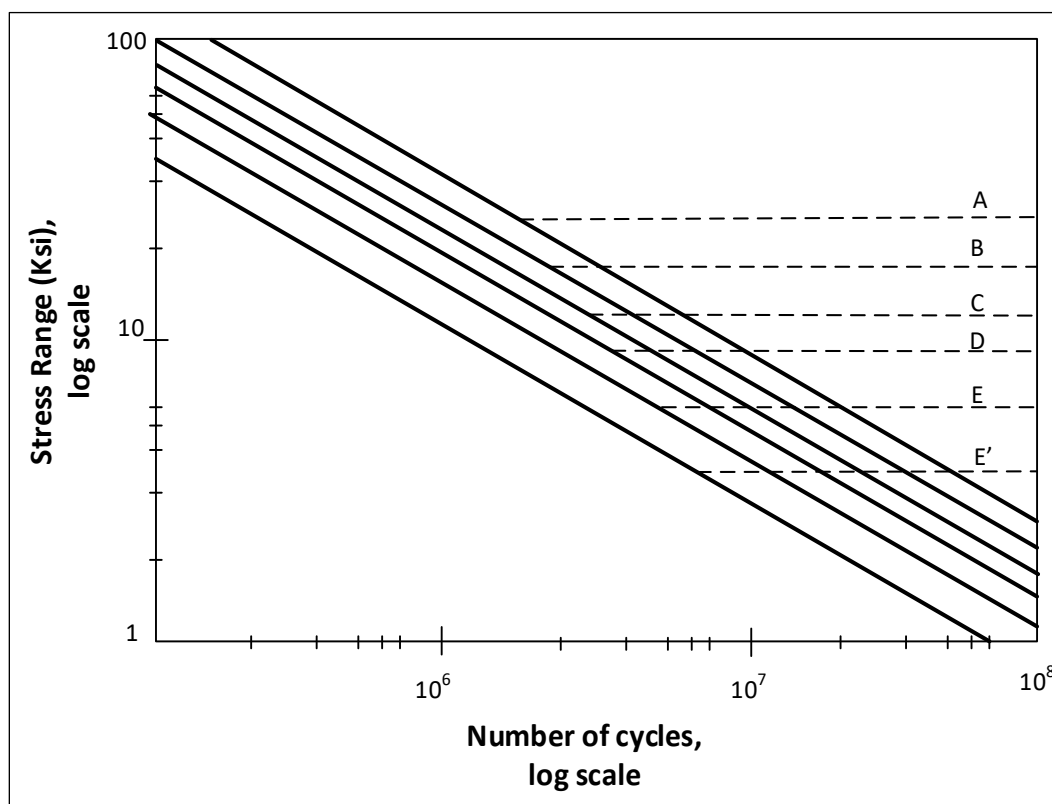


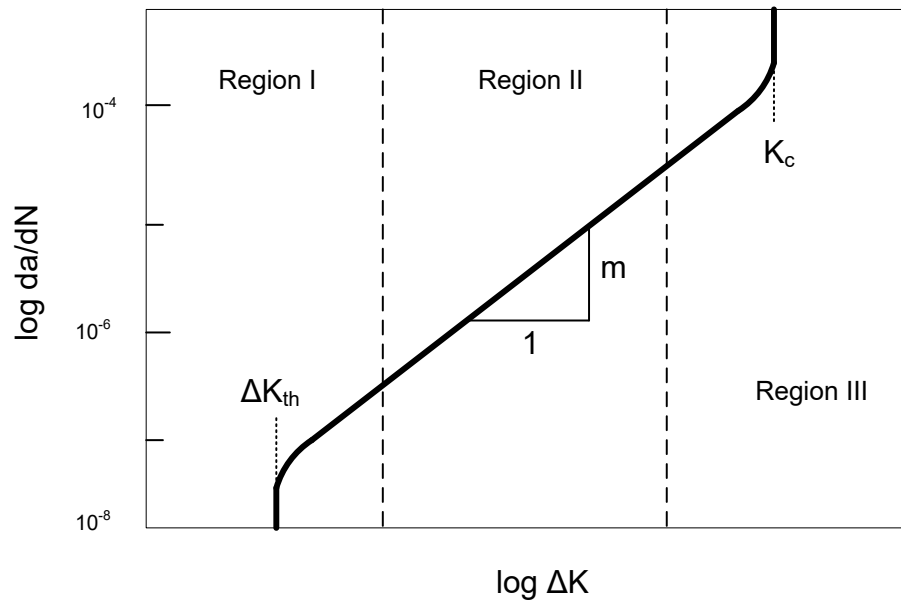
Table 1. Constant amplitude fatigue limits (AASHTOLRFD 2010).

Detail Category	Constant Amplitude Fatigue Limit (CAFL)
	MPa (ksi)
A	165 (24)
B	110 (16)
B' or C'	83 (12)
C	69 (10)
D	48 (7)
E	31 (4.5)
E'	18 (2.6)

2.6 Fatigue rate curve

For fatigue crack propagation, a curve for crack growth rate is commonly known as the da/dN versus ΔK curve, which is typically divided into three distinct regions (Region I, II, and III) as shown in Figure 8.

Figure 8. Typical da/dN versus ΔK curve.



Region I represents the nucleation of the fatigue crack. Microscopic features such as grain size, type of bond, applied stress, temperature, and environmental conditions, influence this region. There exists a factor range for stress intensity below, which fatigue cracks should not propagate. This is known as the fatigue crack growth threshold and is represented as ΔK_{th} .

Region II represents the crack propagation zone in which linear elastic fracture mechanics concepts are applicable. In this region, stable crack growth is seen in this region and the effects of microstructure, mean stress, and ductility are small.

In Region III, the stress intensity factor begins to approach the fracture toughness of the material (K_c), which represents the unstable crack growth just before the fracture. The plastic zone near the crack tip is considerably larger and concepts of LEFM are not applicable in this region. In the unstable crack growth zone, EPFM concepts accurately predict the unstable crack growth and fracture of the material.

2.7 Fatigue crack growth rate models

Many aspects of fatigue crack growth were well understood in the mid-20th century. A damage model for the crack growth under a variety of service loads was required (Beden et al. 2009). Many researchers have conducted thorough studies on both the constant amplitude fatigue loading and the variable amplitude fatigue loading. Beden et al. (2009) reviewed these models; some are presented in the following sub-articles.

The generalized equation that relates the change in crack length (da) and number of cycles (dN) to ΔK and R can be described using the following equation

$$\frac{da}{dN} = f(\Delta K, R) \quad (5)$$

where

R = Minimum load to maximum load ratio
 ΔK = Range of stress intensity factor.

2.7.1 Constant amplitude fatigue loading models

Constant amplitude fatigue loading is the most general type of fatigue growth analysis in which no load history has to be considered. There are many fatigue crack growth models that vary in the factors considered and different curve fitting parameters.

2.7.1.1 Paris Model

In 1963, Paris and Erdogan (1963) revealed that the stress intensity factor (ΔK) range is related to fatigue crack growth. The Paris Model demonstrated that plot of crack growth rate versus ΔK is represented by a straight line when plotted on a log-log scale. There is a threshold ΔK value, denoted as ΔK_{th} , below which a crack will not propagate. The ΔK_{th} value for structural steel can be taken as $3 \text{ MPa}\cdot\text{m}^{1/2}$. At high ΔK values ($\Delta K \geq \Delta K_c$), the crack growth is unstable and is accompanied by ductile fracture. This is known as Paris' law and can be given as

$$\frac{da}{dN} = C \Delta K^m \quad (6)$$

where

a = Half crack length

N = Number of cycles

ΔK = Range of stress intensity factors

C and m = Material constants.

It is worth noting that the load ratio (R) is often indirectly considered in Paris' law by using the effective stress range (ΔK_{eff}), which accounts for all parameters affecting crack growth rate including applied loads and residual stresses. Most researchers agree that all structural steels have similar crack growth rates and the variance observed in C values is a material variation (Dexter and Mahmoud 2004). The most reported values of C represent a conservative upper bound fit to the data. Typical values of C and m obtained for different types of steels are tabulated in Table 2 (Barsom and Rolfe 1999).

Table 2. Different values for Paris' law constants C and m for different types of steels (Barsom and Rolfe 1999).

Type of Steel	C [m/(cycle*MPa*in. ^{0.5})] ([in./cycle*ksi*in. ^{0.5}])	m [no unit]
Martensitic Steel	6.01×10^{-11} (2.6×10^{-9})	2.25
Ferrite-Pearlite Steel	8.32×10^{-12} (3.6×10^{-10})	3
Austenitic Stainless Steel	6.93×10^{-14} (3.0×10^{-10})	3

2.7.1.2 Walker Model

Paris' law does not directly take into account the stress ratio (R). This limitation was improved by Walker (1970), who included the effect of the stress ratio and the maximum stress intensity factor through the introduction of a new parameter (ΔK). The equation proposed by Walker was

$$\overline{\Delta K} = K_{\max}(1 - R)^{\gamma_w} \quad (7)$$

where

$$K_{\max} = \Delta K / (1 - R)$$

therefore,

$$\overline{\Delta K} = \frac{\Delta K}{(1-R)^{1-\gamma_W}} \quad (8)$$

Hence, the Walker law can be written as

$$\frac{da}{dN} = C_W (\overline{\Delta K})^{m_W} \quad (9)$$

or

$$\frac{da}{dN} = C_W \left(\frac{\Delta K}{(1-R)^{1-\gamma_W}} \right)^{m_W} \quad (10)$$

For $R=0$, the above equation becomes

$$\frac{da}{dN} = C_W (\Delta K)^{m_W} \quad (11)$$

where

C_W and m_W are material constants (Walker 1970).

This is similar to Paris' law and includes the effect of stress ratio but also introduces a new parameter (γ_W). This new parameter is determined by the trial and error method and it is possible that no value of γ_W can be found. In this scenario, the Walker (1970) model cannot be used to predict fatigue crack growth rate.

2.7.1.3 Forman Model

Forman (1972) improved the Walker model by suggesting a new model, which includes the unstable region, Region III, of the fatigue rate curve. The Forman law can be given by the following equation

$$\frac{da}{dN} = \frac{C_F (\Delta K)^{m_y}}{(1-R)K_C - \Delta K} = \frac{C_F (\Delta K)^{m_y}}{(1-R)(K_C - K_{max})} \quad (12)$$

Here, K_c is fracture toughness of the material and C_F and m_y are material constants (Forman 1972). This equation indicates that as K_{max} approaches K_c then da/dN tends to infinity. Hence, the model is capable of representing Region II (stable growth) as well as Region III (accelerated

growth) of the fatigue rate curve. For each data point, the Forman equation is capable of representing the data for different stress ratios using the following quantity

$$Q = \frac{da}{dN} [(1 - R)K_c - \Delta K] \quad (13)$$

If different ΔK and R combinations fall together on a straight line, then the Forman model may be used. Comparing above equations, the Forman law can be written as

$$Q = C_F (\Delta K)^{m_y} \quad (14)$$

In continuation to the Forman model, Hartman and Schijve (1970) proposed a new equation as follows

$$\frac{da}{dN} = \frac{C_{HS} (\Delta K - \Delta K_{th})^{m_{HS}}}{(1-R)K_c - \Delta K} \quad (15)$$

where

C_{HS} and m_{HS} are material constants defined by Hartman and Schijve (1970).

This gives another version of the Forman law

$$\frac{da}{dN} = \frac{C_{MOD} (\Delta K)^{m_{MOD}} (\Delta K - \Delta K_{th})^{0.5}}{(1-R)K_c - \Delta K} \quad (16)$$

Where C_{MOD} and m_{MOD} are material constants for the modified Forman law. The disadvantage of using the previous equations is that ΔK_{th} is sensitive to the value, or R , a specific value of ΔK_{th} needs to be substituted for the particular value of R .

2.7.1.4 Collipriest Model

Collipriest (1972) proposed a crack growth model capable of describing all three regions of the fatigue rate curve while incorporating the stress ratio effect. It is given by the following expression

$$\frac{da}{dN} = C (K_c / \Delta K_{th})^{\frac{m}{2}} \text{EXP} \left[\ln \left(\frac{K_c}{\Delta K_{th}} \right)^{\frac{m}{2}} \tanh^{-1} \left[\frac{\ln \left(\frac{\Delta K^2}{(1-R)K_c \Delta K_{th}} \right)}{\ln \left(\frac{(1-R)K_c}{\Delta K_{th}} \right)} \right] \right] \quad (17)$$

Although this model includes all the three regions of the fatigue rate curve, the various parameters produce a complicated model.

2.7.1.5 Frost, Pook, and Denton Model

Frost et al. (1971) hypothesized that crack growth occurring under cyclic loading is not a result of progressive structural damage, but is due to the formation of striations that are caused by reshaping the crack tip at each cycle because of unloading. This model is based on the increments of crack growth with each, which can be related to changing crack tip geometry during opening and closing of the crack. This relationship can be given by

$$\frac{da}{dN} = \frac{9}{\pi} \left(\frac{\Delta K}{E} \right)^2 \text{ for plane stress} \quad (18)$$

$$\frac{da}{dN} = \frac{7}{\pi} \left(\frac{\Delta K}{E} \right)^2 \text{ for plane strain} \quad (19)$$

Frost et al. (1971) found that the prediction of the plane stress equation and experimental data plotted in terms of $\Delta K/E$ against da/dN are in good agreement at crack growth rates around 3×10^5 mm/cycle. Beden et al. (2009) states that experimental crack growth rates are underestimated at high growth rates and overestimated at low growth rates.

2.7.1.6 Pugno and Ruoff Model

Pugno and Ruoff (2004) generalized Paris' law using Quantized Fracture Mechanics by substituting $K(a)$ with a mean value, $K^*(a, \Delta a)$

$$= \sqrt{[K^2(a)]_a^{a+\Delta a}} \text{ where } \Delta a \text{ is fracture quantum, which is a material}$$

constant for infinite life. Pugno and Ruoff (2004) proposed a generalized law as follows

$$\frac{da}{dN} = C [\Delta K^*(a, \Delta a, \Delta \sigma)]^m \quad (20)$$

where

Δa is a function of $\Delta \sigma$.

Integrating Equation 20, the total number of cycles for fatigue collapse (when the crack length has reached its critical final value at a_c) can be given as

$$N_c^{P*} = \frac{1}{C} \int_a^{a_c} \frac{da}{[\Delta K^*(a, \Delta a, \Delta \sigma)]^m} \quad (21)$$

In Equation 21, Δa can be recovered using Wohler's prediction in the limit case of $a \rightarrow 0$ and it can be written as

$$N_c^W = \frac{\bar{C}}{\Delta \sigma^k} \quad (22)$$

hence,

$$\Delta a: N_c^{P*}(a \rightarrow 0) = N_c^W \quad (23)$$

This simple law would allow the ability to study not only the final fracture, but also the fatigue crack growth $N_c^{P*}[a(N)]$ where $a \leq a(N) \leq a_c$.

2.7.1.7 Wheeler Model

Wheeler (1972) proposed a model that introduced a new parameter, called retardation. This model can be applied to any fatigue crack growth equation $da/dN = f(\Delta K, R)$. Wheeler's law can be given as

$$\frac{da}{dN} = \phi_R f(\Delta K, R) \quad (24)$$

where

$$\phi_R = \left(\frac{R_y}{a_p - a} \right)^y \text{ for } (a + R_y) < a_p$$

or

$$\phi_R = 1 \text{ for } (a + R_y) \geq a_p$$

and

ϕ_R = retardation parameter

R_y = extent of current yield zone

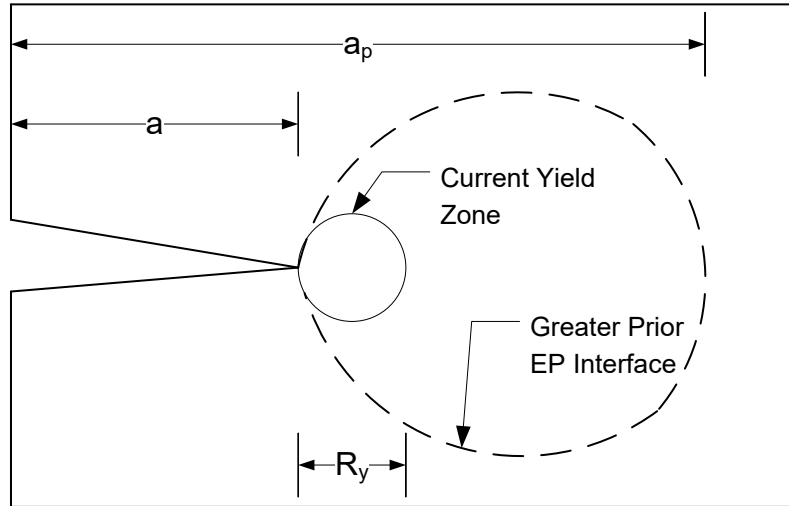
y = shape factor

$a_p - a$ = distance from crack tip to elasto-plastic interface.

These parameters are illustrated in Figure 9. For plane strain conditions, Wheeler suggested

$$R_y = \frac{1}{4\pi\sqrt{2}} \left(\frac{K_I}{\sigma_y} \right)^2 \quad (25)$$

Figure 9. Crack tip yield zones (Wheeler 1972).



2.7.1.8 Willenborg, Engle, and Wood Model

Willenborg et al. (1971) modified Wheeler's Model by determining the amount of retardation as a function of stress intensity factor to cancel the effect of overload plastic zone. The modified stress intensity factor can be written as

$$K_r = (K_{max})_{OL} \left(1 - \frac{\Delta a}{Z_{OL}} \right)^{\frac{1}{2}} - K_{max} \quad (26)$$

Where $(K_{max})_{OL}$ is the maximum stress intensity factor during overload, Δa is the amount of crack growth since the overload, Z_{OL} is the overload plastic zone size, and K_{max} is the maximum stress intensity factor for normal loading. Johnson (1981) gave an equation for the overload plastic zone as follows

$$Z_{OL} = \frac{1}{\beta\pi} \left[\frac{(K_{max})_{OL}}{\sigma_y} \right]^2 \quad (27)$$

2.7.1.9 Barsom Model

Barsom (1976) described the stress intensity factor in terms of root mean square value of the stress intensity factor range, ΔK_{rms} . It can be given as

$$\Delta K_{rms} = \sqrt{\sum_{i=1}^n \Delta K_i^2} \quad (28)$$

where ΔK_i is the stress intensity factor for i^{th} cycle of loading consisting of n cycles. This model does not account for retardation of crack growth rate.

Barsom obtained a single stress intensity parameter that will describe crack growth rate under both constant amplitude loading and variable amplitude loading. If the requirements of the above equation are satisfied, Barsom proposed the following relationship

$$\frac{da}{dN} = A_B (\Delta K_{rms})^{m_B} \quad (29)$$

where

A_B and m_B are constants and

$$\Delta K_{rms} = \sqrt{\frac{\sum_{i=1}^k \Delta K_i^2}{n}} \quad (30)$$

ΔK_{rms} is the parameter that represents the root mean square of the individual load cycle in the spectrum. This model is simple to use as it requires to determine the curve fitting parameters A_B and m_B .

2.7.2 Variable amplitude fatigue loading models

Crack growth in structures depends on the amplitude, stress ratio, and frequency of the load (Beden et al. 2009). It is difficult to model the randomness in these parameters since the variable loading is random in nature. Overload cycles retard the crack growth rate while under load cycles accelerate the growth. Different approaches were used to develop these models for variable amplitude fatigue loading namely, yield zone size, crack closure approach, and strain energy density factor. Due to complex mechanisms existing in these models, no universal model has been derived.

2.7.2.1 Chang, Szamossi, and Liu Model

Two different approaches were considered for experiments conducted on center-cracked tension specimens under random spectrum loading by Chang et al. (1981). One approach did not account for load interactions such as tensile overload retardation, compressive load acceleration, etc. The model can be given as

$$\frac{da}{dN} = C \left[\frac{\Delta K}{(1-\bar{R})^{1-\gamma}} \right]^m \quad (31)$$

Here, γ is a constant to be determined through experiments.

And if $\Delta K > \Delta K_{th}$

$$\begin{aligned} 0 \leq \bar{R} \leq R_{cut}^+ & \quad \bar{R} = R \\ 0 \leq \bar{R} \geq R_{cut}^+ & \quad \bar{R} = R_{cut}^+ \end{aligned}$$

where

R = stress ratio
 R_{cut}^+ = cut off value of stress ratio.

$$\text{For } \Delta K \leq \Delta K_{th} \quad \frac{da}{dN} = 0$$

where, $\Delta K_{th} = (1-R) \Delta K_{tho}$

ΔK_{tho} = threshold value of ΔK for $R=0$.

2.7.2.2 Hudson model

Hudson (1981) used a similar approach as Barsom (1976) to predict aircraft typically experiences the fatigue crack growth under random spectrum loading that. This approach neglects the load interactions effect and provides an average growth rate for fatigue cracks when load interactions are limited. The maximum and minimum mean square stress levels can be calculated using the following equations:

$$\sigma_{\max rms} = \left[\frac{1}{N} \sum_{r=1}^N (\sigma_{\max})^2 \right]^{\frac{1}{2}} \quad (32)$$

$$\sigma_{\min rms} = [\frac{1}{N} \sum_{r=1}^N (\sigma_{\min})^2]^{\frac{1}{2}} \quad (33)$$

Where $\sigma_{\max}$ and $\sigma_{\min}$ are the maximum and minimum stresses of random loading and N is the total number of these stresses. The root mean square stress ratio can be given as

$$R_{rms} = \frac{\sigma_{\min rms}}{\sigma_{\max rms}} \quad (34)$$

The root mean square maximum and minimum stress intensity factors can be given using a correction factor for center-cracked specimen

$$K_{\max rms} = \sigma_{\max rms} \sqrt{\pi a \sec(\frac{\pi a}{W})} \quad (35)$$

and

$$K_{\min rms} = \sigma_{\min rms} \sqrt{\pi a \sec(\frac{\pi a}{W})} \quad (36)$$

Where, a is the half crack length and W is the specimen width. The root mean square stress intensity range can be given as

$$\Delta K_{rms} = K_{\max rms} - K_{\min rms} \quad (37)$$

Hudson used the above parameters along with the Forman equation to predict fatigue crack growth rates

$$\frac{da}{dN} = \frac{C \Delta K_{rms}^m}{(1-R_{rms})K_c - \Delta K_{rms}} \quad (38)$$

Where, K_c is the elastic fracture toughness.

2.7.2.3 Newman Model

Newman (1981) used the crack closure approach for predicting fatigue life. Newman (1981) calculated the crack opening stress as a function of crack length and loading history from an analytical model. The law proposed by Newman (1981) was written as

$$\frac{da}{dN} = C_1 \left[\frac{\Delta K_{eff}}{1 - (\frac{K_{max}}{C_3})^2} \right]^{C_2} \quad (39)$$

where

$\Delta K_{eff} = (\sigma_{max} - \sigma_{op})Y\sqrt{\pi a}$. C_1 , C_2 and C_3 are constants determined using constant amplitude loading data by least squares.

Newman (1981) re-predicted the results using Equation 35 and giving a new equation as follows

$$\frac{da}{dN} = C_1 \Delta K_{eff}^{C_2} \left[\frac{1 - \left(\frac{\Delta K_o}{\Delta K_{eff}} \right)^2}{1 - \left(\frac{K_{max}}{C_5} \right)^2} \right] \quad (40)$$

where

$$\Delta K_o = C_3 \left(1 - C_4 \frac{\sigma_o}{\sigma_{max}} \right); \text{ and } K_{max} = \sigma_{max} Y \sqrt{\pi a}$$

In 1997, Newman developed a much more realistic finite element model. It includes a plastic zone, which causes interference between crack surfaces. Until now, this finite element model is the best to predict fatigue crack growth (Beden et al. 2009).

2.7.2.4 Johnson Model

Johnson (1981) used multi-parameter yield zone for determining fatigue crack growth under random variable loading. It accounts for crack growth retardation and acceleration by modifying the stress ratio in the Forman equation. The model proposed by Johnson (1981) can be written as

$$\frac{da}{dN} = \frac{C \Delta K^n}{(1 - R^{eff})^m K_C - \Delta K} \quad (41)$$

where

$m=1$ at $R>0$ and $m=2$ at $R<0$.

R^{eff} accounts for all the load interactions when the full stress intensity range is used, adjusting its value for each cycle. C and n are obtained from the constant amplitude loading data. The threshold (ΔK_{th}^*) can be expressed as

$$\Delta K_{th}^* = (1 - R^{eff})\Delta K_{th} \quad (42)$$

where

ΔK_{th} is obtained for $R=0$. The effective stress ratio then will be

$$R^{eff} = \frac{K_{min} - K_R}{K_{max} - K_R} = \frac{K_{min}^{eff}}{K_{max}^{eff}} \quad (43)$$

K_R is the residual stress intensity generated due to plasticity around the crack tip. The maximum allowable stress ratio will be

$$R_{max} = \left[\frac{0.2Z_{OL}}{t} \right] + 0.6 \quad (44)$$

where

Z_{OL} is the plastic zone size.

2.7.2.5 Modified Miner Model

Verma (1990) introduced a model based on Miner's rule (Miner 1945), which does not account the rain flow counting technique to predict the growth rate of fatigue crack under random loading. The equation can be given as

$$\Delta K_{eff} = \sum \left[\frac{n_i \Delta K_i^m}{N_T} \right]^{\frac{1}{m}} = \sum \left[\frac{n_i}{N_T} \right]^{\frac{1}{m}} \Delta K_i \quad (45)$$

where

ΔK_{eff} = effective stress intensity factor range

N_i = number of cycles

ΔK_i = stress intensity factor range for i^{th} cycle

N_T = total number of cycles

m = constant.

2.8 Fatigue crack repair and retrofit methods

Many fatigue crack repair and retrofit methods are available. Repairing existing cracked material can be performed either by removing the crack through gouging and filling the gouged area with weld metal or by

modifying the stresses at the crack tip without removing the cracks. In some cases, whether the crack is removed or not, reinforced plates can be added to strengthen the troubled area. In general, repair and retrofit methods can be classified as surface treatments, repair of through-thickness cracks, or modifying the specific detail or entire global structure in order to reduce further cracking (Dexter and Ocel 2013).

2.8.1 Surface treatments

Surface treatments include grinding, gas tungsten arc (GTA) re-melting, impact treatments (only for shallow cracks), and hole drilling. Grinding includes disc grinding and burr grinding, and is used to partially or fully remove the cracked details. GTA re-melting is similar to welding and is usually applied to the transition area between the weld toe and base metal. Hole drilling is when a hole is drilled at the crack tip to reduce the stress concentration at the tip of the crack extending fatigue life. During the welding procedure, small micro cracks could be generated during the welding procedure, which might grow, becoming fatigue cracks under cyclic loads that can be removed by grinding. Disc grinding does not increase the fatigue life in appreciable amounts, but burr grinding provides 50% higher allowable stress range over untreated details (Dexter and Ocel 2013). Grinding should be performed, such that the sparks generated due to grinding fly parallel to the direction of the primary stress.

GTA re-melting reduces the stress concentration at weld toe. While a gas shielded tungsten electrode is manually moved along the weld toe, the metal is only melted without adding any extra material while gas shielded tungsten electrode is manually moved along the weld toe. The effectiveness of this method requires higher operator skills as well as adequate penetration, which is difficult to attain for field operations.

The different impact treatment methods introduce local compressive residual stresses near the crack tips and are only applicable for shallow cracks (typically less than 3 mm [.12 in.]). Air hammer peening includes an air hammer with a blunt tip to deform the weld toe, creating local compressive stresses (Figure 10). This helps in reducing the tensile stress range and increasing the fatigue life. Ultrasonic impact treatment (UIT) uses ultrasonic waves applied to a needle or peening hammer tap to the weld toe. UIT has proven to be more effective than air hammer peening, possibly increasing the fatigue strength of the detail by one category (Dexter and Ocel 2013).

Drilling holes reduces the stress concentration at the crack tip (Figure 11). This method is only good for Mode I cracking, thus special attention must be taken when the crack grows between 30-60 degrees which indicates that the shear stress is the driven mechanism for crack growth. Larger holes are better as long as the strength of the detail is not altered. To improve the effectiveness of these holes, the cold expansion method is used; a pin, slightly larger in diameter than the hole, is punched through the hole and as the pin passes through the hole it deforms the hole plastically, introducing compressive residual stresses. In some cases, structural bolts can be inserted in the hole and pre-tensioned, providing a compressive stress field around the hole.

Figure 10. Air hammer peening for repairing fatigue cracks (Dexter and Ocel 2013).



Figure 11. Hole drilling method to stop crack propagation (Dexter and Ocel 2013).



2.8.2 Repair of through-thickness cracks

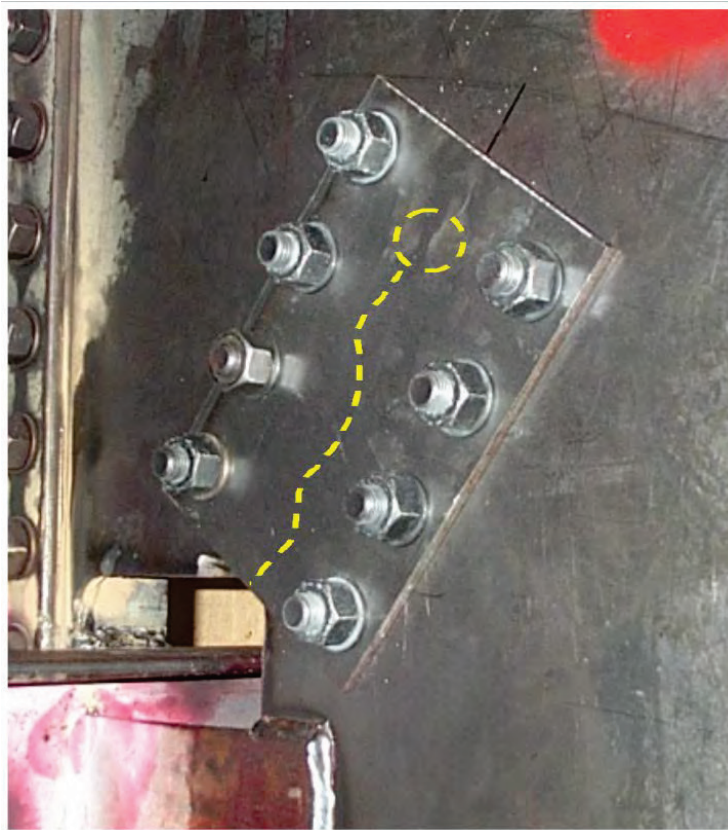
Fully developed cracks (through-thickness cracks) cannot be repaired simply by using surface treatment methods. Through-thickness cracks require more extensive repairs such as 1) vee-and-weld and 2) adding doubler/splice plates; hole drilling is also commonly used as a repair method (Figure 12). The vee-and-weld method is used for long through-thickness cracks, the material is gouged out along the crack in the shape of a V, and then the gouge is filled with a V-shaped groove weld (i.e., the entire cracked area is filled with weld metal). Quality of the vee-and-weld is better when made in a fabrication shop and it may lower in the field, as it requires skilled, experienced labor. Environmental conditions may also affect the procedure.

Figure 12. Vee-and-Weld repair method to repair through-thickness cracks (Dexter and Ocel 2013).



Doubler plates or splices are another method of repairing through-thickness fatigue cracks (Figure 13). These plates add extra material to the detail, increasing the cross-section or provide continuity to the cracked detail (i.e., bridging the crack). The added cross-section reduces the stress range experienced by the detail but increases the dead load. Bolted doubler plates are generally preferred over the welded doubler plates. With welded doubler plates, the new weld might start to develop cracks. Bolted connections also have a better fatigue life category than welded connections are AASHTO (2010) Category B while welded connections that are AASHTO (2010) may vary from Category B to E'. Welded connections also require proper alignment of the plate that increases the difficulty of the installation and can reduce the effectiveness of the repair.

Figure 13. Addition of a doubler plate to repair through-thickness crack Dexter and Ocel 2013).



2.8.3 Modification of the detail

Detail modification relies on the design to reduce the stress range in the cracked detail, subsequently reducing the crack driving force. For example, if the detail has sharp corners it is highly likely to have high stress concentration near these sharp corners. To reduce the stress concentration caused by the presence of sharp corners, the corners can be modified to be rounded in shape (i.e., introduce a transition radius to allow for smooth stress flow). The overall geometry of the detail might also be changed to reduce the stress concentration on the detail. It is very important to keep in mind that the modified details should be checked for fatigue.

2.8.4 Repairs using carbon fiber reinforced polymer (CFRP) composites

The use of fiber-reinforced polymers to increase the fatigue life of structures started in mid-1980. The main advantage of using CFRP material is that it is lightweight and durable, which makes it easy to handle. A recent feasibility study was conducted by Mahmoud and Riveros (2013) on the potential for using CFRP for the repair of underwater steel

structures. The literature review in the section below highlights some key studies listed in that feasibility study.

2.9 Literature review on the feasibility of the use of CFRP for fatigue repair

2.9.1 Crack growth in CFRP-retrofitted panels

There have been various studies performed to evaluate the increase in fatigue life of steel structures using fiber reinforced polymer (FRP) or CFRP (Tavakkolizadeh and Saadatmanesh 2003; Alemdar et al. 2012; Wu et al. 2012; Yu et al. 2014). The majority of the studies were conducted on concrete structures with limited field applications (Shaat et al. 2003). Unlike reinforced concrete structures, studies on the use of CFRP for repairing steel structures are scarce. The majority of existing work on metallic structures for evaluating the effectiveness of CFRP in slowing down crack growth was conducted on aluminum panels for the aerospace industry. For steel structures, research findings have shown that CFRP sheets and strips are effective in restoring the lost capacity of a damaged steel section as well as strengthening the sections to resist higher loads, extend fatigue life, and reduce crack propagation.

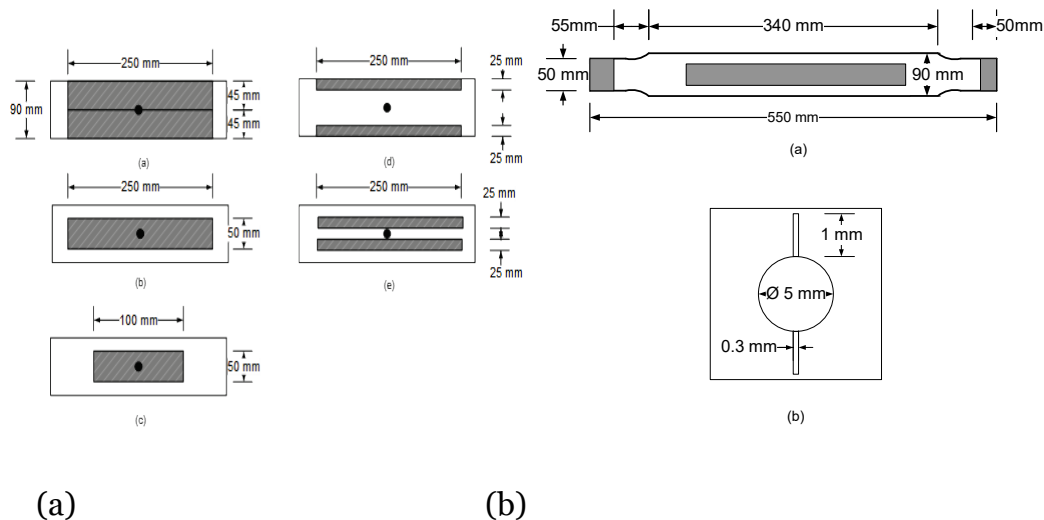
Tavakkolizadeh and Saadatmanesh (2003) studied the potential increase in fatigue life of the steel girder by attaching epoxy-bonded CFRP strips to the tension flange by assessing the number of cycles to crack initiation. Findings showed that the fatigue life of the retrofitted specimens was between 2.6 to 3.4 times that of the unretrofitted specimens for stress ranges of 345 to 207 MPa, respectively. This improvement is equivalent to upgrading the detail from the AASHTO (2010) category D to category C.

Alemdar et al. (2012) studied the effectiveness of CFRP overlays on welded connections under fatigue loading. The CFRP-retrofitted, pre-cracked specimen sustained an additional 2.88 million cycles after crack initiation without any measurable crack growth. These experiments also showed that the CFRP overlays were able to reduce the stress range at the critical point of the welded connection below the crack propagation threshold.

Wu et al. (2012) presented a study on the use of ultrahigh modulus CFRP for strengthening center-cracked steel plates. In this study, an ultrahigh modulus CFRP plate with a modulus of 460 GPa was used to strengthen initially cracked steel plates. Five different strengthening configurations

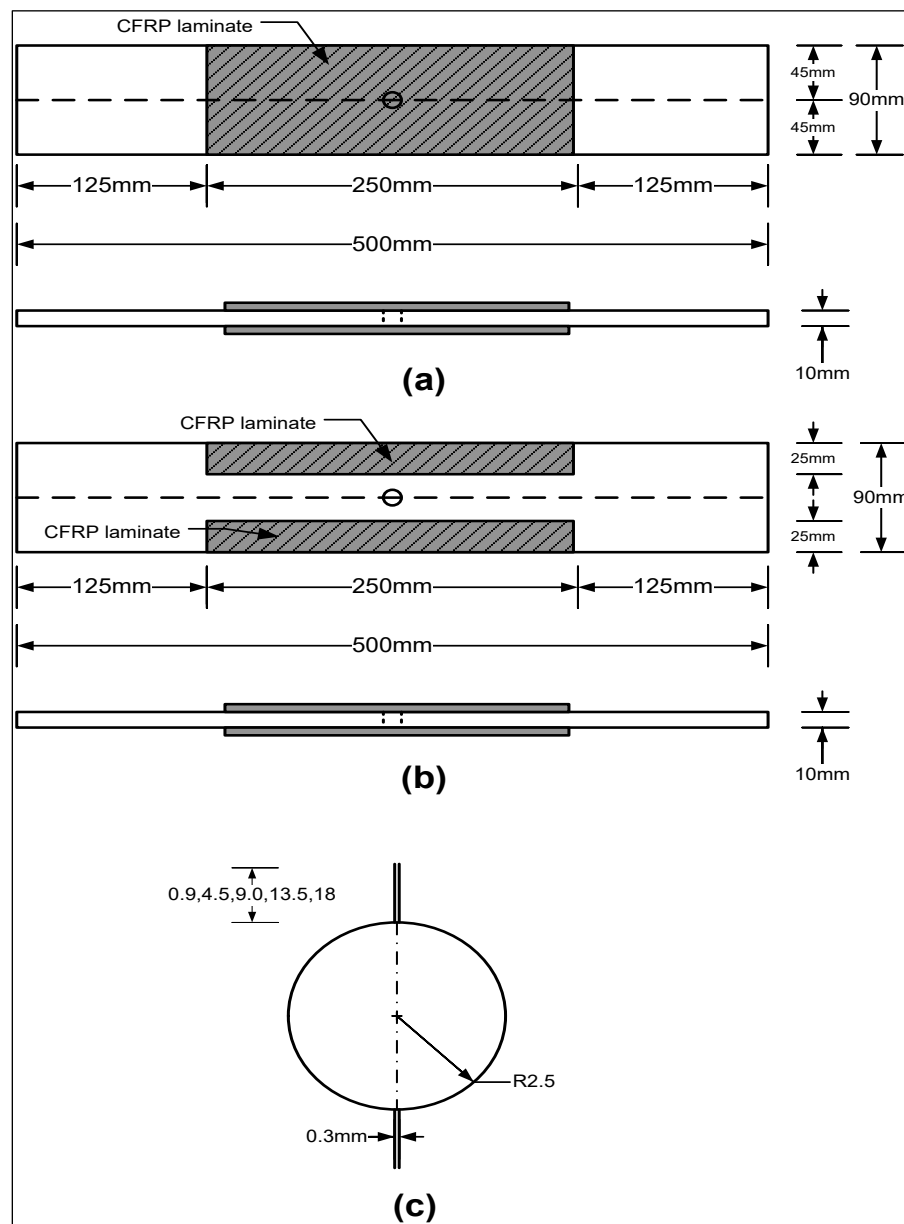
were used by changing patch length and patch width and applying the patches on one or both sides. The specimens were tested under fatigue loading with a frequency of 20 Hz, stress ratio of 0.1, and a nominal stress of 150 MPa. The experimental results showed the greatest fatigue life was eight times more than that of the unstrengthened steel plates. It was concluded that the CFRP bond length, bond width, and location have considerable influence on fatigue performance of CFRP-strengthened specimens and CFRP needs to be attached close to the crack tip to achieve better results. The specimen details and CFRP configuration are shown in Figure 14.

Figure 14. Chao and Duan (2012) (a) Specimen details (b) CFRP configuration.



Yu et al. (2014) investigated the effect of CFRP applied at different stages of crack propagation in a steel coupon. A numerical study was conducted on CFRP bonded steel plates with different degrees of damage using the boundary element method (BEM). The results of this study were then compared with experimental results, which showed that the BEM might be used to investigate fatigue crack propagation in CFRP bonded steel plates. The analysis included the effect of bond length, bond width, CFRP stiffness and shear modulus of the adhesive on stress intensity factor. The specimen configuration is shown in Figure 15. Numerical models showed similar results with experimental results. It was found that the stress intensity factor is reduced with an increase in the shear modulus of adhesive from 0 MPa to 350 MPa; further increase in the shear modulus did not affect the stress intensity values by much. Considerable reduction of the stress intensity factor was seen as the patch surface area increased. Results showed that as the CFRP's elastic modulus was increased the stress intensity factor decreased.

Figure 15. Specimen geometry for Yu et al. (2014) tests (a) patch configuration A (b) patch configuration D (c) notch details.



2.9.2 CFRP debonding and development length

Shield et al. (2003) conducted a series of experimental tests to evaluate the effective bond length of CFRP in fatigue-repaired steel girders. The effective bond length is the shortest CFRP strip length that results in the strip developing its full strength. It was concluded that the adhesive's ductility governed the effective bond length, and kept the CFRP strips from achieving their ultimate strength. In addition, the experiments showed significant reduction in the strain of the retrofitted cracked specimens, except in the

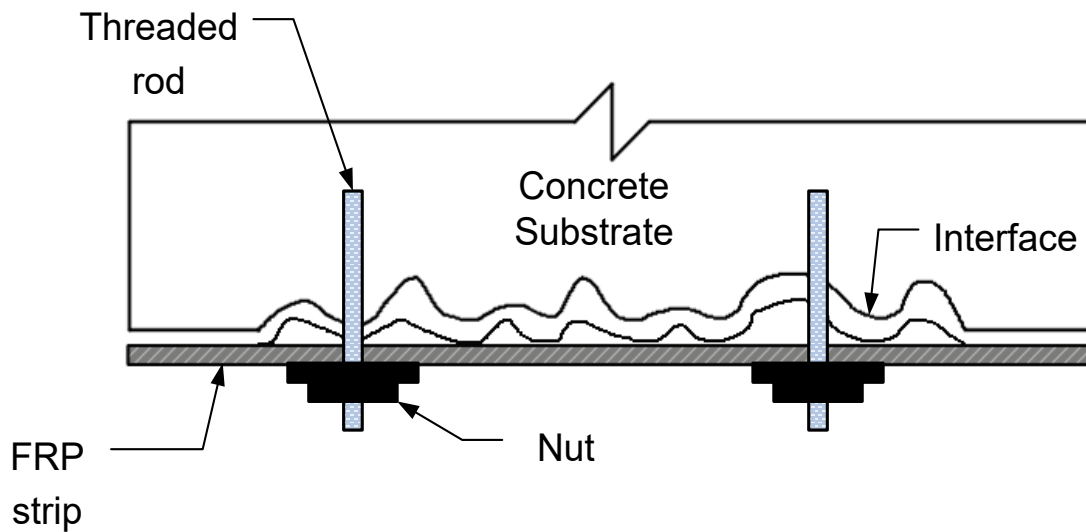
case of small cracks, where it was difficult to identify clearly the benefits. The study showed that the bonded CFRP strips reduced the stresses at the crack tip by approximately 60%. The total recommended length of a one-layer CFRP strip applied for retrofit should be a minimum of 20 in. long (two 8-in.-long bonded regions on either side of a 4-in.-long debonded region).

Schnerch et al. (2006) focused on the surface preparation methods and means of preventing galvanic corrosion since performance of the bond dictates the failure of the joints. In this study, the use of several types of adhesives resulted in rupture of the CFRP strips, which indicates the development length is proportional to the number of CFRP layers used. Analytically, it was predicted that high shear stresses would develop at the end of the CFRP, which was confirmed by the experimental program in this study. Selection of the proper adhesive and surface treatments is necessary to achieve the highest bond strength.

Bocciarelli et al. (2009) investigated the debonding strength of axially loaded, double shear lap joints between steel plates and CFRP through analytical, numerical, and experimental analysis. Two steel plates were joined together using two CFRP plates, with epoxy making a lap shear joint with different lengths. The steel-adhesive interface was the dominant failure. It was found that the greater the thickness, the greater the strength will be in the adhesive joints.

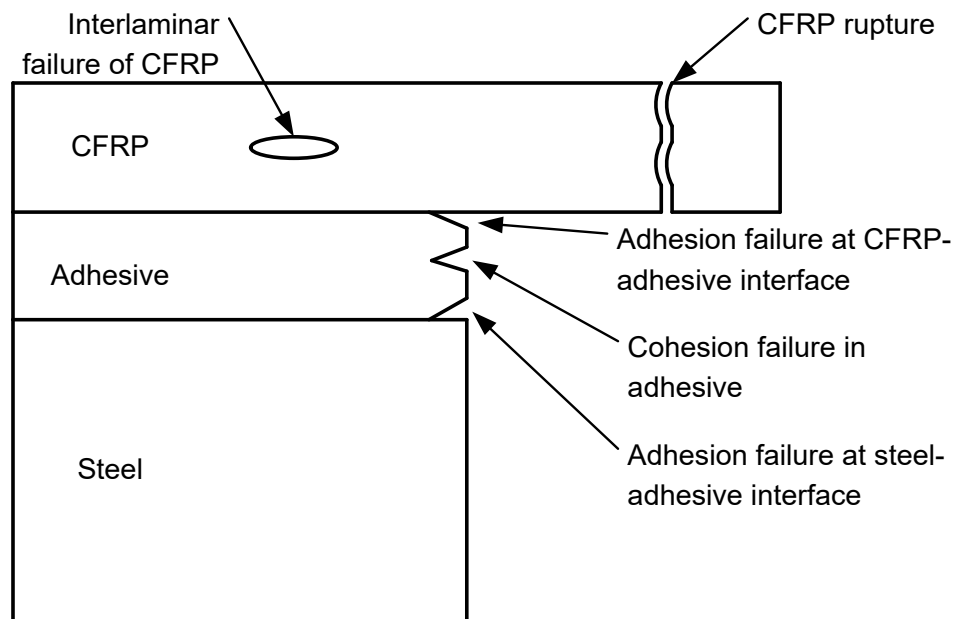
Bond interface is the weakest link in the joint; Wu et al. (2011) developed a new hybrid bonded FRP technique to reduce FRP debonding. The new proposed hybrid system suggested by Wu et al. (2011) is shown in Figure 16. A thin concrete layer is peeled off before applying FRP. FRP is then applied using the required adhesive and mechanical fasteners are drilled through the FRP to the concrete substrate. This increases the frictional resistance at the interface and in turn, increases the bond strength. It was concluded that the failure of the beam was attributed to the rupture of the FRP. Furthermore, if the number of FRP layers is increased, the higher strength of the bond is achieved.

Figure 16. Hybrid bonded FRP technique (Wu et al. 2011).



Teng et al. (2012) studied debonding failures of CFRP-strengthened steel coupons. Considering the failure plane, debonding failures between the steel and CFRP may occur in the adhesive (cohesion failure at the interface between the adhesive and adherends (adhesion failure), or a combination of both. These different types of failures are illustrated in Figure 17. Adhesion failure of the interfacial bond strength depends on the steel and CFRP surfaces as well as the bond capability of the adhesive. The test results showed that the grit-blasting method produced significantly higher adhesion strengths over the solvent cleaning and hand grinding methods. The test results also confirmed that there exists an effective bond length in such bonded joints, beyond which, any further increase in the bond length does not lead to any further increase in the bond strength, but does lead to an increase in the ductility of the debonding process.

Figure 17. Possible failure modes of CFRP to steel bonded joints.



3 Experimental Test Setup

3.1 Introduction

This chapter describes the details of the experimental setup. It includes the geometries of test specimens, test setup, instrumentation plan and surface preparation, mechanical properties of CFRP and adhesive, test matrix, and testing protocol.

It is important to design the test setup for the required material and taking into consideration fatigue strength, since repeated cycles on the reaction frame could cause premature fatigue cracks to develop. The geometry of the test specimen was selected to allow for the application of large CFRP patches, mimicking actual field applications. To investigate strains in both the steel specimens and CFRP strips, strain gauges were installed at various locations on the specimens as well as on the CFRP. Surface preparation is an important step before installing the CFRP strips and strain gauges on the specimen to achieve effective bonding of the CFRP and strain gauge adhesive. Problems related to the fatigue crack propagation in the field of civil engineering are generally associated with Mode I loading. Although this does not always hold true, it was necessary to test all the specimens under Mode I to develop a fundamental understanding of the effectiveness of the proposed repair under a uniform state of stress.

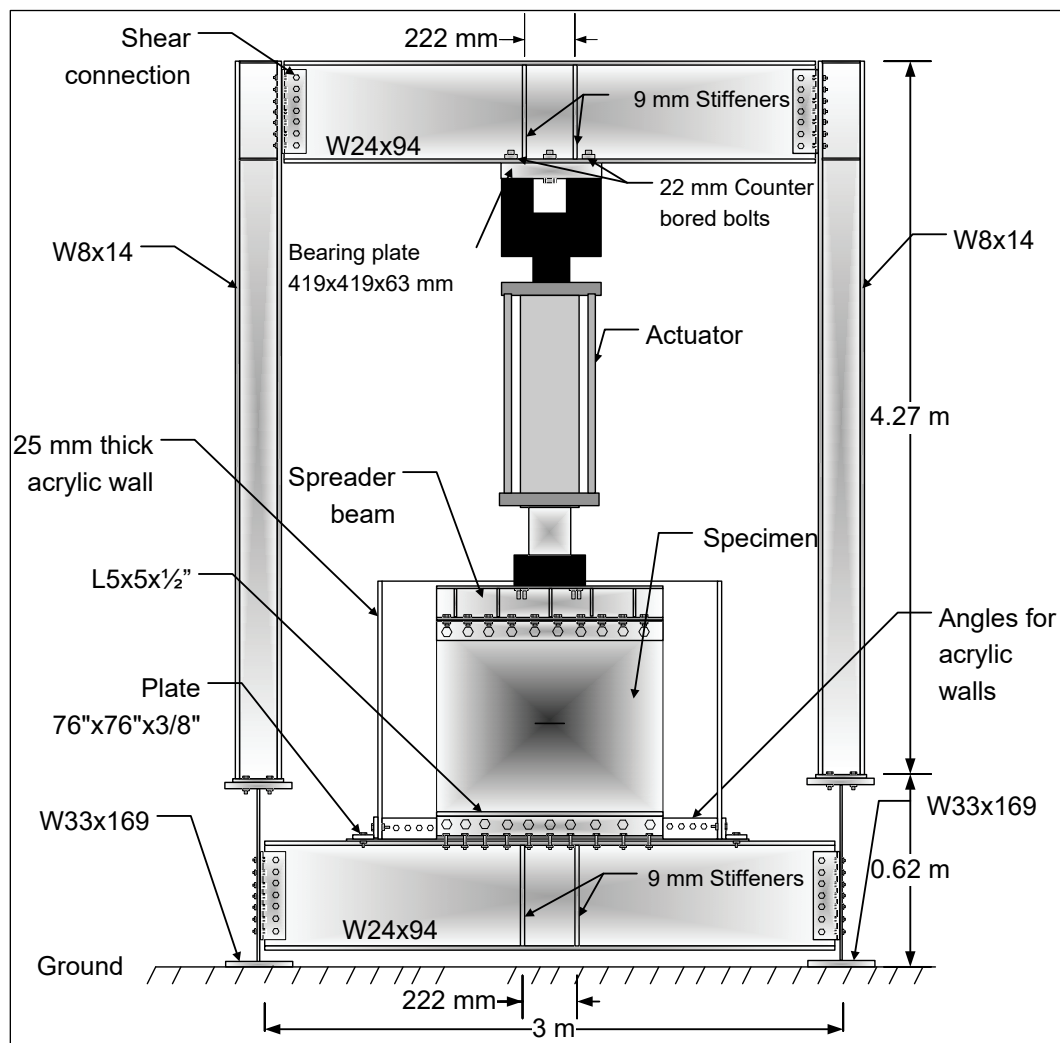
3.2 Geometric configuration of test setup

The thickness of the specimens was chosen to be 9.5 mm, corresponding to typical plate thicknesses in hydraulic steel structure applications. The width and length (1m x 1m) of the specimen was chosen to allow for the installation of large CFRP patches. A self-reacting frame was designed using the American Institute of Steel Construction Manual (AISC 2011) to provide the required strength. All forces applied to this frame were counter acting each other and only the dead load of the entire system was assumed to be transferred to the floor.

As seen in Figure 18, the self-reacting frame consists of a 2.83 m (10 ft) long W610 × 140 (W24 × 94) top beam connected to two, W200 × 59 (W8 × 40) columns by double angle shear connections. The angles used for the shear connections were L102 × 102 × 9.5 (L4 × 4 × 3/8) with seven 19 mm

($\frac{3}{4}$ in.) diameter bolts. The columns were resting on two W840 $\times$ 251 (W33 $\times$ 169) girders running parallel to each other with a center-to-center distance of 2.83 m (10 ft). Columns were connected to a base plate of thickness 51 mm (2 in.) and four 19 mm ($\frac{3}{4}$ in.) diameter bolts. The total length of each column was 4.27 m (14 ft). Another W610 $\times$ 140 (W24 $\times$ 94) beam was connected at the bottom to the W840 $\times$ 251 (W33 $\times$ 169) girders on both sides using double angle shear connections. The angles used for shear connections were L102 $\times$ 102 $\times$ 9.5 (L4 $\times$ 4 $\times$ $\frac{3}{8}$) with seven 19 mm ($\frac{3}{4}$ in.) diameter bolts.

Figure 18. A geometrical drawing showing a front view of the test setup including the actuator, self-reacting frame, the acrylic tank and the tested specimen.

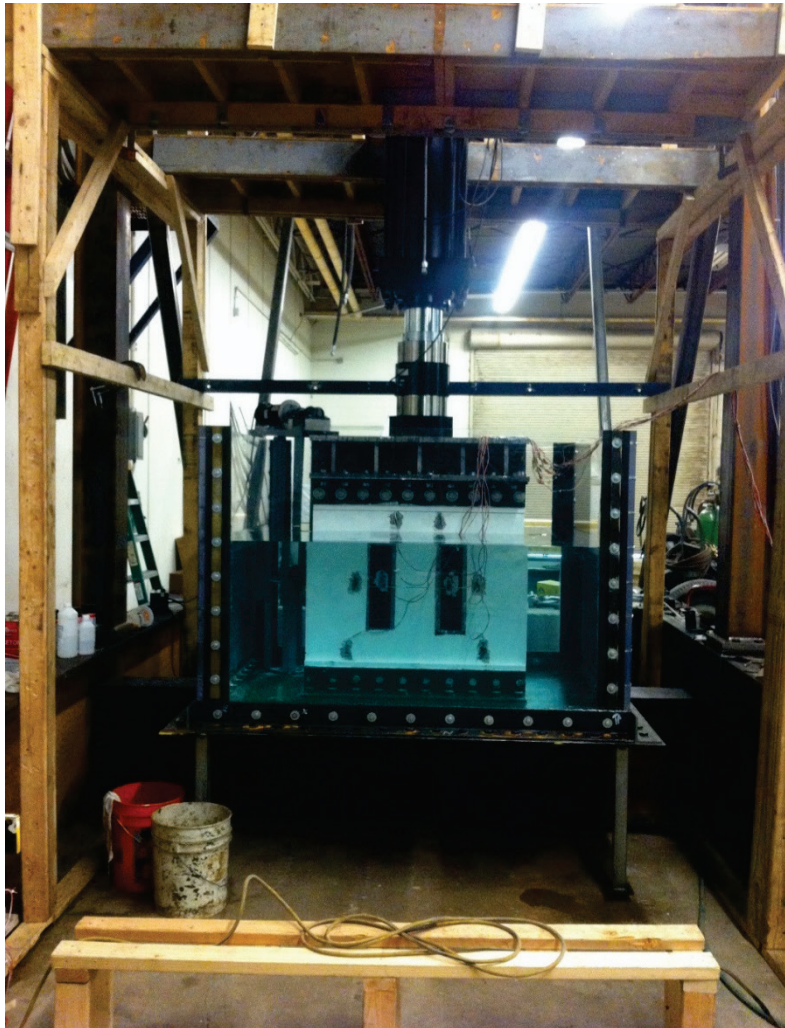


Miter gates operate in a wet environment; hence, it was important to test the specimens underwater. A tank made of acrylic walls, 25 mm (1 in.) in thickness with a steel base plate of 1.93 m $\times$ 1.93 m $\times$ 9.5 mm (76 in. $\times$ 76 in. $\times$ 3/8 in.) connected to the top flange of the bottom W610 $\times$ 140 (W24 $\times$ 94) girder with a specimen resting on the base plate, was built to test the specimens underwater. Back-to-back L133 $\times$ 133 $\times$ 13 (L5 $\times$ 5 $\times$ 1/2) angles were used to connect the whole assembly using 10 shear bolts measuring 22 mm (7/8 in.) in diameter and 20 tension bolts measuring 32 mm (1 1/4 in.) in diameter. The tensile stresses on the 32 mm (1 1/4 in.) bolts were 172 MPa (25 ksi), each. Filler plates, 25 mm (1 in.) thick, were provided on both sides of the specimen between the angles to reduce prying action assuming these plates to be underdeveloped. A transparent acrylic material was chosen to allow external monitoring of the specimens. The inside-to-inside dimensions of the tank were 1.75 m $\times$ 1.75 m $\times$ 1.22 m (68.75 in. $\times$ 68.75 in. $\times$ 48 in.). The acrylic sheets were connected to the base plate with four L102 $\times$ 102 $\times$ 9.5 (L4 $\times$ 4 $\times$ 3/8) angles all around the tank. The bolts going through acrylic sheets and the angles were of 13 mm (1/2 in.) in diameter and the bolts going through the angles and base plate were 19 mm (3/4 in.) in diameter. The sizes of these bolts were chosen, such that the bolts can resist the shear force acting on the acrylic walls and the tension force acting on the base plate. To make the connections of the acrylic sheets watertight, they were covered by silicone. A hole was made in the steel base plate of the tank to empty the tank through a hose using a knob, effectively, when needed. Figure 19 shows the physical front view of the test setup including the actuator, self-reacting frame, the base plate of the acrylic tank, and the tested specimen. Figure 20 shows the physical front view of the test setup including the actuator, self-reacting frame, acrylic tank with water, and tested specimen.

Figure 19. A geometrical drawing showing a front view of the test setup including the actuator, self-reacting frame, acrylic tank, and tested specimen.



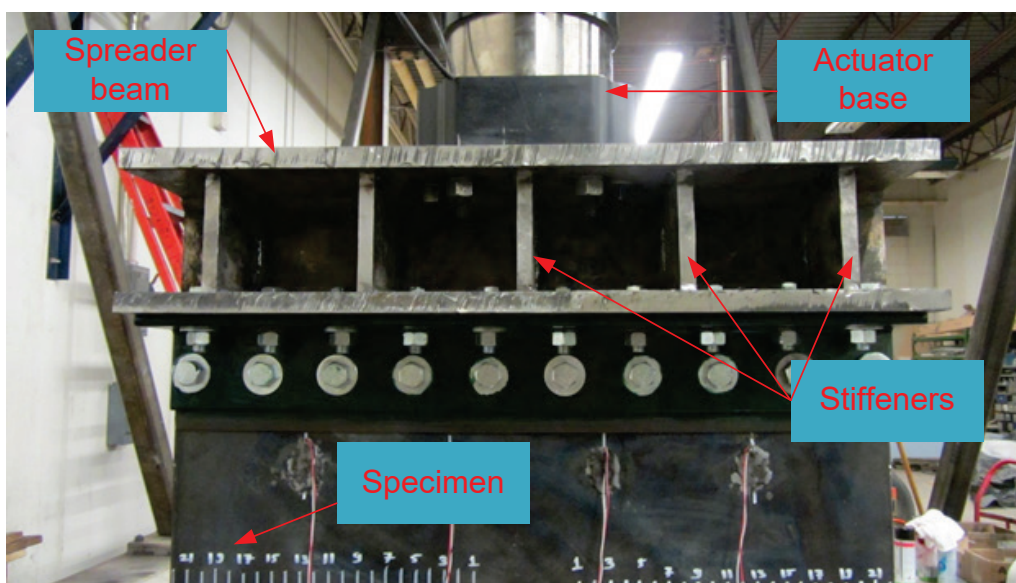
Figure 20. A physical front view of the test setup including the actuator, self-reacting frame, the base plate of the acrylic tank and the tested specimen.



Specimens were loaded using a 979 kN (220 kip) hydraulic actuator manufactured by MTS Systems Corporation. A built-up spreader beam with five stiffeners on each side of the web applied an even distribution of the load induced by the actuator (See Figure 21). It was assumed that each stiffener would carry and distribute the load equally throughout the specimen. All the welds were smooth (without having any flaw) to eliminate fatigue problems arising due to a bad weld quality. The actuator was connected to the top beam by a bearing plate that was bolted to the flange of the beam. Six bolts with diameter of 22 mm (7/8 in.) were used in this connection. The swivel of the actuator was connected to the bearing plate with four bolts that were 38 mm (1 1/2 in.) in diameter with a length of 46 cm (18 in.). Eight cap screw bolts measuring 22 mm (7/8 in) were used for the connection between actuator and spreader beam. The spreader beam

was connected to the specimen using two back-to-back $L5 \times 5 \times 1/2$ angles along the length of the specimen (Figure 21). Filler plates were 13 mm (1/2 in.) thick and used between the angles and the specimens to reduce prying action by controlling the deformation in the angles. All bolts were pre-tensioned using the turn-of-nut method per the Research Council on Structural Connections (RCSC 2014). As per AISC, this method provides a clamping force of 70-85% of the yield stress in the bolts. Detailed drawings of the test setup and connections can be found in Appendix B.

Figure 21. A physical front view of the spreader beam including the specimen, the angle connecting the specimen and actuator.



To investigate the worst possible scenarios underwater testing with NaCl salt and sand was conducted for Specimens 4 and 5. Miter gates are built in rivers where fluvial sediment and salt flow originating from erosion further upstream are deposited into the catchment area. Concentrations of NaCl salt in river water is less as compared to that of seawater. Seawater contains NaCl salt concentration of 35 g/l. This concentration of seawater was used in this study to investigate the worst possible scenarios. The test water was a mix of 90 kg (200 lb) of NaCl salt and similar amounts of sand (particle size of 0.45-0.55 mm). The sand and salt used in this study can be seen in Figure 22 (a) and (b), respectively. The size of the sand particles represents the fluvial sediments typically suspended in river water. The total volume of water was 2306 liters (the height of water inside the tank was 76 cm (30 in.)). To circulate the water and keep sand particles suspended, a propeller of 30 cm (12 in.) in diameter was built on a frame inside the tank as shown in Figure 23.

Figure 22. (a) 0.45-0.55 mm sand used (b) 23 kg (50 lb) NaCl salt blocks.

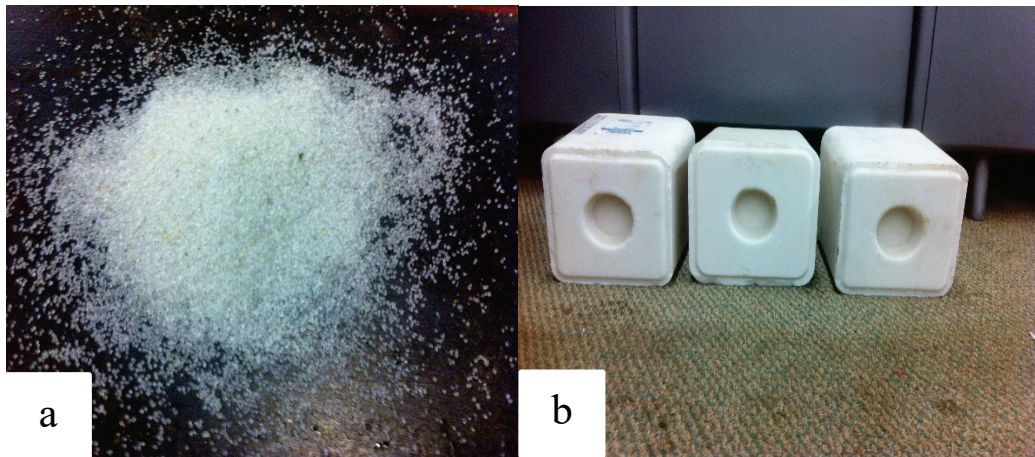
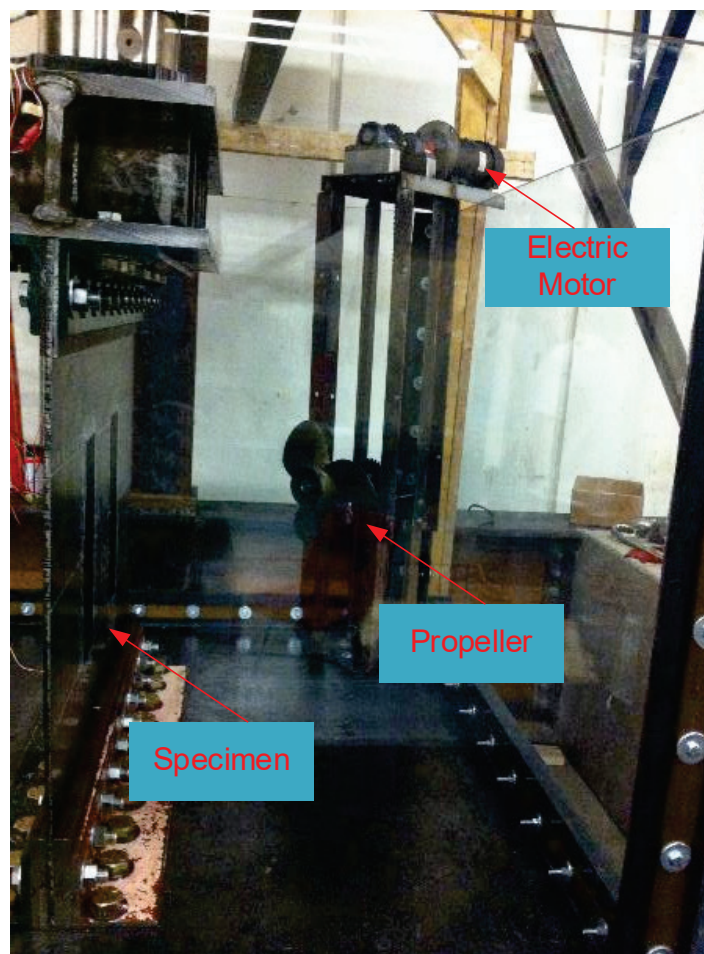


Figure 23. Propeller with electric motor in the tank facing back face of the specimens 4 and 5 at 45°.



The propeller was placed in one corner of the tank facing the back face of Specimens 4 and 5 at a 45 degree angle. The distance of the propeller from the base plate was adjusted, such that its center was at the same height (50

Instrumentation plan and crack measurements

Bondable, 3-wired, linear strain gauges, designated as WK-06-125BT-350/W with 350 Ω , manufactured by Micro Measurements were installed at various locations on the specimens as shown in Figure 24 through Figure 27 (Specimens 1, 2, 3, 4, and 5, respectively). The locations of strain gauges were selected to evaluate the stress distribution and shear lag. Strain gauges were also installed along the crack plane to allow for the assessment of the increase of stresses as the crack approaches the gauges. Prior to installation, residues on the specimen surface were removed using CSM-2 degreaser, MCA-2 conditioner A, and M-PREP neutralizer 5A. The gauges were bonded to the specimen using a GAK-2-AE-10 kit (provided by Micro Measurements). To protect the strain gauges from the water in the tank, gauges were covered with a M-COAT J-3 polysulfide kit and then covered with M-COAT W-1 wax, also provided by Micro Measurements (Figure 28).

3.3 Instrumentation plan and crack measurements

Bondable, 3-wired, linear strain gauges, designated as WK-06-125BT-350/W with 350 Ω , manufactured by Micro Measurements were installed at various locations on the specimens as shown in Figure 24 through Figure 27 (Specimens 1, 2, 3, 4, and 5, respectively). The locations of strain gauges were selected to evaluate the stress distribution and shear lag. Strain gauges were also installed along the crack plane to allow for the assessment of the increase of stresses as the crack approaches the gauges. Prior to installation, residues on the specimen surface were removed using CSM-2 degreaser, MCA-2 conditioner A, and M-PREP neutralizer 5A. The gauges were bonded to the specimen using a GAK-2-AE-10 kit (provided by Micro Measurements). To protect the strain gauges from the water in the tank, gauges were covered with a M-COAT J-3 polysulfide kit and then covered with M-COAT W-1 wax, also provided by Micro Measurements (Figure 28).

Figure 24. Locations of strain gauges (SG) on Specimen 1.

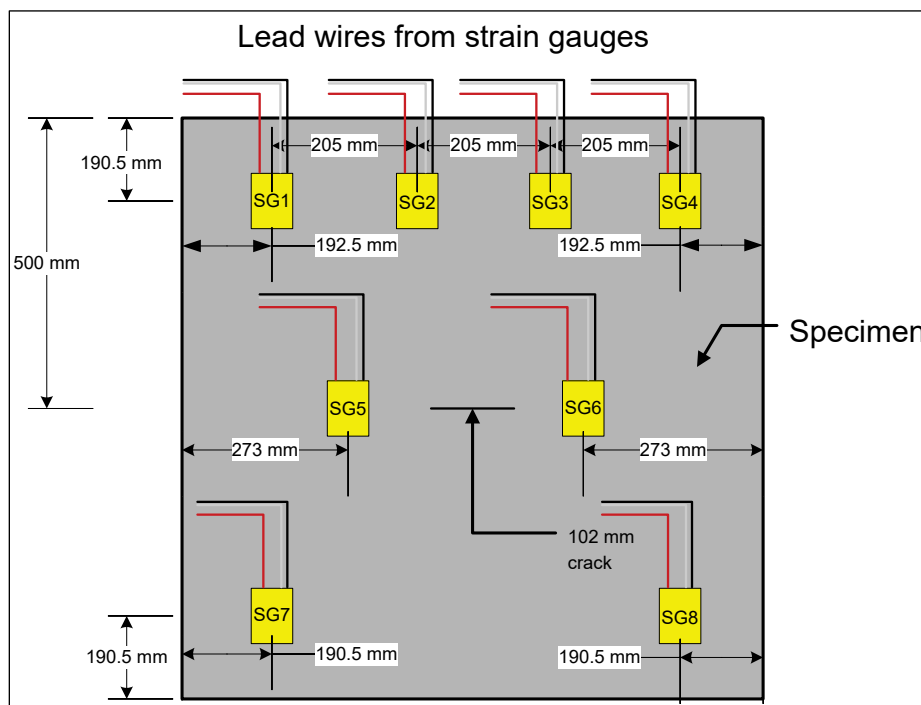


Figure 27. Strain gauge locations on Specimen 5.

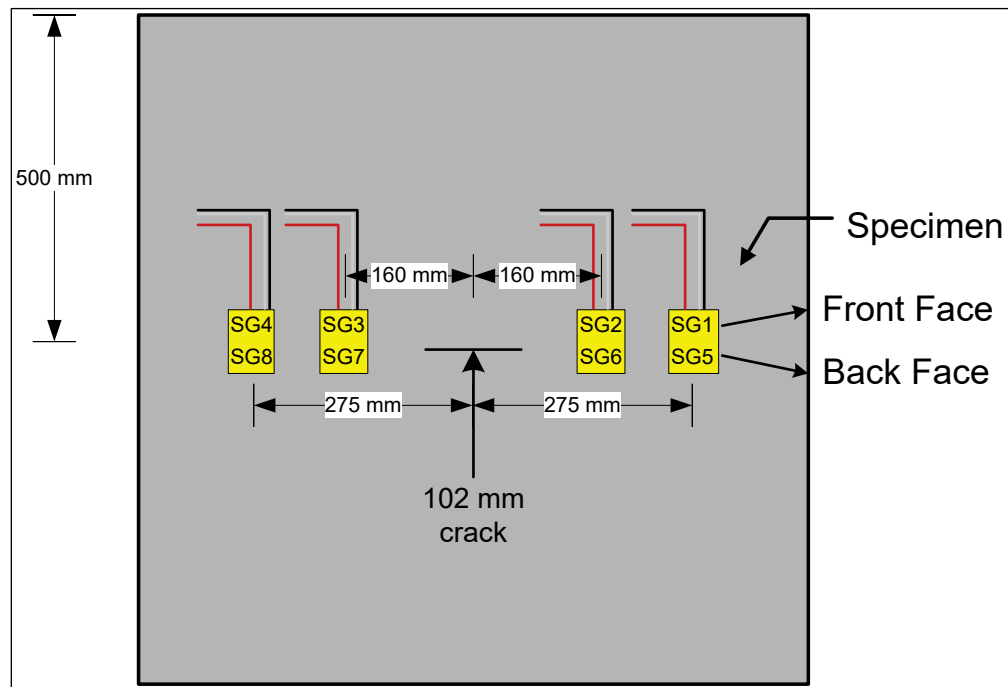
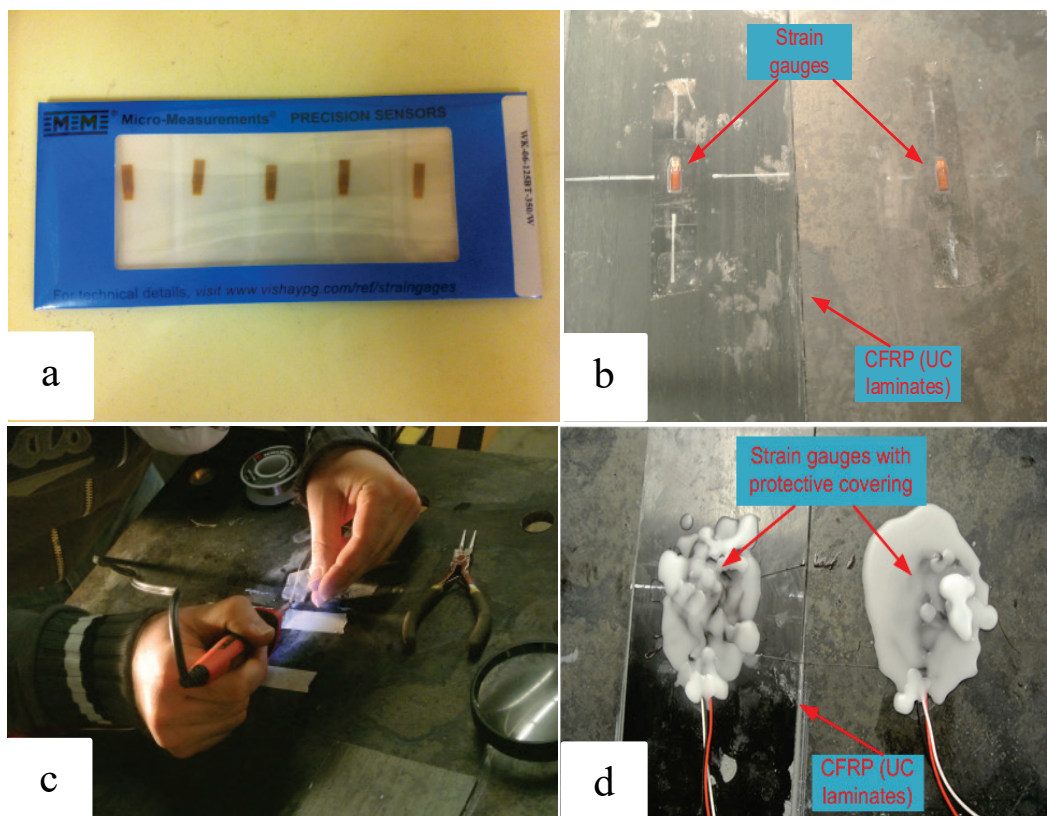


Figure 28. Strain gauge installation (a) Strain gauges from Micro Measurements (b) Strain gauge on the specimen and CFRP after installation (c) Soldering lead wires for strain gauges (d) Protective covering for strain gauges.



The installed gauge on the specimen included a protective covering to prevent water seepage into the gauge as shown in Figure 29 (b). Soldered lead wires from the strain gauges were connected to a Campbell Scientific CR1000 data acquisition system to obtain the axial strains in the specimens from each gauge at different locations. Another CR1000 was used for collecting the displacement and force feedback from the MTS actuator through the MTS 407 controller. Figure 30 shows a schematic of the data flow and the data acquisition system (DAQ). An actual photo of the data collection set up is shown in Figure 31.

Vertically marked grid lines on the specimen measured crack length. To mark these lines, a permanent oil paint marker was used. Every line was spaced with a distance of 2 cm (.78 in.), each on both sides of the crack so the length of the propagating crack could be measured effectively. A regular ruler was used to measure the distances between these lines. These grid lines can be seen in Figure 32.

Figure 29. (a) Typical linear strain gauge used. (b) Protective covering for strain gauges after installation on the specimen.

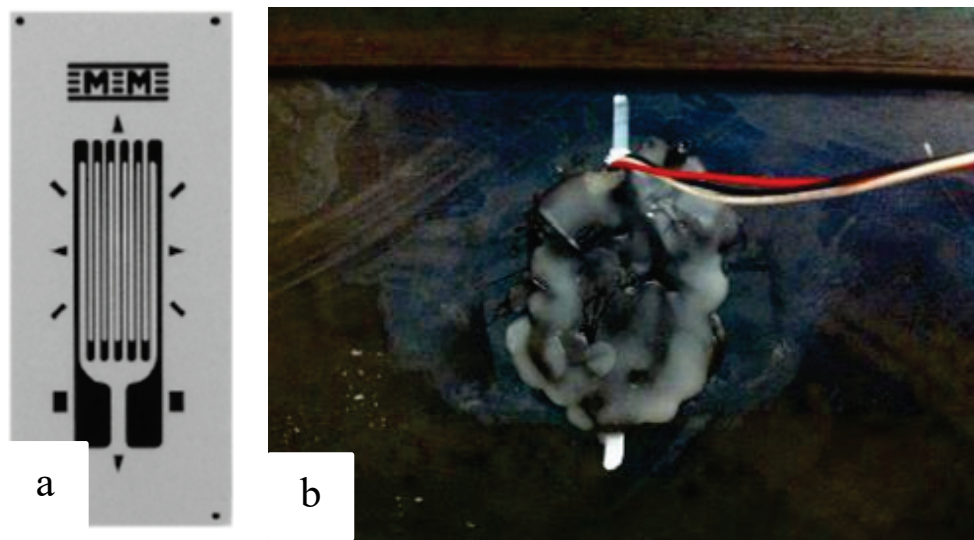


Figure 30. Schematics of data flow and the DAQ system.

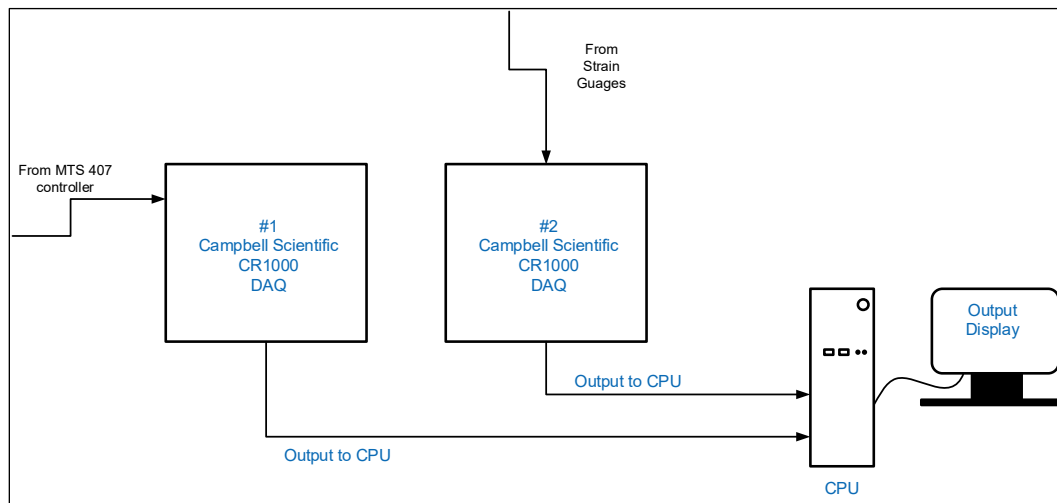


Figure 31. Setup comprising of MTS 407 controller, two DAQ systems and a computer for data collection.

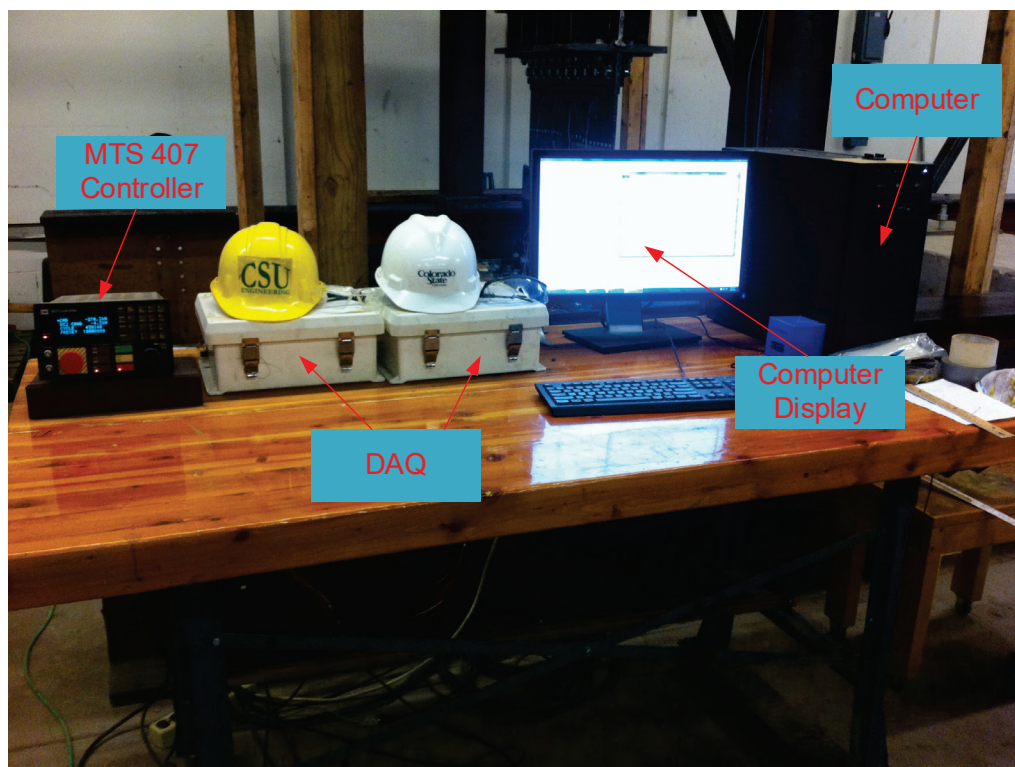
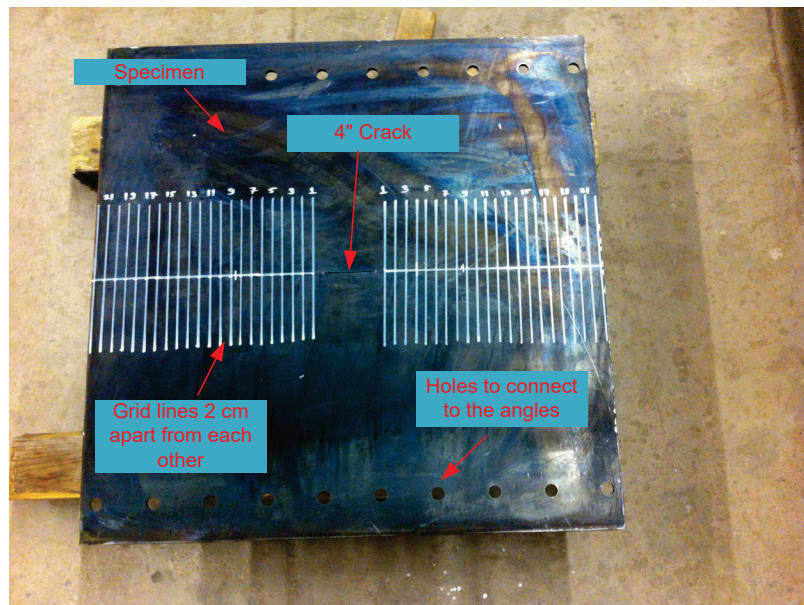
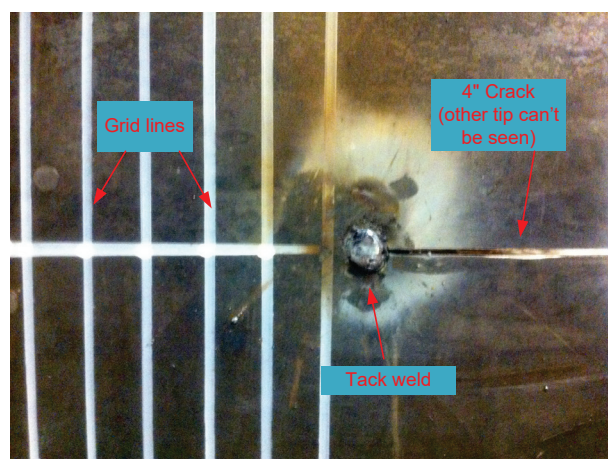


Figure 32. Grid lines marked 2 cm (.78 in.) apart on the specimen to measure the half-crack length on either side of the crack.



To facilitate faster initiation of the crack growth, tack welds were introduced at the crack tips. Tack welds represent the worst fatigue category (category E) with the constant amplitude fatigue limit of 18 MPa (2.6 ksi). A typical tack weld at the crack tip is shown in Figure 33.

Figure 33. Tack weld introduced at crack tip to facilitate faster crack growth.



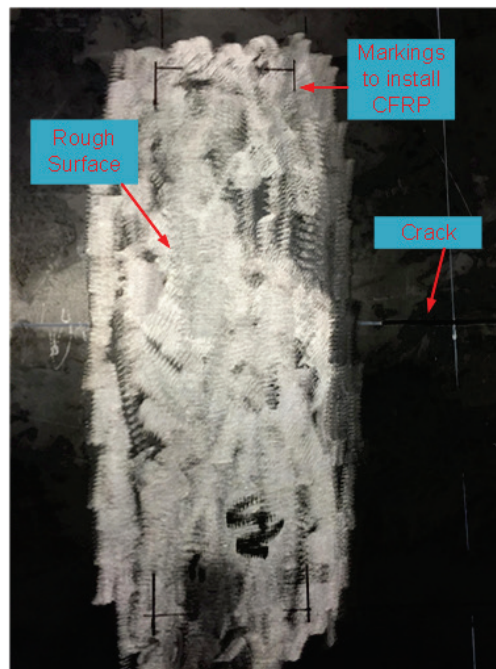
3.3.1 CFRP installation and surface preparation

Improper installation of CFRP can result in de-bonding of the CFRP. The application procedure used to install the CFRP is explained in the following section.

3.3.1.1 CFRP installation

The steel's surface was prepared by grinding the surface (Figure 34) and, cleaning the grounded surface with acetone. The possibility of debonding was reduced by grinding the steel's surface to remove the oxide coating and creating a rough surface.

Figure 34. Prepared surface before installation of CFRP.

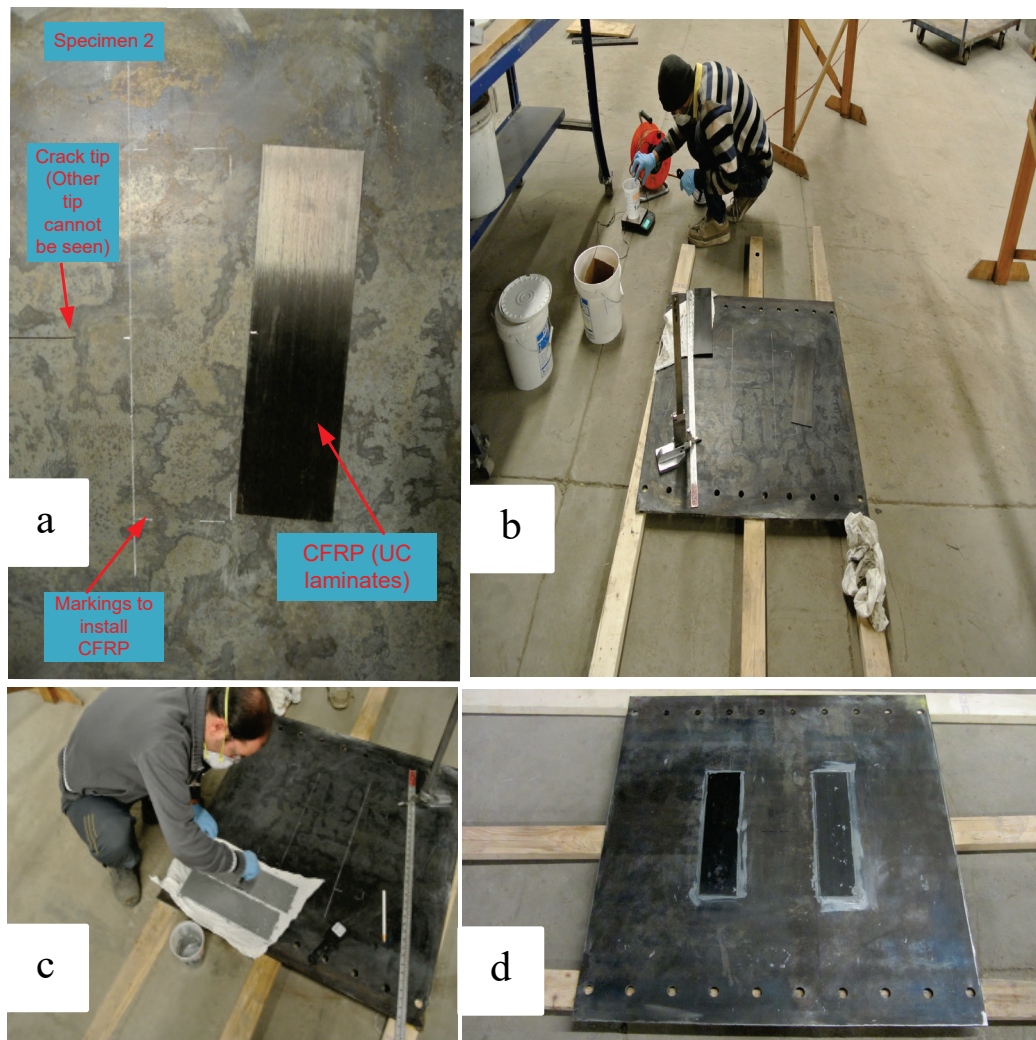


An adhesive resin was mixed to bond the CFRP to the steel. The adhesive resin and hardener were mixed in equal proportions of weight using a mixer and then applied on the appropriate surface using a spatula. The CFRP was placed on top of the adhesive and then a roller was used to apply resin that is more adhesive over the CFRP until the required adhesive thickness was achieved. The installation process of the CFRP is shown in Figure 35.

Specimen 2 was not ground to investigate the effect of bonding of adhesive on the oxide coating, while specimens 3–5 were ground before starting the tests. The specimens were cleaned with acetone to remove all the minute

dust particles and achieve the ideal bonding between the adhesive and steel surface. Two different installation methodologies were investigated on either face of the specimen to investigate the installation method. On one face, the adhesive was applied on the steel and then CFRP was placed on top of the adhesive layer, while on the other face, the adhesive was applied to the CFRP and then the CFRP was placed on the steel surface. After installation of the CFRP, the adhesive was compressed before it hardened. The thickness of the adhesive was measured using a height gauge. Concrete blocks were placed on the CFRP to avoid any expansion of the adhesive. Figure 35 shows the CFRP installation process through a series of photos. CFRP is a highly orthotropic material, having the highest strength in the direction of fibers. To maximize the CFRP's strength and stiffness, it was important to orient the CFRP, such that the carbon fibers were perpendicular to the crack growth. A detailed drawing of the location of the CFRP attached to the specimen is shown in Figure 36.

Figure 35. CFRP installation on Specimen 2 (a) Markings on the specimen to install CFRP (b) preparation of adhesive (c) applying adhesive on the CFRP (d) CFRP on specimen after installation.

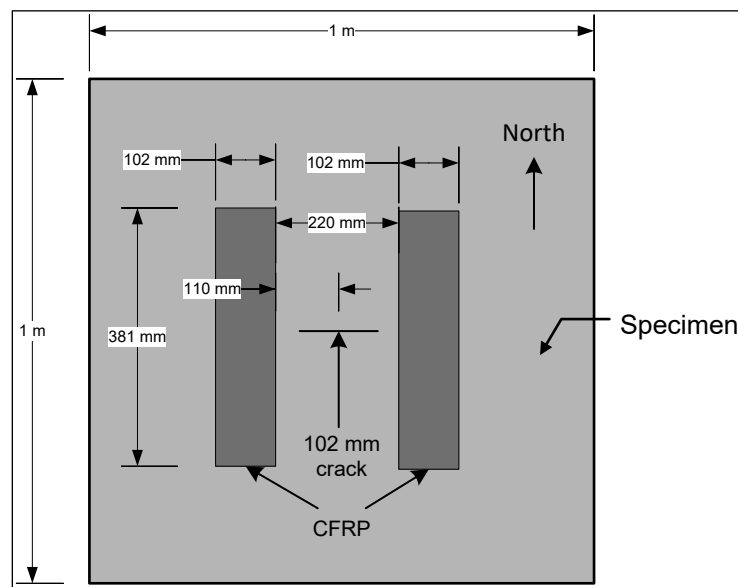


3.4 Mechanical properties for CFRP and adhesive

During testing two types of CFRP and adhesive were used. Table 3 gives the mechanical properties for CFRP and adhesive. The two types of CFRPs used were Tyfo UC laminates and Tyfo SCH-41 sheets, manufactured by Fyfe Co., LLC. Due to the submerged environment of lock gates, the adhesive needed to be able to cure underwater; two adhesives used were Hudco 3200 and Tyfo S.

The two CFRPs differed in physical and mechanical properties. The Tyfo UC was in a smooth-laminate plate form with a thickness of 1.4 mm (.05 in.) and the Tyfo SCH-41 was a fibrous form with a thickness of 1mm (.03 in.). The Tyfo UC has a higher elastic modulus than Tyfo SCH-41.

Figure 36. CFRP bonded to specimen 110 mm (4.3 in.) from the center of the crack.



The adhesives were chosen for their strength and ability to withstand a watery environment. The Hudco Formula 3200 is a 100% solid, two-component system, which when mixed in the ratio of 1 part resin to 1 part curing agent (hardener), by weight or by volume, yields a smooth non-sagging paste. The elastic modulus and yield strength of the two adhesives differed greatly as seen in Table 3. Though Hudco Formula 3200 has a lower capacity than Tyfo S, it has better performance underwater and was therefore investigated as a possible underwater adhesive. Due to the lower tensile capacity of the adhesives, it was not possible to engage fully the strength of the CFRP.

Table 3. Mechanical properties of CFRP and adhesive provided by manufacturer.

Material	Density, g/cm ³ (lb/in. ³)	Young's Modulus, GPa (ksi)	Poisson's Ratio
Steel	7.75 (0.28)	200 (29,008)	0.3
Tyfo UC Laminates (CFRP)	1.8 (0.065)	139.6 (20,247)	0.4
Tyfo SCH-41 (CFRP)	1.74 (0.063)	82 (11,893)	0.4
Hudco Formula 3200 (Adhesive)	1.35 (0.049)	0.14 (20.31)	0.4
Tyfo S (Adhesive)	1.11 (0.040)	3.18 (461.22)	0.4

3.5 Test matrix

Four, 1 m × 1 m × 9.5 mm, specimens were tested under cyclic fatigue loading. Specimen nomenclature is used throughout the report (Figure 37).

The nomenclature was based on the specific CFRP type used, type of adhesive, and bond length. Table 4 gives the test matrix that was followed and the section below describes the specimen's tested.

Figure 37. Specimen nomenclature.

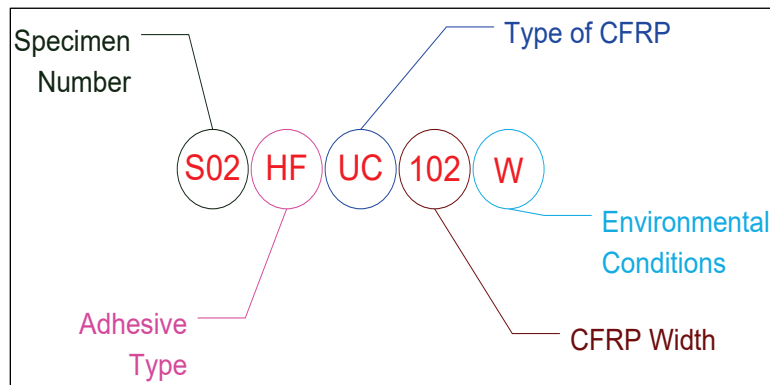


Table 4. Test matrix.

Specimen	Nomenclature	CFRP Width, mm (in.)	Type of CFRP	Bond Length, mm (in.)	Environmental Condition
Specimen 1	S01-NA-NA-ONW	NA	NA	NA	No water
Specimen 2	S02-HF-UC-102NW	102 (4)	Tyfo UC laminates	381 (15)	No water
Specimen 3	S03-S-SCH-102NW	102 (4)	Tyfo SCH-41 sheets	381 (15)	No Water
Specimen 4	S04-S-SCH-102W	102 (4)	Tyfo SCH-41 sheets	381 (15)	Underwater
Specimen 5	S05-NA-NA-OW	NA	NA	NA	Underwater

S01-NA-NA-ONW – Control specimen, no CFRP, not underwater.

S02-HF-UC-102NW - Tyfo UC laminates, 102 mm (4 in.) CFRP width, 381 mm (15 in.) bond length, not underwater.

S03-S-SCH-102NW - Tyfo SCH-41 sheets, 102 mm (4 in.) CFRP width, 0.5 mm (0.02 in.) of adhesive thickness and 381 mm (15 in.) bond length, not underwater.

S04-S-SCH-102W - Tyfo SCH-41, 102 mm (4 in.) CFRP width, 381 mm (15 in.) bond length, underwater.

S05-NA-NA-OW – No CFRP, underwater

3.6 Testing plan and loading protocol

Testing of all specimens started with three shakedown tests. The first two shakedown tests were conducted using static tension loading with the load increasing from 30 kN (7 kip) to 510 kN (115 kip). Following the static shakedown, a cyclic shakedown test was conducted in with the specimens subjected to a few cycles with the load ranging from 30 kN (7 kip) to 510 kN (115 kip) in tension. The intention of the initial static and cyclic shakedown tests were to allow for all frame components to come to full contact with each other and evaluate the load path in the system. After the first shakedown test, all bolted connections were fully pre-tensioned to eliminate the potential of fatigue failure of bolts. The shakedown tests were conducted under force control, with the specified forces incrementally increased for each test.

After the three shakedown tests, the cyclic tests were conducted under force control, such that the stress range in each specimen was set at 55 MPa (8 ksi). The stress range achieved was a maximum applied load of 55 MPa (8 ksi) stress and the minimum applied load resulted in a zero stress (i.e., the stress ratio, $R = \sigma_{\min} / \sigma_{\max}$ was 0). Under displacement control, the nominal stress range would decrease as the crack propagates; therefore, force control was used during testing to ensure a constant nominal stress range on the specimen as the crack propagates. The cyclic fatigue loading was applied using a servo valve and a 979 kN (220 kip) hydraulic actuator with a frequency of 0.5 Hz. A MTS 407 controller was used to send the command signal to the 979 kN (220 kip) actuator. The displacement and force feedback of the actuator were received back by the controller and sent to the Campbell Scientific CR1000 data acquisition system, which was connected to a computer that recorded the data.

4 Experimental Results and Observations

4.1 Introduction

As mentioned in Chapter 3, five specimens were tested with different types of CFRP and varying adhesives in different environmental conditions. Dimensions of each specimen were 1 m × 1 m × 9.5 mm (39.4 in. × 39.4 in. × 0.37 in.).

The data for half crack length (a) versus the number of cycles (N) was recorded for all the specimens. The half crack length vs cycles plots are intended to show the effects of CFRP on the propagation rate of the crack with a reduced propagation rate of the specimens with CFRP when compared to Specimen 1 (control specimen without CFRP). As discussed in Chapter 2, there is scatter in fatigue data; therefore, for the center crack tension (CCT) panel of Specimen 1, a log-log plot of crack propagation rate (da/dN) versus change in stress intensity factor (ΔK) was generated to obtain the C and m constants of the Paris' law. A numerical analysis to determine an effective ΔK , due to the CFRP's influence on the crack, is required to generate the crack propagation rate vs intensity factor plot for the specimens with CFRP.

The strain values as the crack interacted with the CFRP were recorded in order to determine how the CFRP influenced the strain. Data for half crack length versus strain in the corresponding CFRP was collected for specimens with CFRP. This plot was selected to investigate the maximum strain attained by the CFRP as the crack interacted with CFRP.

4.2 Test results for individual specimen

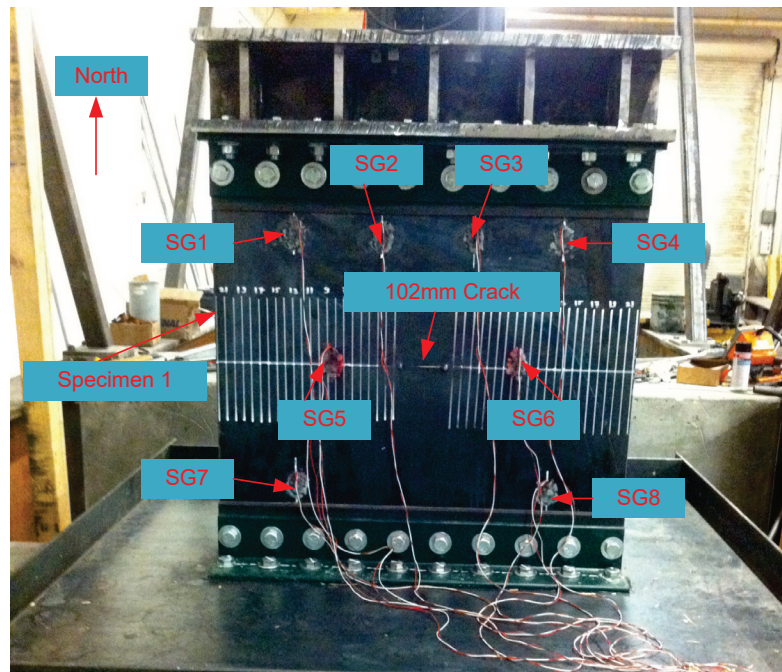
The following sections discuss the results for individual specimens. Note that while shakedown tests were conducted for all of the specimens, only one shakedown test for specimen 1 is documented herein. Shakedown tests for Specimen 2 through 4 are similar to Specimen 1 and therefore, are not presented.

4.2.1 Test results and observations for Specimen 1

It was necessary to check the reliability and performance of the self-reacting frame and its various components such as the strength of the components and the bolted connections and the response of the actuator

under applied load. As indicated in section 3.5, three shakedown tests were conducted before commencement of the actual cyclic fatigue test. Strain gauge data was collected during these tests to check the load path in the specimen. Figure 38 shows the locations of the strain gauges on Specimen 1.

Figure 38. Strain gauge locations on Specimen 1.

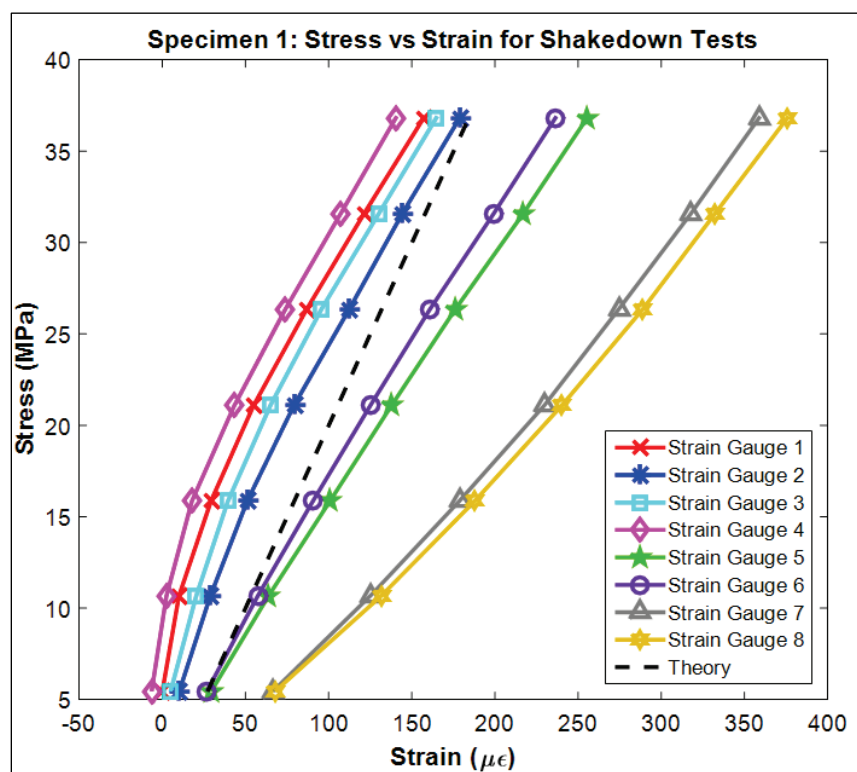


4.2.1.1 Strain gauge results for the shakedown tests

As mentioned in section 3.5, the shakedown test was conducted in order for the frame to readjust itself so that all the components were in contact with each other. The linear stress-strain relationships for the shakedown tests were obtained by recording the strain gauge data. As can be seen from Figure 38, eight strain gauges were bonded to the specimen at different locations; local coordinates were assumed on the specimen with north pointing upward. The readjustment of the frame is clearly seen in Figure 39 through the bilinear stress-strain relationship captured by the gauges. The initial portion of the response is a result of the adjustment of the frame (i.e., slip is occurring between components and elements, etc.) and the second portion is due to full transfer of load in the specimen. The initial strain offsets were not removed since the slope of the plotted curves is the relevant parameter for comparison.

It was predicted that all of the strain gauges would show similar strain values, except for Strain Gauges 5 and 6. The reason they did not show similar strain values can be attributed to the fact that Strain Gauges 1 through 4 were very close to the spreader beam having a very large bending stiffness as compared to Strain Gauges 7 and 8, which were very close to the W24 $\times$ 94 beam at the bottom having comparatively less bending stiffness. The strain data measured by Strain Gauges 1 through 4 were similar to each other and those measured by Strain Gauges 7 and 8 were also similar to each other. Strain Gauges 5 and 6 show different strain data than the others due to the presence of the crack at the center of the specimen, which introduces high stress concentration at the crack tips; hence, influencing the strain values in the strain gauges at the same horizontal plan. As can be seen in Figure 39, the curves for Strain Gauge 5 and 6 indicated very similar slopes as compared to a theoretically calculated slope, (i.e., approximately 20–30%). Strain Gauges 5 and 6 were selected as the main strain gauges, because of their position in alignment with the crack and away from any support that might introduce higher strains than the nominal. The stress range of 55 MPa (8 ksi) was confirmed by the recorded strains of Gauges 5 and 6 of 275 $\mu\epsilon$.

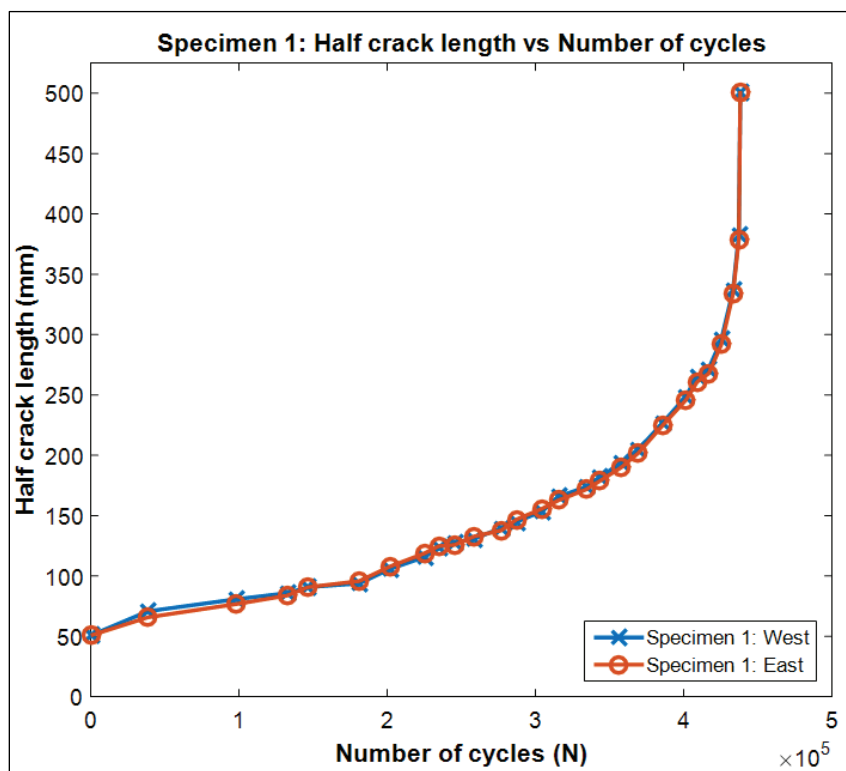
Figure 39. Stress vs. Strain data from strain gauges installed at various locations on Specimen 1.



4.2.1.2 Crack length versus number of cycles for Specimen 1

Crack length was measured as the crack propagated along the specimen width and the corresponding number of cycles, was recorded from the MTS 407 controller display. Initially, the crack propagation was faster due to the presence of the tack welds at the crack tip. As the crack grew away from the tensile residual stress field introduced by the tack weld, it showed a stable/slower propagation. The fatigue life of the specimen was dominated by the stable crack growth. Near the end of fatigue life, unstable growth was noted as the crack reached its critical length. Both, east and west cracks, showed similar behavior for half crack length versus number of cycles, emphasizing the even stress distribution imposed on the specimens. Figure 40 shows half crack length vs number of cycles on west and east sides of the specimen. As seen in Figure 40, the plots are exponential curves with a crack growing in an unstable manner after reaching a critical length of around 300 mm (≈ 12 in.). The total number of cycles required for the half crack to reach full width of the specimen was 439,140.

Figure 40. Half crack length vs. number of cycles for Specimen 1.



The crack surfaces were studied after the specimen fractured. The crack surface was flat and smooth for 152 mm (≈ 6 in.) corresponding with stable crack growth and following the laws of LEFM. The flat and smooth

chevron marks can be attributed to brittle crack extension. As the crack continued to grow from 152 mm (≈ 6 in.) to 300 mm (≈ 12 in.) the surface showed a slanted face as well as chevron marks, indicating combined brittle-ductile (i.e., transition) crack growth. After 300 mm (≈ 12 in.), the crack surface showed shear lips as well as necking, indicating pure ductile failure. Figures 41 through 43 show the west half-crack surfaces after the specimen was fully fractured.

Figure 41. Crack surfaces for west half crack after fracturing the Specimen 1: (a) Flat crack surface up to 150 mm (5.9 in.) from the center showing brittle fracture (b) Slightly slanted crack surface from 150 mm - 300 mm (5.9 – 11.8 in.) indicating ductile-brittle crack extension.

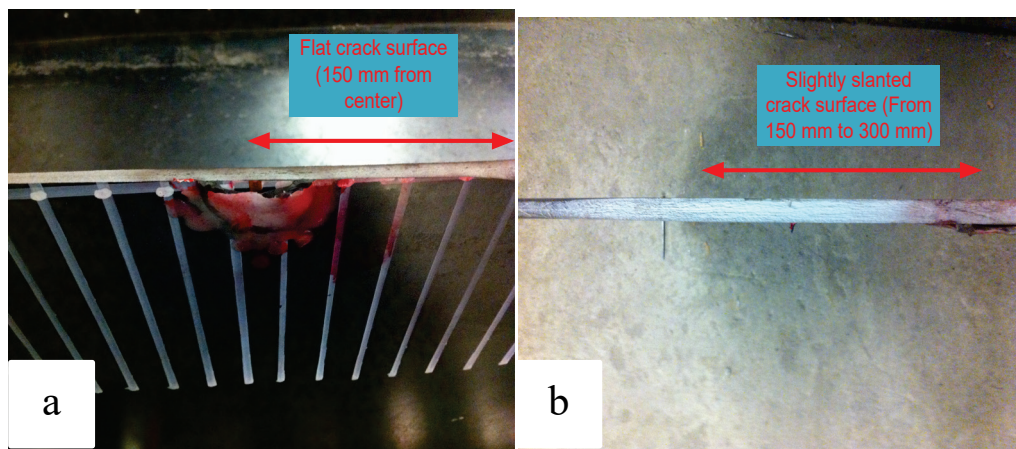


Figure 42. Crack surfaces for west half crack after fracturing the Specimen 1: (a) Shear lips form 300 mm to 500 mm (11.8 – 19.7 in.) indicating pure ductile fracture (b) Necking of the specimen indicating ductile crack extension.

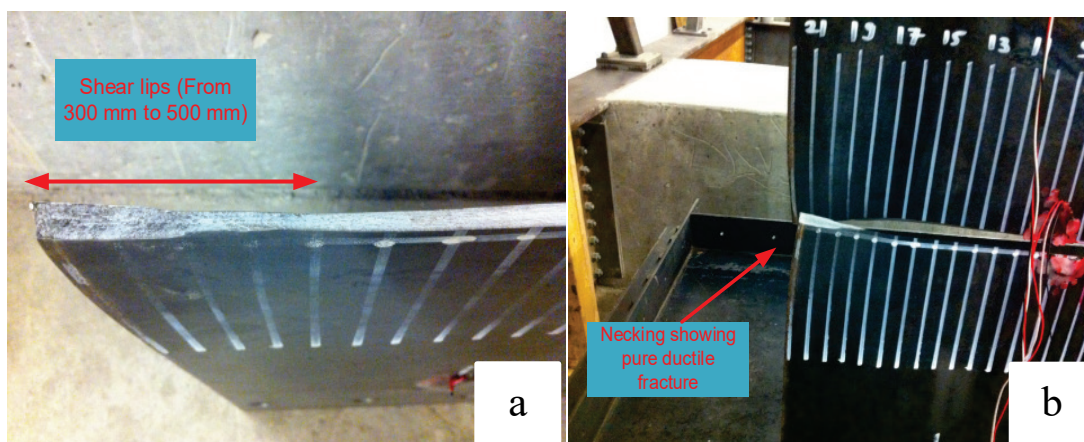
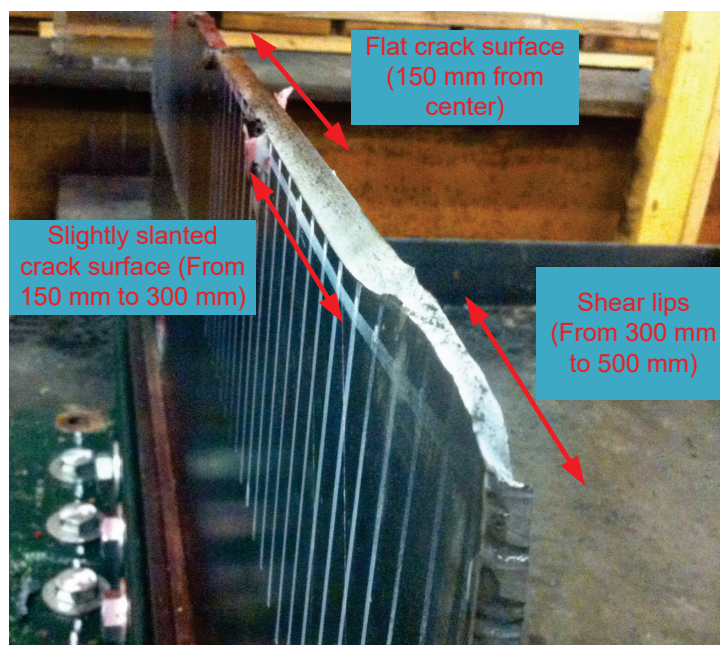


Figure 43. Crack surfaces for west half crack showing all the different fractures along the length of the crack after fracturing the specimen.

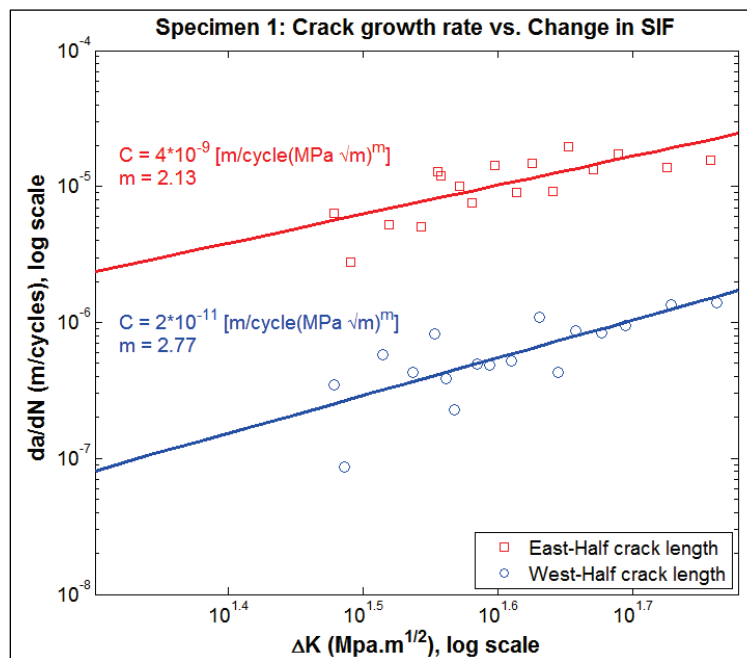


4.2.1.3 Crack growth rate vs. change in stress intensity factor

A log-log plot (Figure 44) was developed for crack growth rate (da/dN) versus ΔK to obtain the values of the Paris' law constants C and m from a straight trend line generated (C being the y -intercept and m being the slope of the line). As mentioned in Chapter 2, there is a scatter in fatigue data and getting a single value for these constants is not possible. The change in crack length is da with dN as the change in the number of cycles for the corresponding change in crack length. ΔK is $K_{max} - K_{min}$ with K_{max} obtained from the maximum stress applied and K_{min} from minimum stress applied to the specimen.

The values for Paris' law constants C and m , were found to be 2×10^{-09} m/cycles (MPa $m^{1/2}$) [8.65×10^{-8} in./cycles (ksi in. $^{1/2}$)] and 2.13, respectively, for half crack length on the east side of the specimen. The values for the west side crack were found to be 2×10^{-11} m/cycles (MPa $m^{1/2}$) [8.65×10^{-10} in./cycles (ksi in. $^{1/2}$)] and 2.77, respectively.

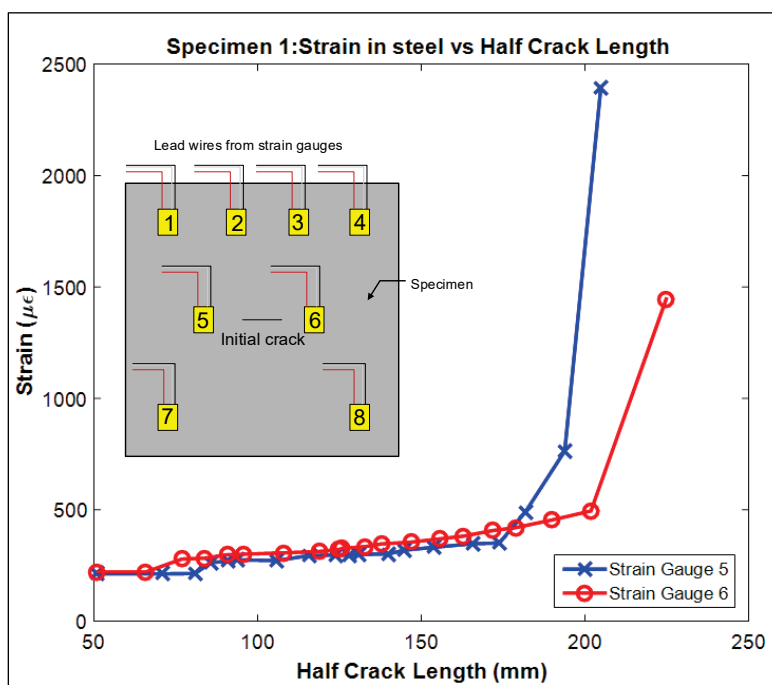
Figure 44. A log-log plot of crack growth rate (da/dN) vs. change in stress intensity factor (ΔK) for half crack lengths on the east and west side of Specimen 1.



4.2.1.4 Change in strain with half crack length

A plot was generated for strain in steel versus the half crack as shown in Figure 45 and the strain in the steel increases gradually and tends to infinity as the crack approaches the strain gauges. In addition, the strain values recorded by Strain Gauge 5 were less than that of strain gauge 6. As the respective half cracks approached the strain gauges, the measured strain in Gauge 5 approached infinity (20 mm [0.79 in.]–30 mm [1.18 in.] earlier) before Strain Gauge 6.

Figure 45. Strain in steel vs. half crack length for Specimen 1 with respective strain gauge locations.



4.2.2 Test results and observations for Specimen 2

Specimen 2, retrofitted with CFRP, was tested under dry conditions with center crack of length 101.6 mm and Tyfo-UC laminates CFRP attached at 110 mm (4.3 in.) from the center of the crack using Hudco Formula 3200 as explained in Chapter 3. It is important to note that the Hudco Formula 3200 adhesive has very low modulus and is not intended to use with CFRP. The reason for investigating its use is due to its ability to cure underwater, which could provide an opportunity of easy repair. Tack welds were introduced at the crack tips similar to Specimen 1 to facilitate faster initial crack growth. The CFRPs were installed without any surface preparation. The motive behind this was to check the effect of surface preparation on the performance of the CFRP. This is driven by the desire to evaluate the possibility of practical field applications where divers can simply install the CFRP underwater on the cracked element without having to prepare any surfaces. Similar to Specimen 1, the applied nominal stress range was 55 MPa (8 ksi). Eight strain gauges were installed on the specimen with Strain Gauge 4 and Strain Gauge 5, applied on the front face of the two CFRPs as discussed in Chapter 3.

4.2.2.1 Crack length vs. number of cycles for Specimen 2

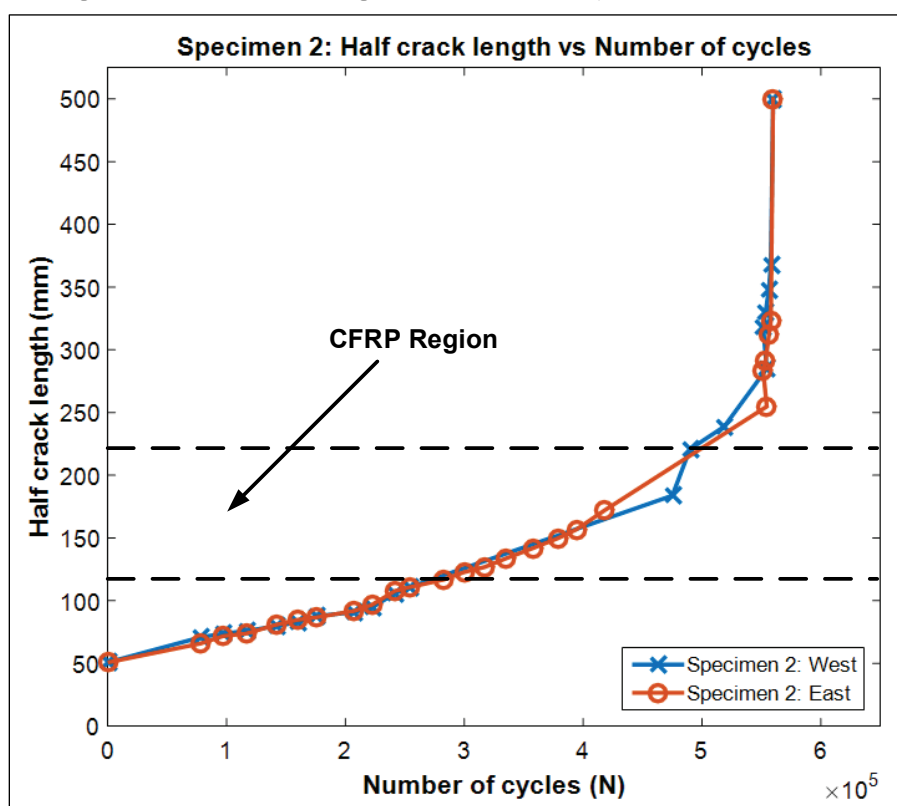
Crack length was measured similar to Specimen 1. Cracking in the tack welds was noted at around 16,028 cycles with 52.8 mm (2.1 in.) half crack length. However, the cracks did not start to propagate until 63,294 cycles. The half cracks on each side propagated in a stable manner until they reached the CFRPs (110 mm [4.3 in.]) with 254,251 cycles. At this point, the CFRP on the east side of the front face showed complete debonding, while all other CFRPs were intact (note: at this point the half crack length on the west side could not be measured as it was under the CFRP). Debonding of the CFRP installed on the east side of the front face might have been a result of a lack of surface preparation or of significant straining on the adhesive resulting from the large crack opening in combination with the lack of surface preparation. At around 378,756 cycles, and east half crack length of 150 mm (5.9 in.), all the remaining CFRP showed debonding (Figure 46). Note that as the CFRP was debonded from one side below the crack line, therefore it was assumed fully debonded.

Figure 46. Steel surface after CFRP debonding (front left) at 378,756 cycles for Specimen 2.



The east half-crack length could be measured since the CFRP was already debonded. At 417,637 cycles, the east half crack length at 172 mm (6.8 in.), surface preparation was performed by grinding off any adhesive residue coating, roughing the surface, and later cleaning it with acetone. The front left CFRP debonded even after surface preparation at 475,045 cycles with a west half-crack length of 184 mm (7.2 in.), but all other CFRPs intact. This debonding was believed to have occurred because of the very large crack size that caused significant straining on the adhesive. This configuration was kept until 489,840 cycles and then the debonded front west CFRP was once again replaced. At 544,473 cycles, near fracture, all the CFRP patches debonded. The total number of cycles to fracture the specimen was 559,828. A plot of crack length versus number of cycles can be seen in Figure 47.

Figure 47. Half crack length vs. Number of cycles for Specimen 2.



A thorough study of the crack surface showed a smooth surface with chevron marks until 184 mm (7.2 in.), indicating linear elastic behavior. From 184 mm (7.2 in.) to 374 mm (14.7 in.), the crack surface was slanted and smooth with chevron marks indicating a combined ductile-brittle crack extension. From 374 mm (14.7 in.) onwards until fracturing the

specimen, the crack surface showed shear lips indicating pure ductile fracture. Necking at the end also indicates pure ductile fracture of the specimen when both half cracks reached the end. The west half crack grew at higher rates after 220 mm (8.66 in.) than the east crack; in fact, the west half crack reached the end first, forcing the east half crack to become an edge crack for 4–5 cycles.

4.2.2.2 Change in strain with half crack length

Two different plots were generated for strain in steel versus half crack length, and strain in CFRP versus half crack length, as shown in Figure 48 and Figure 49 (Table 5 gives the cycle number corresponding to the points in Figure 49), respectively. As can be seen in Figure 48, strain in steel increases gradually and tends to infinity as the crack approaches the strain gauges. The strain values recorded by Strain Gauge 3 were less than that of Strain Gauge 6. When half crack lengths read 180 mm (7.1 in.), strain values for Strain Gauge 3 showed higher values than that of Strain Gauge 6 and as the respective half cracks approached the strain gauges, Strain Gauge 3 values approached infinity earlier (20–30 mm [0.79 – 1.18 in.]) as compared to Strain Gauge 6 values. It can be seen that Gauge 6 measured almost constant strain when the east half crack was under CFRP.

Strain gauge values for Strain Gauge 5 could not be recorded as it stopped reading the values as soon as the test was started. This could be attributed to either human error while installing this strain gauge or a malfunctioning strain gauge. Strain Gauge 4 values against west half crack length can be seen in Figure 49. Also in Figure 49, the strain in Gauge 4 increased gradually until point 2 (70 mm [2.76 in.]) shown by Segment I, implying the effectiveness of the CFRP in reducing crack growth. Segment II shows a jump in the strain, implying higher strain in the CFRP as the crack propagated further (Figure 49). Segments III, IV and V show rapid increase in the strain. This could be attributed to the rapid debonding of CFRP. At point 6 (110 mm [4.33 in.]) the CFRP totally debonded. Further data for Strain Gauge 4 could not be recorded as the CFRP debonded multiple times. It can be noted that strain in steel (SG3) showed higher values than in CFRP, but as the crack grew and the CFRP was replaced, strain in steel increased gradually, implying effectiveness of CFRP.

Figure 48. Strain in steel vs. half crack length for Specimen 2 with strain gauge locations.

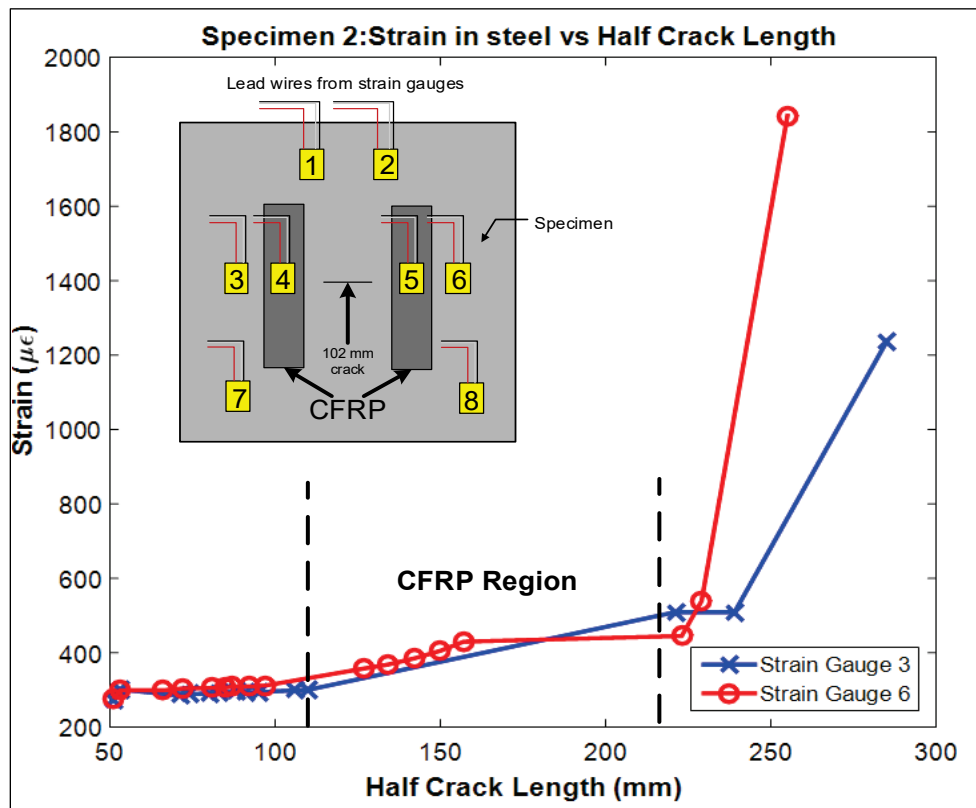


Figure 49. Strain in CFRP vs. half crack length for Specimen 2 with strain gauge locations.

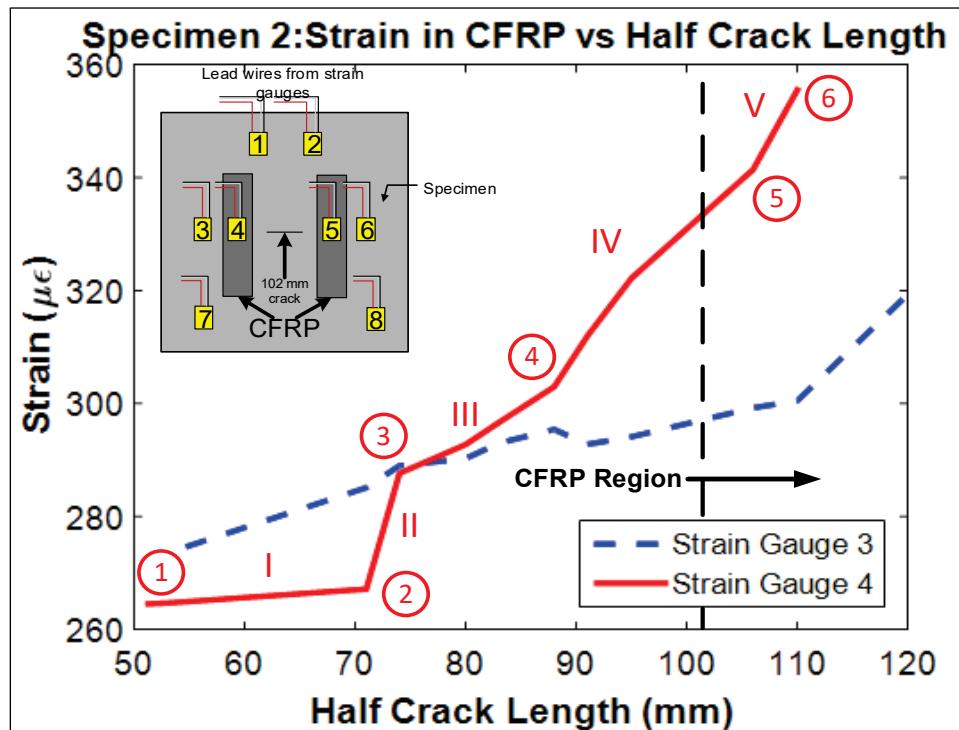


Table 5. Number of cycles for the points shown in Figure 49.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
Cycles	63294	77951	97188	160174	241708	254251

4.2.3 Test results and observations for Specimen 3

Specimen 3 was tested under dry conditions with an initial center crack length of 101.6 mm (4 in.). CFRP Tyfo SCH-41 sheets were attached at 110 mm (4 in.) from the center of the crack using Tyfo-S epoxy as explained in Chapter 3. This epoxy adhesive has a relatively high modulus value and is designed to be used with CFRP. Tack welds were introduced at the crack tips similar to Specimen 1 and 2 to facilitate faster crack initiation. For this specimen, the CFRP was installed with the surface preparation detailed in Chapter 3. A stress range of 55 MPa (8 ksi) was applied to the specimen. Eight strain gauges were installed on the specimen with Strain Gauge 4 and Strain Gauge 5 on two CFRP on the front face as discussed in Chapter 3.

4.2.3.1 Crack length vs. number of cycles for Specimen 3

The tack welds accelerated the crack initiation at first, but after coming out of the residual stress field of these welds, the crack propagated in a stable manner until reaching the CFRP. At 72,201 cycles, the half crack length on the west side was 61 mm (2.4 in.) and on the east side was 59 mm (2.3 in.). After reaching the CFRP, localized debonding of the CFRP at the crack location was observed. At 517,028 cycles, Strain Gauge 5 was replaced as it showed no value. This might be attributed to human error while attaching the strain gauge on the CFRP or the incompatibility of the strain gauges on the surface of the CFRP. When the cycle number reached 572,487, the crack had propagated from underneath the CFRP with a half crack length of 226 mm (8.9 in.) on both sides. After this, stable crack propagation was observed until it reached the critical crack length after which it showed unstable propagation. All four CFRPs did not fully debond until 673,274 and half-crack lengths of 393 mm [15.5 in] (west) and 392 mm [15.4 in.] (east). The increased number of cycles to half-crack length clearly highlights the importance of using proper adhesive and surface preparation for effective repair in comparison with Specimen 2. The total number of cycles to fracture the specimen was 673,830. The plot of the half-crack length versus number of cycles shown in Figure 50. Figures 51 and 52 show the typical crack growth in the specimen with CFRP still intact and fractured specimen, respectively.

Figure 50. Half crack length vs. number of cycles for Specimen 3.

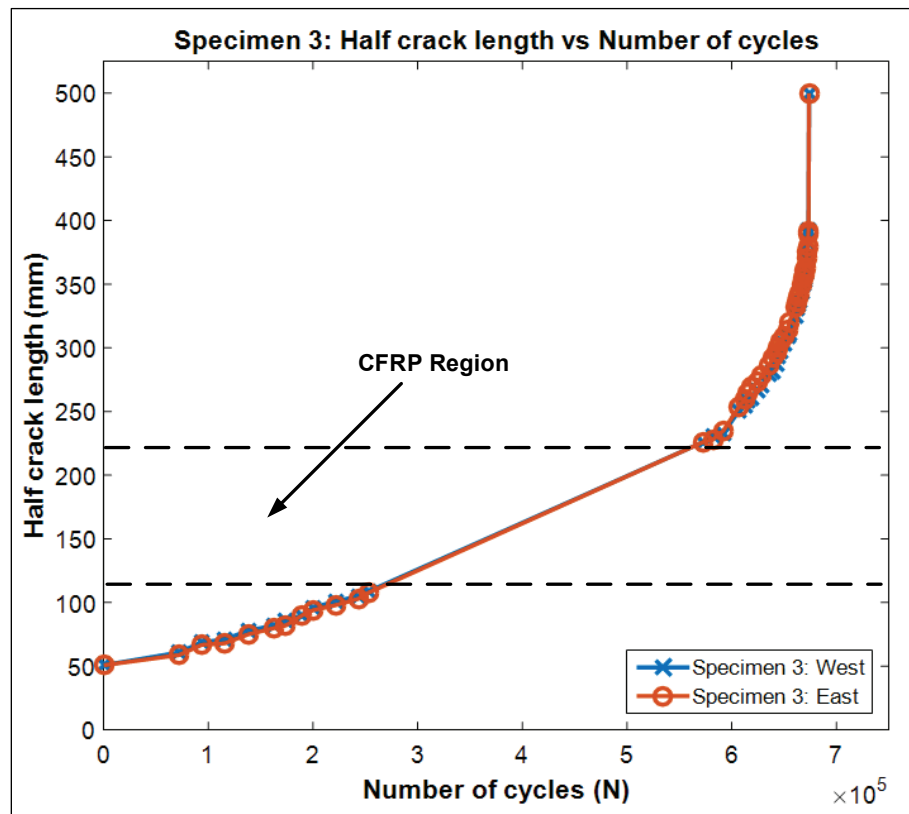


Figure 51. Crack propagation on each side of CFRP for Specimen 3.

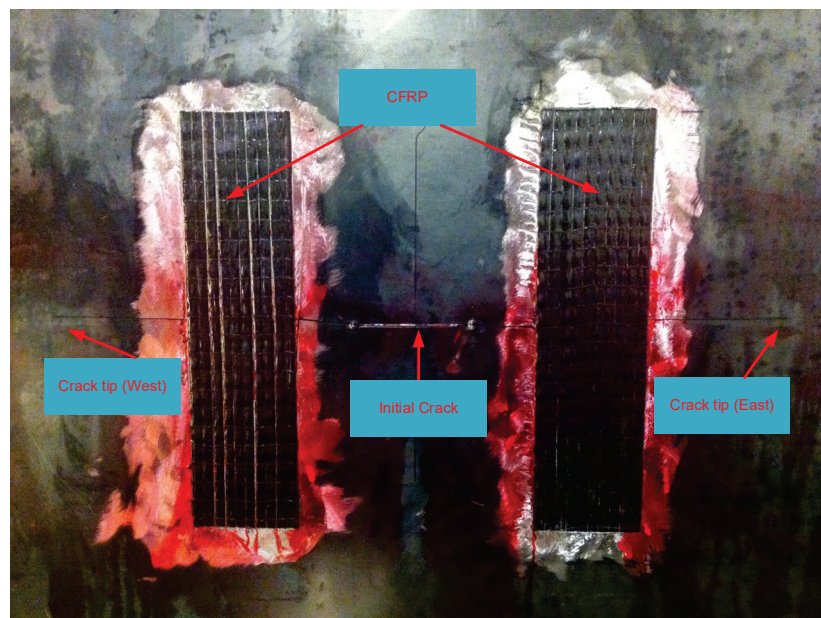


Figure 52. Fractured Specimen 3.



4.2.3.2 Change in strain with half crack length

Two different plots were generated for strain in steel versus half crack length and strain in CFRP versus half crack length as shown in Figures 53 and 53, respectively. As can be seen in Figure 53, strain in steel increases gradually and tends to infinity as the crack approaches the strain gauges. As the respective half cracks approached the strain gauges, Strain Gauge 3 values approached infinity at same crack length as Strain Gauge 6. The strain values recorded by Strain Gauge 3 were less than that of Strain Gauge 6.

As can be seen in Figure 54 and Table 6, strain values for both strain gauge 4 and Strain Gauge 5 increased gradually till the crack reached the CFRP as indicated by Segment I from point 1 to point 2 (until 110 mm [4.33 in.]). Half crack lengths could not be measured as the cracks were under the CFRP. As soon as the cracks propagated past the CFRP (220 mm [8.66 in.]), the respective strain gauges showed very high strain values implying a rapid strain increase in the CFRP (indicated by point 6). Maximum strain in west and east CFRP were $1313 \mu\epsilon$ and $1575 \mu\epsilon$. This is approximately 15.5% of the ultimate tensile strength of CFRP in the direction of fibers. A large increase in the CFRP when the crack had propagated from underneath the CFRP implies the effectiveness of the CFRP in transferring load and that no debonding had occurred.

Figure 53. Strain in steel vs. half crack length for Specimen 3 with strain gauge locations.

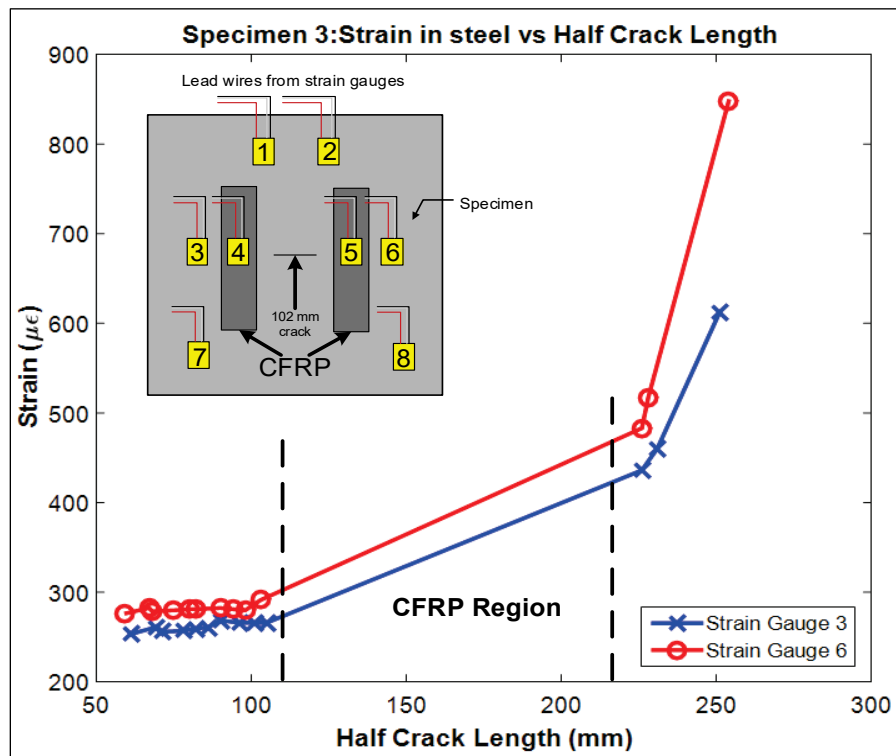


Figure 54. Strain in CFRP vs. half crack length for Specimen 3 with strain gauge locations.

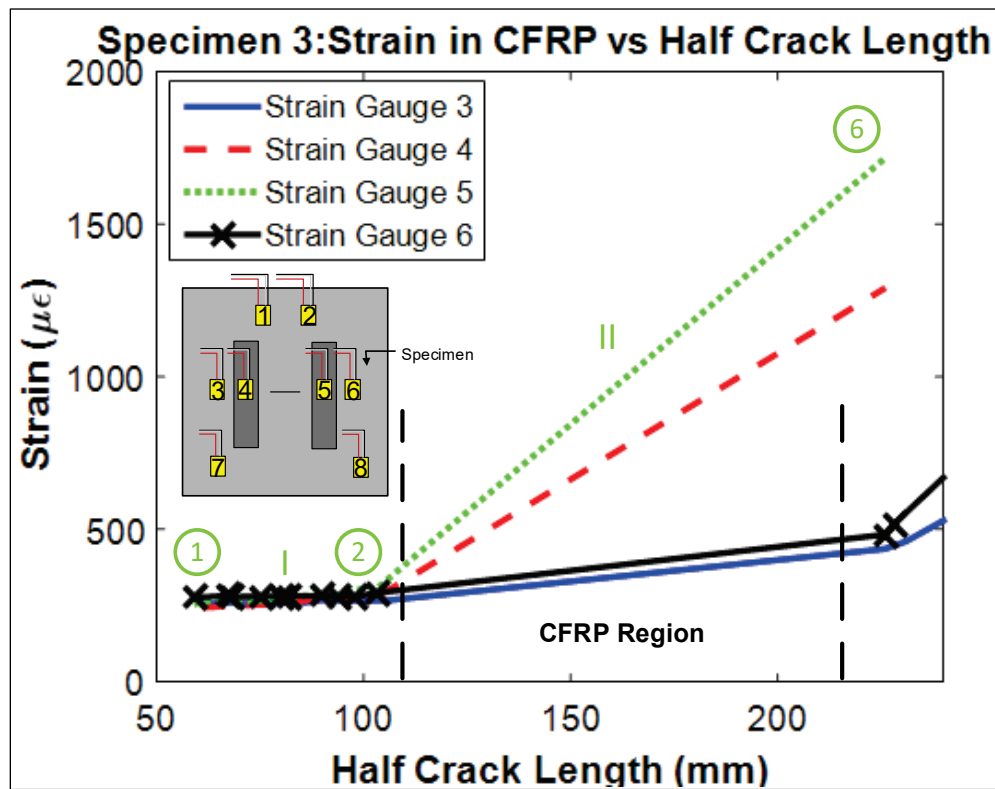


Table 6. Strain in CFRP vs. half crack length for Specimen 3 with strain gauge locations.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
Cycles	72,201	243,297	NA	NA	NA	572,487

4.2.4 Test results and observations for Specimen 4

Specimen 4 was tested under wet conditions with a center crack of length 101.6 mm and Tyfo SCH-41 sheets CFRP attached 110 mm (4.3 in.) from the center of the crack using Tyfo-S epoxy as explained in Chapter 3. Tack welds were introduced at the crack tips, similar to the other specimens, to facilitate faster crack initiation. The CFRPs were installed with surface preparation. A stress range of 55 MPa (8 ksi) was applied to the specimen. The water was prepared with 90 kg (200 lb) of salt and the same amount of sand with 0.45–0.55 mm (0.018–0.022 in.) particle size was introduced in the tank containing 2,306 liters of water.

4.2.4.1 Crack length vs. number of cycles for Specimen 4

For this specimen, the east crack initiated at 60,141 cycles but the west crack showed no initiation. As the test progressed, the west crack caught up with its east side counterpart. Both cracks propagated in a stable manner until 200,535 cycles when the west CFRP on the back face (east from front face) was very debonded. The surface after CFRP debonding can be seen in Figure 55 (a). The debonding can be attributed to the specimen face being subjected to the turbulence and the bombardment of the sand particles. When the east crack was 152 mm (5.98 in.) at 246,568 cycles, the east CFRP on the back face started showing debonding at the top edges as can be seen in Figure 55 (b). Although the crack propagated in a stable manner, the west CFRP on the back face was fully debonded at 292,948 cycles. The performance of the CFRP on the front face was very different from that installed on the back face. On the front face, debonding was observed at a very large half crack length of 365 mm (14.4 in.) on the west side and 362 mm (14.2 in.) on east side for the west CFRP. When the CFRP fully debonded, a loud breaking noise was heard, indicating a sudden failure of the CFRP. The experiment was stopped at 432,579 cycles, as there was a possibility of damaging the acrylic walls while fracturing the specimen. A plot for crack length vs number of cycles for this specimen is shown in Figure 56. The reason the CFRP performance was much better on the front face than on the back face was attributed the front face being isolated from the turbulence generated by the propeller and the effect of the sand particles through the partitions as discussed in Chapter 3. A final picture showing the back face of the specimen is shown in Figure 57.

Figure 55. Specimen 4 showing: (a) Steel surface after CFRP debonding (b) Debonding of CFRP at top edges.

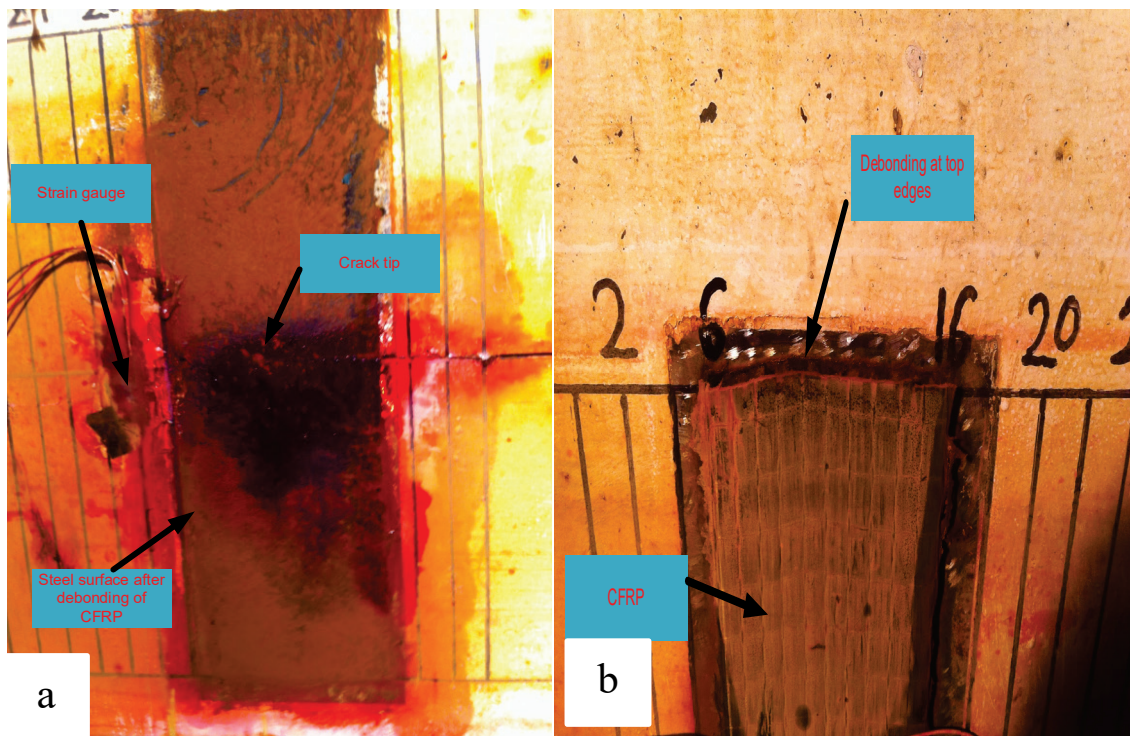


Figure 56. Crack length vs. number of cycles for Specimen 4.

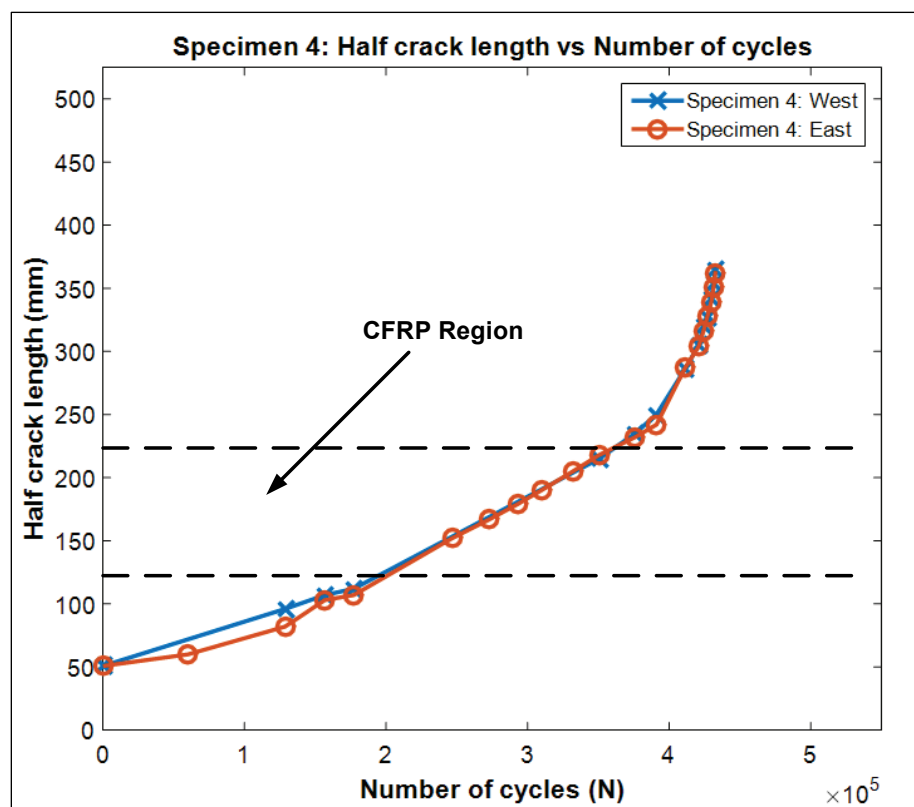
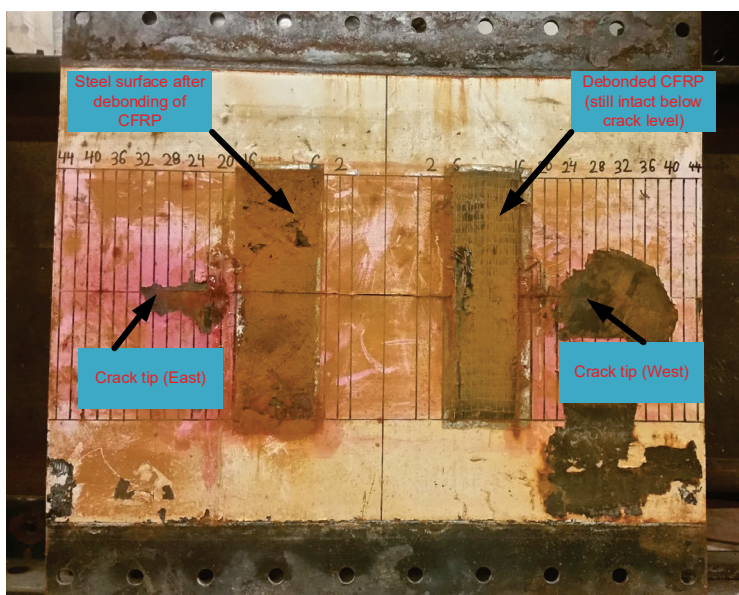


Figure 57. Back face of Specimen 4 after the test.



4.2.4.2 Change in strain with half crack length

Two different plots were generated for strain in steel versus half crack length and strain in CFRP versus half crack length as shown in Figures 58 and 59, respectively. As seen in Figure 58, strain in the steel increases gradually and tends to infinity as the crack approaches strain gauges. The strain values recorded by Strain Gauge 3 were equal to that of Strain Gauge 6. As the respective half cracks approached the strain gauges, Strain Gauge 3 values approached infinity at same crack length as Strain Gauge 6.

Strain gauge values for Strain Gauge 4 could not be recorded as it stopped reading the values as soon as the test was started. This could be attributed to human error while installing the strain gauge, the strain gauge being defective, or the protective covering of this strain gauge had openings, which lead to interaction with water. As can be seen in Figure 59 and Table 7, strain in Gauge 5 increased until the crack reached the CFRP as indicated by Segment I. Segment II shows that as the crack was under the CFRP, there was a further increase in strain until a half-crack length of 175 mm (6.9 in.). This was followed by a clear jump (indicated by Segment III) in the values implying higher strain in the CFRP. The strain kept increasing gradually as soon as the crack passed the CFRP as indicated by Segments IV and V. The maximum strain recorded by Strain Gauge 5 was $1348 \mu\epsilon$, which implies approximately 13.25% of the maximum tensile strength was engaged in the direction of the fibers. Even though debonding occurred at the last minute. Literature says that debonding begins as soon as the crack

is underneath the CFRP; it is hard to tell how the debonding is going. The strain data shows that only a percentage of the CFRP was engaged due to debonding and had an abrupt debonding at full fracture. Strain in the steel was less than strain in the CFRP as expected.

Figure 58. Strain in steel vs. half crack length for Specimen 4 with strain gauge locations.

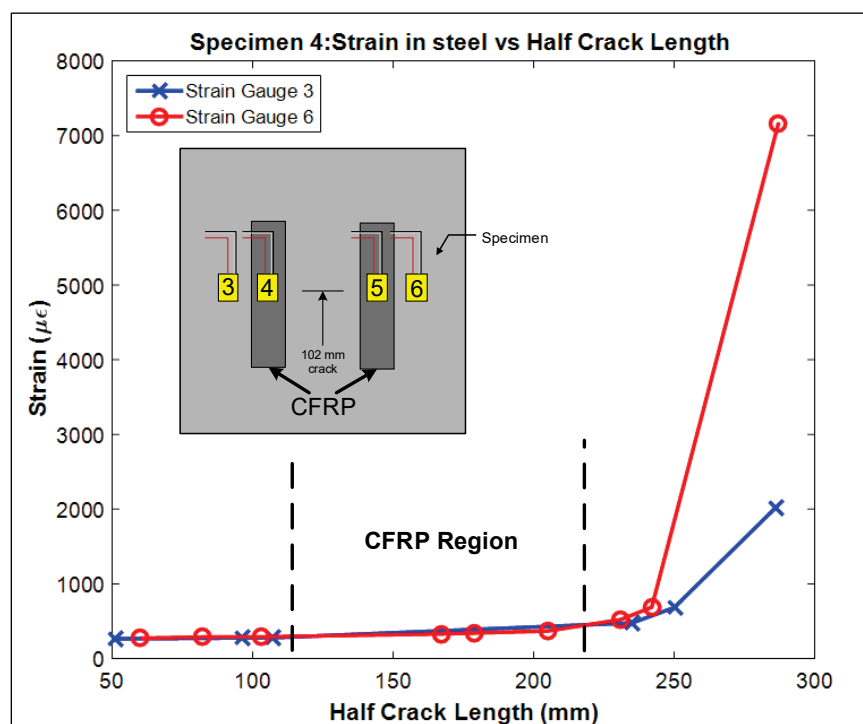


Figure 59. Strain in CFRP vs. half crack length for Specimen 4 with strain gauge locations.

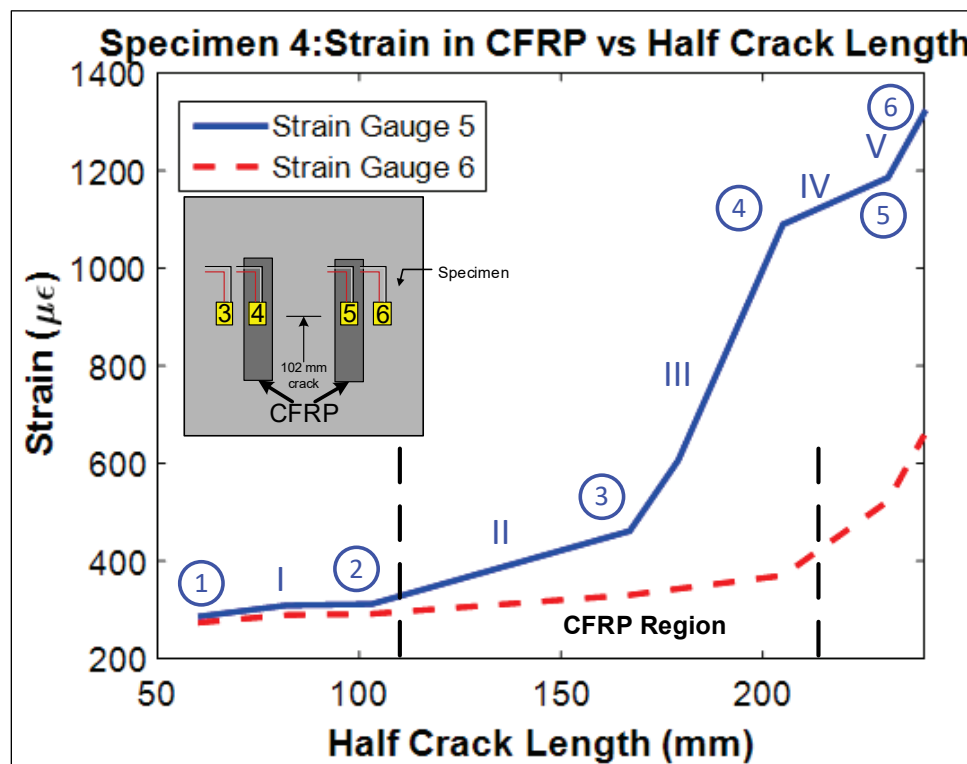


Table 7. Number of cycles for the points shown in Figure 59.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
Cycles	60,141	156,744	273,077	332,003	375,823	411,255

4.2.5 Test results and observations for Specimen 5

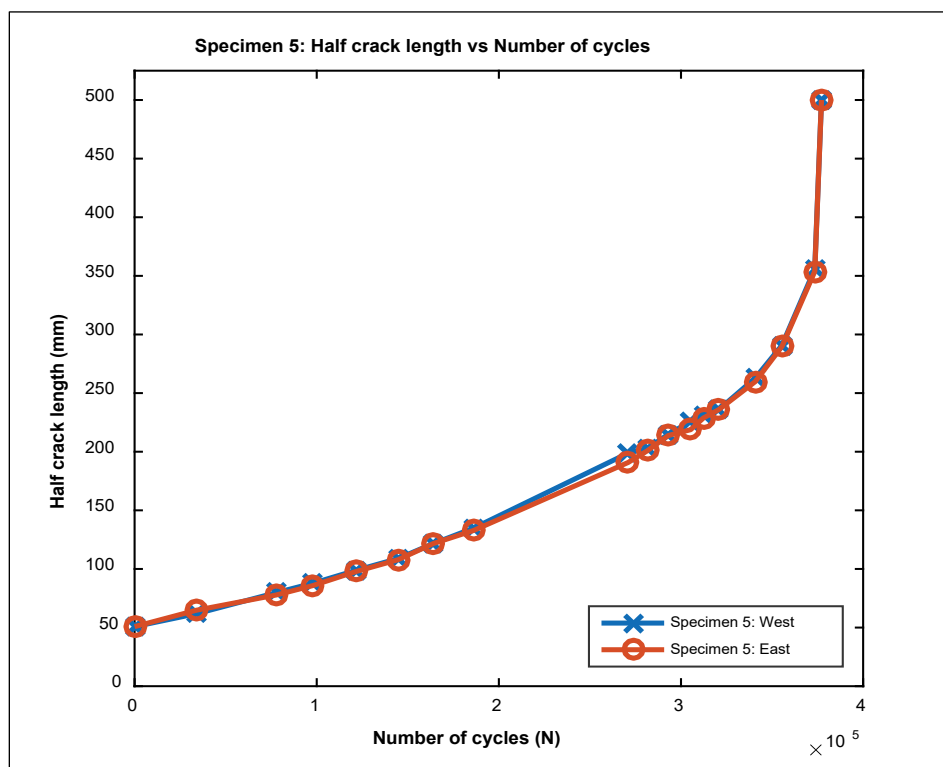
Specimen 5 was tested under wet condition 4 with a center crack length of 101.6 mm (4 in.) and no CFRP. Tack welds were introduced at the crack tips, similar to the other specimens, to facilitate faster crack initiation. A stress range of 55 MPa (8 ksi) was applied to the specimen. The water prepared with 90 kg (200 lb) of salt and the same amount of sand with 0.45–0.55 mm (.01–.02 in.) particle size.

4.2.5.1 Crack length vs. number of cycles for Specimen 5

Crack length was measured as the crack propagated along the specimen width and the corresponding number of cycles, shown on the MTS 407 controller, were recorded. The fatigue life of the specimen was dominated by stable crack growth. Near the end of fatigue life, unstable growth was noted as the crack reached its critical length. Both east and west cracks

showed similar behavior for half crack length versus number of cycles, emphasizing the even stress distribution imposed on the specimens. Figure 60 shows half crack length vs. number of cycles on west and east side of the specimen. As seen in Figure 60, the plots are exponential curves with crack growing in a stable manner after reaching a critical length of around 300 mm (≈ 12 in.). The total number of cycles required for the half crack to reach full width of the specimen was 377,123.

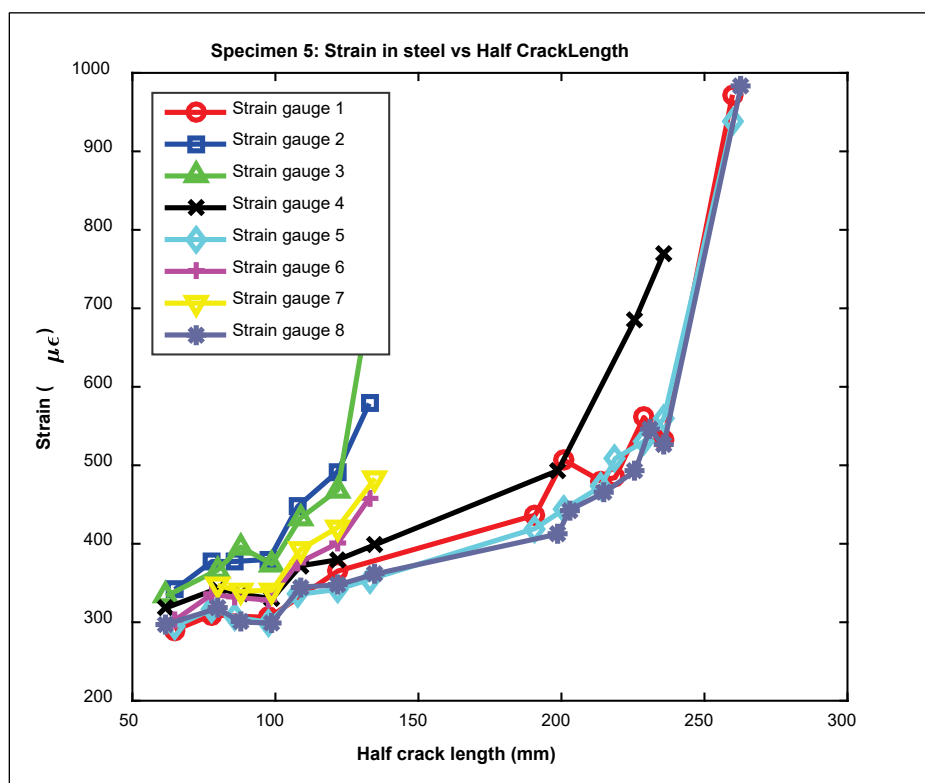
Figure 60. Crack length vs. number of cycles for Specimen 5.



4.2.5.2 Strain change in strain with half crack length

The strain gauge data from both sides of the plate showed the strain increasing exponentially as the half-crack length increased. In general, strain in the steel increased gradually and tended to infinity as the crack approached the strain gauges. Strain Gauges 2, 3, 6, and 7 measured the strain until the crack reached their location at 160 mm (6.3 in.) from the center. Gauges 2, 3, 6, and 7 showed higher strains compared to Gauges 1, 4, 5, and 8 for half-crack length smaller than 160 mm (6.3 in.) as shown in Figure 61. The other four Strain Gauges, 1, 4, 5, and 8, recorded the strains before the crack tip approached their location at 275 mm (≈ 11 in.) from the center of the specimen. The very large strains, when the crack approached the gauge, is an indication of large plasticity at the crack tip.

Figure 61. Strain in CFRP vs. half crack length for all strain gauges in Specimen 5.



4.3 Comparison of results

This section includes the comparison of the results obtained for the individual specimens as discussed in previous sections. The main discussion of this section is the half-crack length versus number of cycles and the half-crack length versus strain values in both the steel and CFRP.

4.3.1 Half crack length vs. number of cycles

It is important to compare the results for the individual specimens to obtain an overall clearer perspective on the effectiveness of CFRP for underwater repair of steel panels. Figure 62 shows a plot comprising of half crack length versus number of cycles for all the five specimens. In addition, it took 439,140 cycles for Specimen 1 to fracture. Specimen 2 with Tyfo UC laminates and Hudco Formula 3200 showed better results than specimen 1 containing no CFRP. (As noted previously, the Hudco Formula 3200 is a paste with very low modulus that is not intended for CFRP use). In this specimen, the CFRP had to be replaced three times due to the inadequacy of the adhesive. Overall, the total number of cycles were recorded to be 559,828 cycles, which is 1.3 times that of Specimen 1.

Specimen 3 took the maximum cycles to fracture with total cycles of 673,830, 1.5 times greater than Specimen 1. This implies that the Tyfo SCH-41 sheets bonded to the steel specimen near the crack tip using Tyfo-S adhesive gives a greater fatigue life over Hudco Formula 3200. Specimen 4 included the effect of turbulence and bombardment of fluvial sediments on one side and the effect of salt on both sides of the specimens. The total number of cycles to fracture was 432,579 cycles. This was approximately the same as Specimen 1, which had no CFRP and was tested in-air. Specimen 5 was tested underwater with no CFRP retrofit and lasted for 377,123 cycles to fracture. This specimen had the least number of cycles to fracture mainly because it was tested under a corrosive environment with no CFRP repair. Specimen 4 (CFRP in-water) showed a 1.15 fatigue life improvement when compared to Specimen 5 (in-water no CFRP). Figure 62 shows the fatigue life improvement seen when a section is repaired with CFRP. A numerical study for crack length vs. number of cycles was conducted for an unrepaired specimen subjected to a corrosive environment using the constants of Paris' law, $C = 2.4 \times 10^{-12} \text{ m/cycles}$ ($\text{MPa m}^{1/2}$) [$1.04 \times 10^{-10} \text{ in./cycles (ksi in.}^{1/2})$] and $m=3$ recommended by British Standards Institute (BSI 2015) for corrosive environments. The results of unrepaired underwater specimens with Paris' law parameters for a corrosive environment indicated that the underwater CFRP repaired specimen, with the effect of turbulence and sand, is approximately 3.5 times better than its unrepaired counterpart shown by a dotted line in Figure 62. This clearly highlights the potential for this repair method to increase fatigue life of underwater repaired specimens.

4.3.2 Strain in steel vs. half crack length

To compare the strain developed in steel while testing each specimen, a plot was generated for the strain in steel vs. half crack length, which can be seen in Figure 63. Strain in the steel should show lesser values for specimens with CFRP as it reduces the strain at crack tips. Strain values for Strain Gauge 6 for Specimen 4 were less than that of the other strain gauges for different specimens. The second lowest value was for Strain Gauge 3 of Specimen 3. Highest strain values were obtained for Strain Gauge 6 of Specimen 2, because of CFRP replacement. It can be noted that the strain values increased gradually for specimens with CFRP until the crack was under the CFRP and later increased exponentially (cannot be seen in figure) as explained in previous sections.

Figure 62. Comparison of half crack length vs. number of cycles for all specimens.

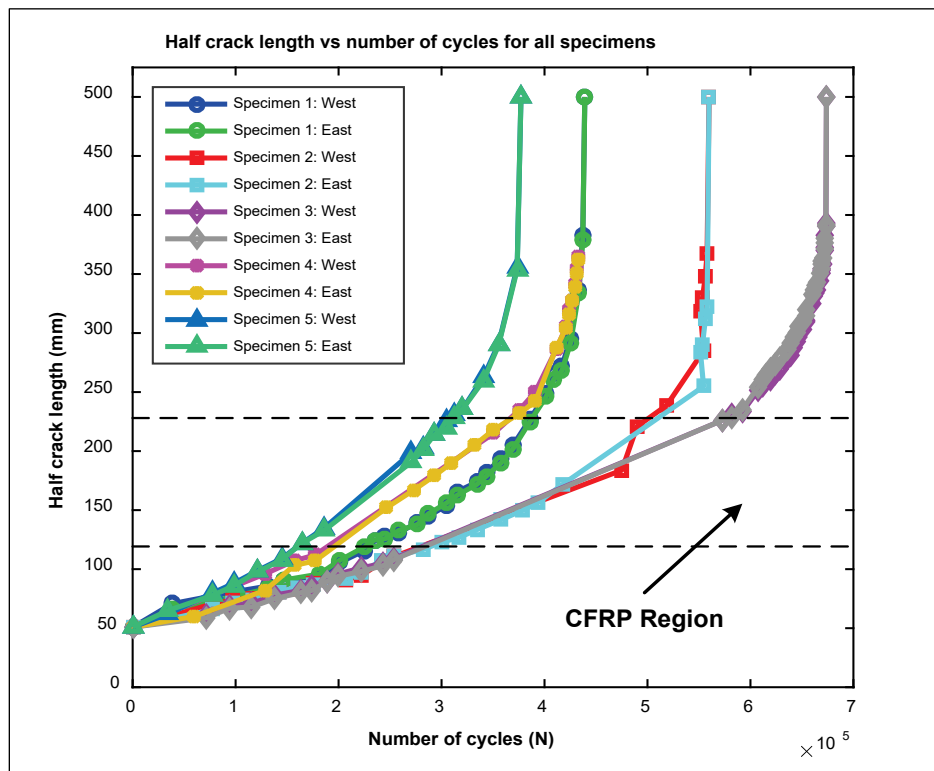
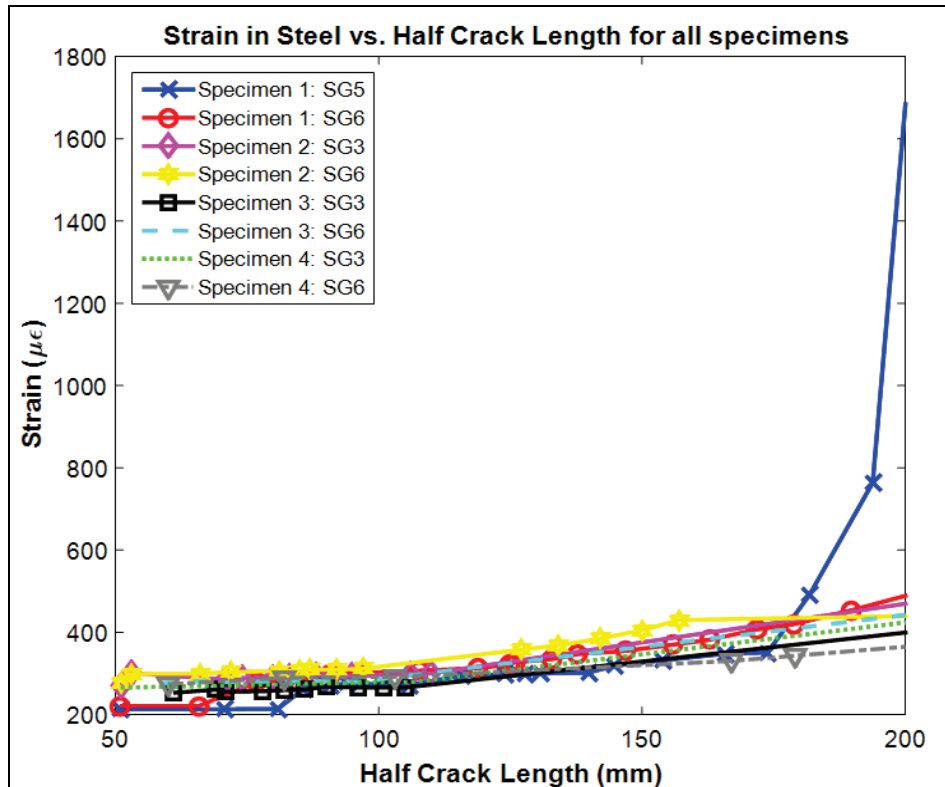


Figure 63. Comparison of strain in steel vs. half crack length for all specimens.



5 Conclusions, Field Implications and Future Work

5.1 Conclusions

A new experimental setup was developed to evaluate the potential for using CFRPs for underwater fatigue repairs of steel panels. Conclusions were drawn from four physical experiments and a numerical analysis for an unrepaired corroded panel.

- A log-log plot of da/dN vs ΔK shows scatter in the data for Specimen 1. Values of the constants of Paris' Law, C and m , found in this study were very close to those found in the accepted studies (Barsom and Rolfe 1999; Dexter and Mahmoud 2004).
- Surface preparation conducted before applying CFRP to the specimen helps to improve bonding of the adhesive to the steel. Tyfo UC-laminates showed debonding multiple times due to the lack of surface preparation and low modulus of elasticity of Hudco Formula 3200 epoxy for Specimen 2. Tyfo SCH-41 sheets showed no debonding until Specimen 3 was fractured. These sheets displayed only localized debonding when the crack was under this particular type of CFRP. On this specimen, surface preparation was conducted and presents a benefit compared to those surfaces that are not clean and prepare property.
- Although debonding several times, UC laminates with Hudco Formula 3200 epoxy increased the fatigue life of the specimen by 1.3 times. This adhesive is not meant to be used with CFRP applications but was evaluated due to the potential advantage it can provide for field application as it can cure underwater (i.e., chamber dewatering is not required). Therefore, UC laminates may have a better fatigue performance if installed with a better adhesive. SCH-41 sheets with Tyfo-S epoxy increased the fatigue life of the specimen by 1.5 times. With its higher modulus value, this proves to be a better selection over the Hudco Formula 3200 counterpart. However, Tyfo S adhesive was not developed to connect the CFRP composite with steel. Other adhesives need to be studied to obtain a better connection between the CFRP composite and steel.
- Approximately 15% of the ultimate tensile strength along the direction of the fibers was engaged for the combination of SCH-41 sheets along with Tyfo-S epoxy for Specimen 3, which was tested under dry

conditions. Approximately 13% of the ultimate tensile strength along the direction of the fibers was recorded for underwater retrofitted plate (Specimen 4) with the same combination.

- Based on the number of cycles to fracture of Specimen 1 (control) versus Specimen 5 (underwater no CFRP) it can be concluded that the salt accelerates the crack propagation rate.
- When comparing the results of Specimen 3 (CFRP in-air) vs. Specimen 4 (CFRP in-water) it can be concluded that along with the acceleration of the crack growth due to salt the watery environment promoted a faster debonding of the CFRP; faster debonding of the CFRP reduces the overall fatigue life of the repair. It can also be concluded that turbulent water leads to a faster debonding than calm water, since the front face of the plate, which was not subjected to turbulence or sand impact debonded later than the back face. Debonding of SCH-41 on the back face of Specimen 4, can be attributed to the combined effect of salt and bombarding sand particles. Debonding was not observed on the front face until the crack was very long and the CFRP achieved full strength. The front face was not subjected to turbulence or the impact of sand.
- The total number of cycles taken to a fracture control specimen and that of the underwater CFRP-retrofitted specimen (Specimen 4) are very close. This implies that salt corrodes the crack tip, accelerating the crack propagation rate. When comparing the results of the underwater repaired specimen with that of a numerically (analytically) obtained solution of underwater, but unrepaired, an improvement of fatigue life of approximately 3.5 times is observed. This clearly demonstrates the potential of this underwater retrofit method.

5.2 Field implications

This study was conducted to experimentally assess the potential of underwater CFRP-retrofitting of large steel panels. The following observations should be considered for field implementations:

- Tyfo UC-laminates show an increase in the fatigue life when used with Hudco Formula 3200 epoxy paste. This epoxy can bond to underwater or wet surfaces and Tyfo UC-laminates do not absorb any water when not covered with epoxy. A combination of both should not be used due to the rapid debonding observed during the experiments.

- Hudco Formula 3200 epoxy can be applied to UC-laminates outside the water and then can be taken underwater to apply to steel at required places.
- Tyfo SCH-41 sheets resulted in the highest fatigue life increase when used with Tyfo-S epoxy. These sheets absorb water and cannot be applied underwater; therefore, repairs will require dewatering of the lock chamber.
- Tyfo-S does not bond to underwater or wet surfaces; however, it can set in dry conditions and then be subjected to water.
- Tyfo-S has a significantly higher modulus than Hudco Formula 3200 and should be used for repairs instead.
- For long term retrofitting, a combination of Tyfo SCH-41 sheets with Tyfo-S epoxy can be used after dewatering the chamber to ensure application in dry conditions and hardening of the CFRP/adhesive components prior to refilling the chamber with water.
- Tyfo SCH-41 sheets are flexible and can be applied at sharp corners and to complicated geometries.

5.3 Future work

The current study emphasizes the need for future work regarding fatigue crack growth in CFRP retrofitted underwater steel panels. In addition to the three specimens remaining to be tested, some of the important research needs include:

- Deriving equations for effective bond length of CFRP for underwater retrofitting.
- Evaluating the effect of water turbulence on crack propagation rate.
- Assessing the effect of steel corrosion on the bonding of CFRP.
- Studying the use of an adhesive that can be applied without dewatering and is more reliable than the Hudco Formula 3200.
- Studying the use of other adhesives that can be applied on dry conditions and are more reliable than the Tyfo-S epoxy.
- Evaluating different arrangements of CFRP such as increased size of CFRP and covering the initial crack with the CFRP.
- Investigate the effect of CFRP on crack propagation in Mode II, Mode III and multimode loading.

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Appendix A: Approximate Calculations for Concentration of Fluvial Sediments

Background

Using Bernoulli's Equation

$P_{\text{total}} = \text{static pressure} + \text{dynamic pressure}$

Free stream

$$P_{t0} = P_0 + \frac{1}{2} * d * V_0^2$$

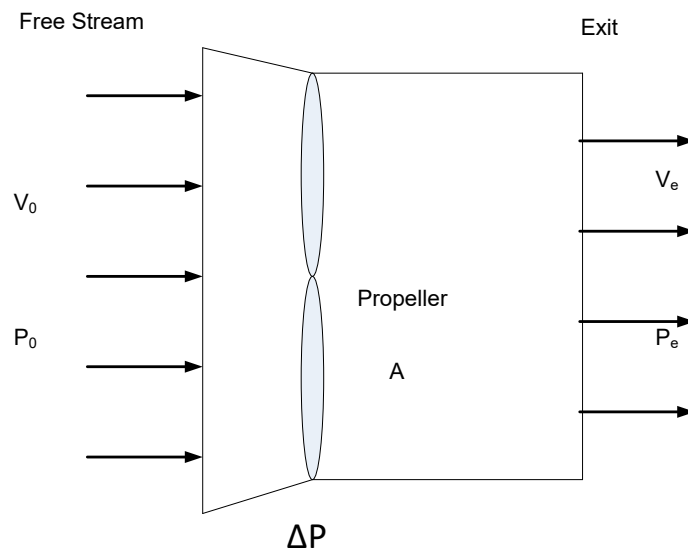
Exit stream

$$P_{te} = P_0 + \frac{1}{2} * d * V_e^2$$

$$\Delta P = \frac{1}{2} * d * [V_e^2 - V_0^2]$$

Putting back in equation of thrust

$$F = \frac{1}{2} * d * A * [V_e^2 - V_0^2] \quad (\text{A1})$$



Using Momentum Theory

Thrust $[F] = \text{mass flow rate} * \text{change in velocity}$

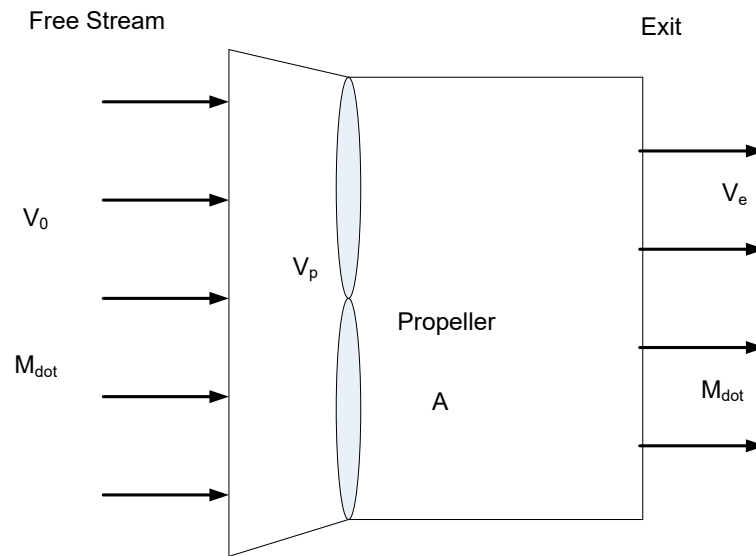
$$= \dot{m} * V_e - \dot{m} * V_0$$

Through the area of the propeller A , mass flow rate is

$$\dot{m} = \rho * V_p * A$$

$$F = \rho * V_p * A * [V_e - V_0]$$

(A2)



Comparing equation A1 and A2

$$V_p = \frac{1}{2} * [V_e + V_0] \quad (\text{A3})$$

Known Parameters

V_0 = Velocity of tug boat

V_p = Velocity at the propeller = can be found from the angular velocity

A = Area of the propeller

From equation A3, we can get exit velocity.

Calculations for this study

$$\text{Propeller Diameter} = 12 \text{ in.} = 0.3 \text{ m}$$

$$\text{Propeller Radius (r)} = 6 \text{ in.} = 0.15 \text{ m}$$

$$\text{Area of propeller (A)} = 0.1 \text{ m}^2$$

$$\text{Revolutions per minute (RPM)} = 500$$

$$\text{Density of water (d)} = 1000 \text{ kg/m}^3$$

$$\text{Angular velocity } (\omega) = \text{RPM} \times 2\pi/60$$

$$= 500 \times \frac{2\pi}{60} = 52.35 \text{ rad/sec}$$

$$\text{Linear velocity at the tip of the propeller blade (V}_P\text{)} = r \times \omega = 0.15 \times 52.35 = 7.85 \text{ m/s}$$

$$\text{In this case } V_0 = 0 \text{ m/s}$$

From equation 3,

$$V_P = \frac{1}{2} [V_e + V_0]$$

$$\text{Exit velocity (V}_e\text{)} = 2V_P - V_0 = 2 \times 7.85 - 0 = 15.7 \text{ m/s}$$

$$\text{Velocity (V) of Mississippi River} = 1.2 \text{ m/s} \quad (\text{Jordan 1965})$$

$$\text{Mass flow rate K [kg/s]} = \text{Conc.}_{\text{sed}} [\text{kg/m}^3] \times V [\text{m/s}] \times A [\text{m}^2]$$

$$= (2200/10^{-3}) [\text{kg/m}^3] \times 1.2 [\text{m/s}] \times 1 [\text{m}^2] \quad (\text{Julien et al. 2005})$$

$$= 2.64 [\text{kg/s}] \quad (\text{A4})$$

After 15 years = $15 \times 365 \times 24 \times 60 \times 60$ seconds

Total mass flow after 15 years $K_{15} = 2.64 \times 15 \times 365 \times 24 \times 60 \times 60$

$$= 1.24 \times 10^9 \text{ kg}$$

To cramp this mass in 20 days

$$1.24 \times 10^9 \text{ kg} = m \times 20 \times 24 \times 60 \times 60$$

$$m = 717.5 \text{ kg/s}$$

Using equation 4 and volume of water = 2.3 m^3

$$717.5 = (C_{s15}/2.3) \times V \times A$$

Here V is the exit velocity of the propeller = 15.7 m/s

$$C_{s15} = 105 \text{ kg}$$

Appendix B: Detailed Drawings of Setup

Figure B1. Front view of the test setup frame.

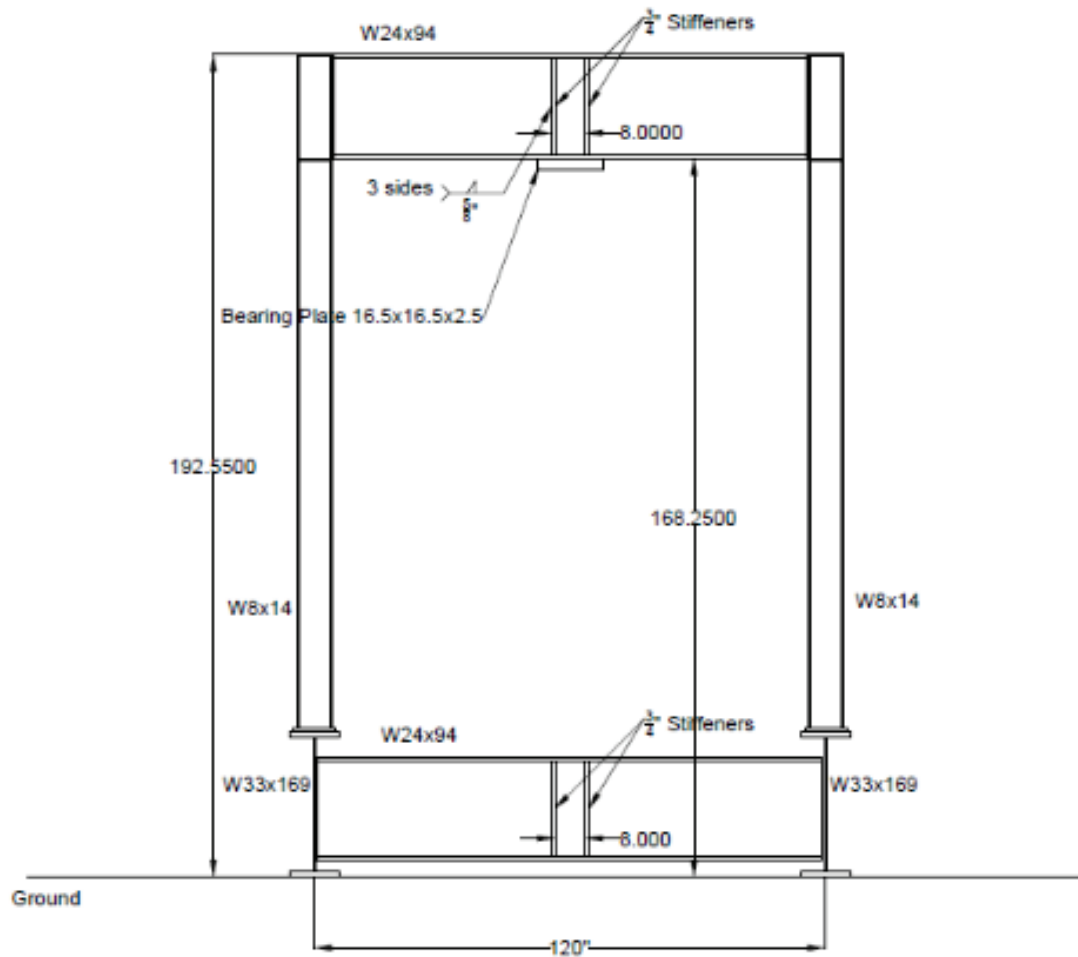


Figure B2. Beam to column shear connection and column base plate connection.

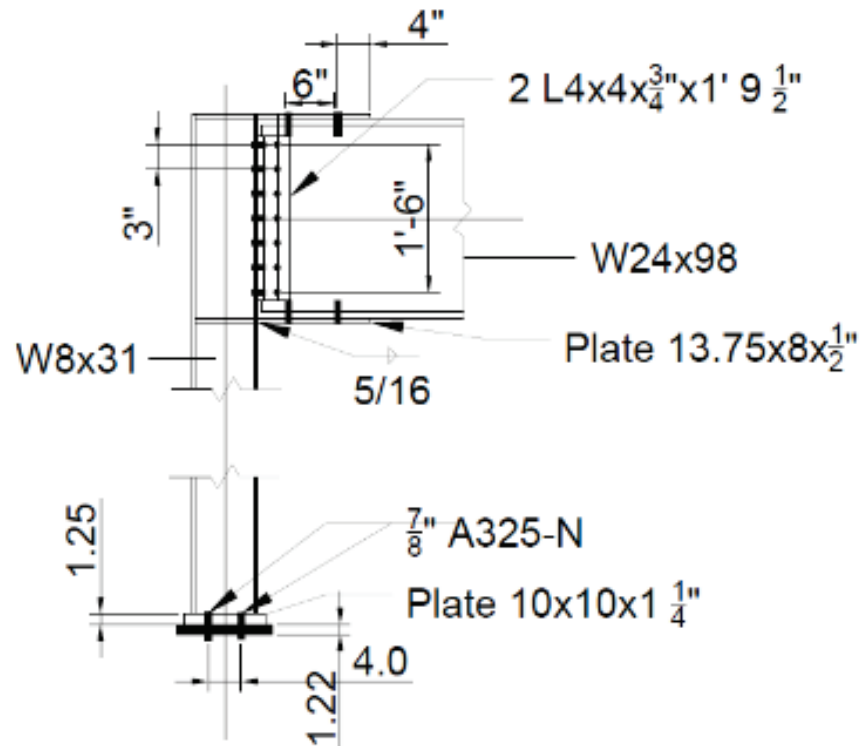


Figure B3. HSS bracing for the frame.

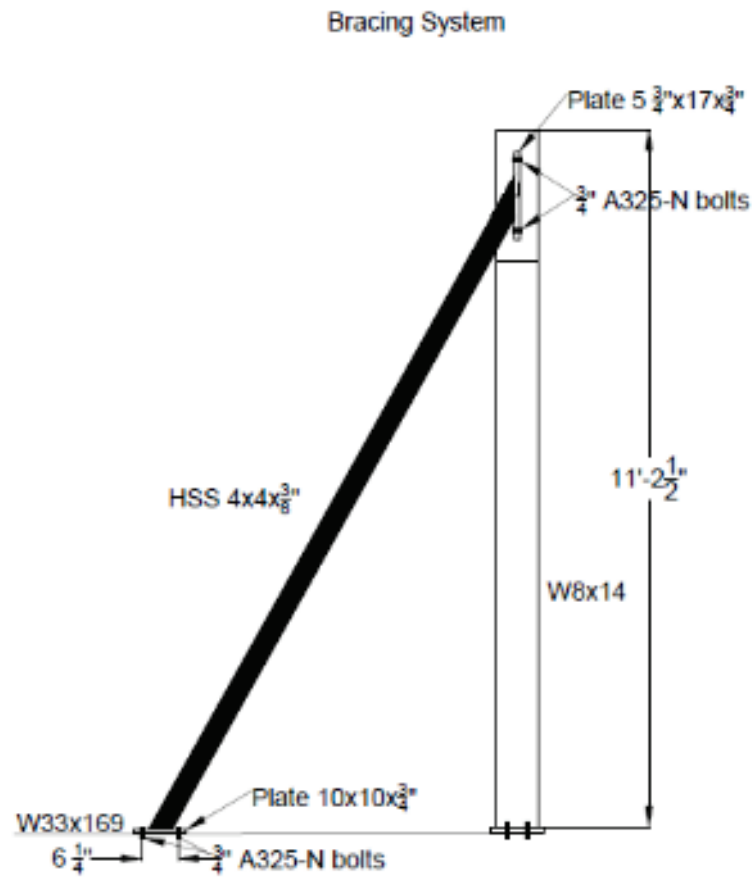


Figure B4. Actuator plate connections to bottom flange of top W24 x 94 beam.

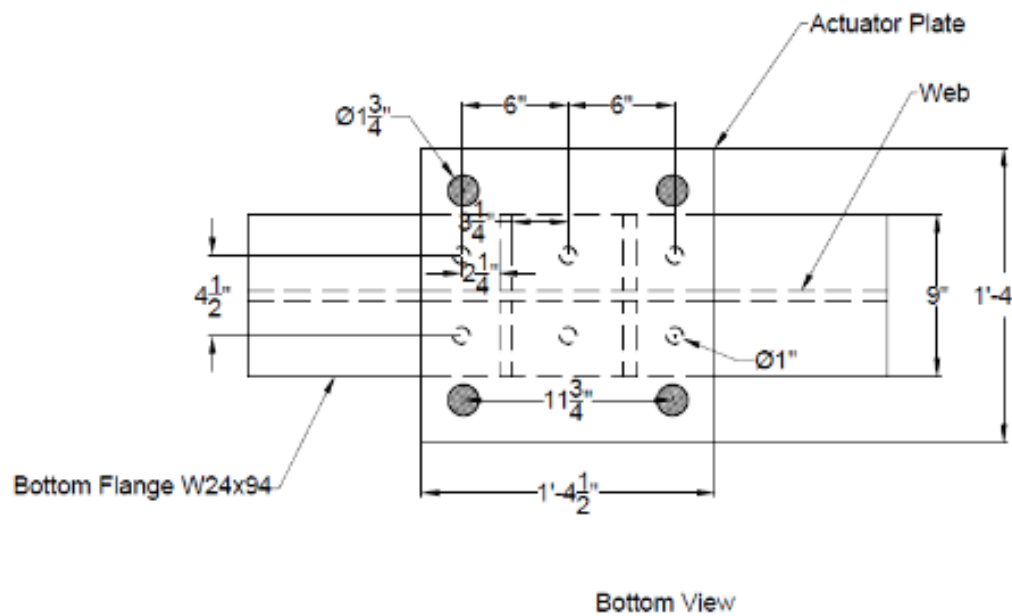


Figure B6. Spreader beam top view with holes to connect actuator swivel.

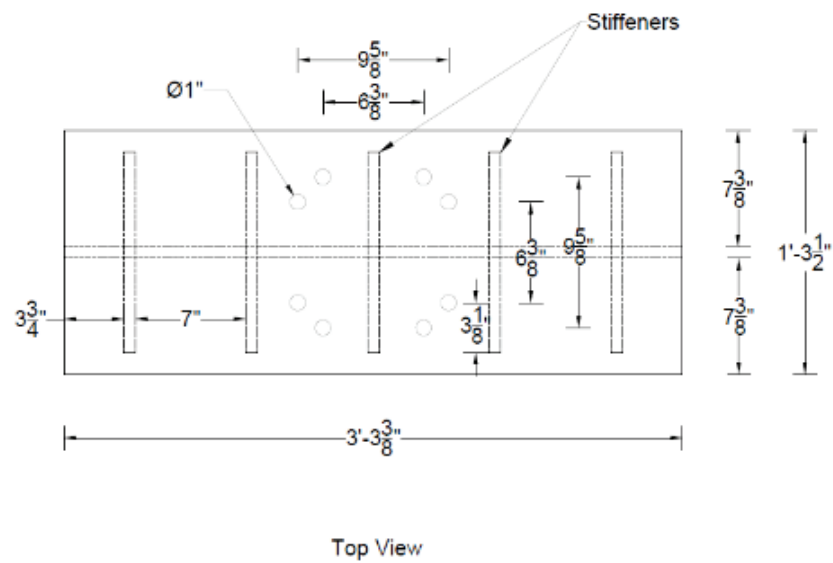
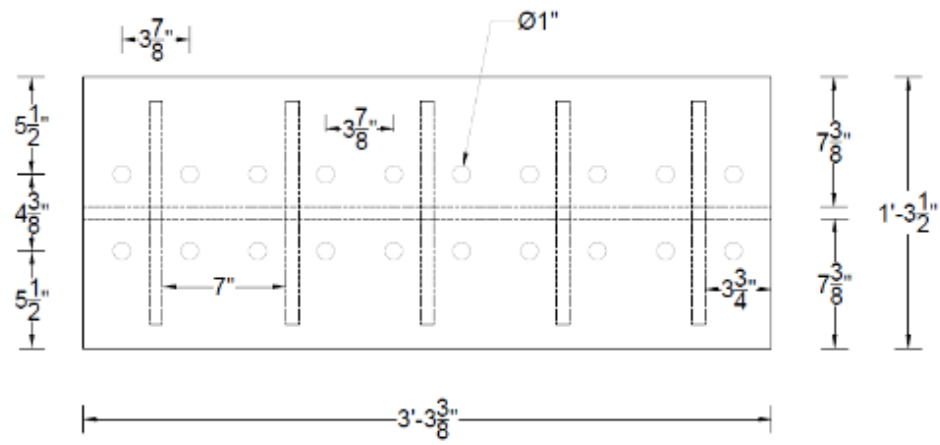


Figure B7. Spreader beam bottom view with holes to connect angles connecting specimen.



Bottom View

Figure B8. Bottom W24 x 94 beam and specimen connection.

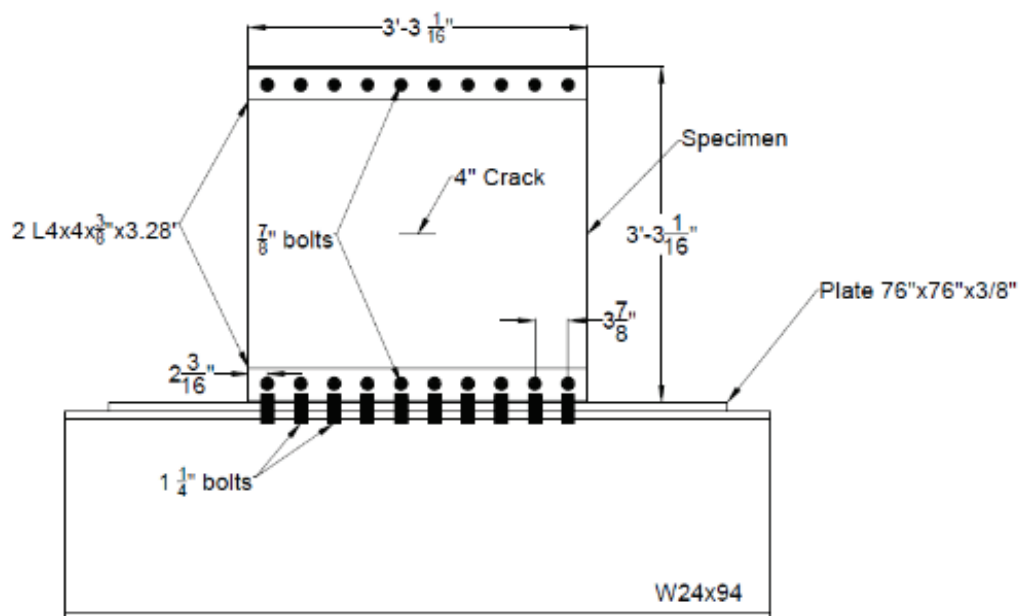


Figure B9. W24 x 94 and W33 x 169 beam connection.

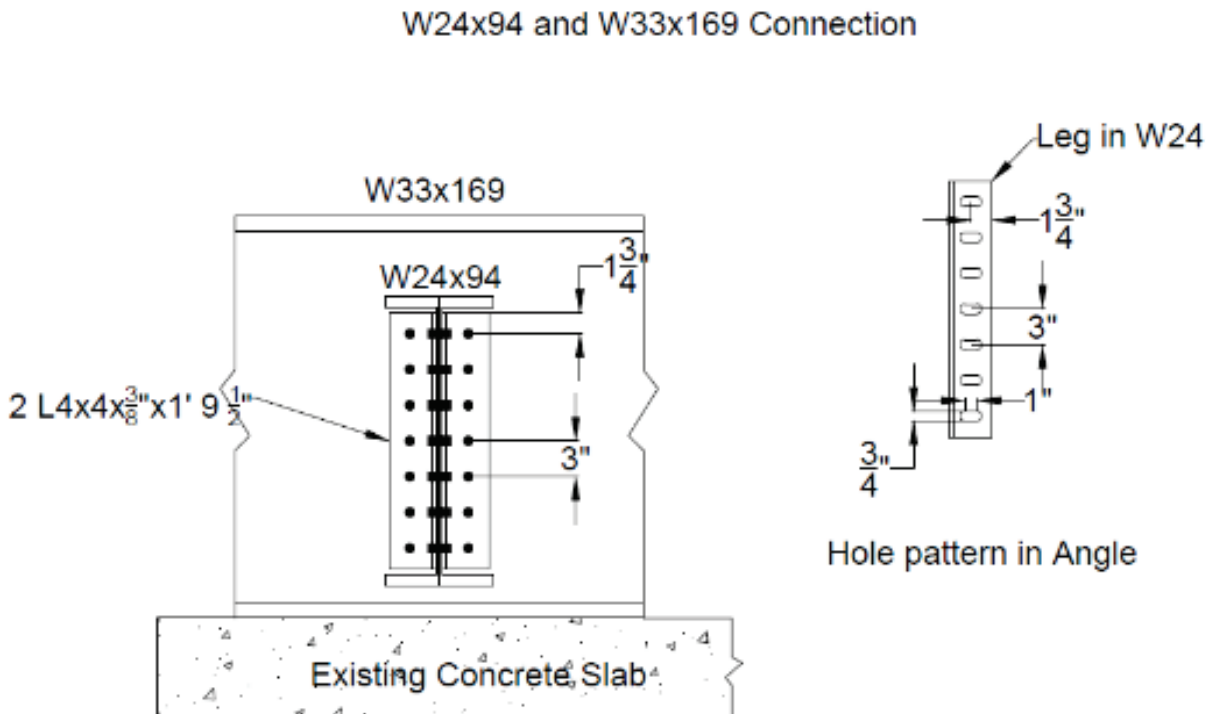
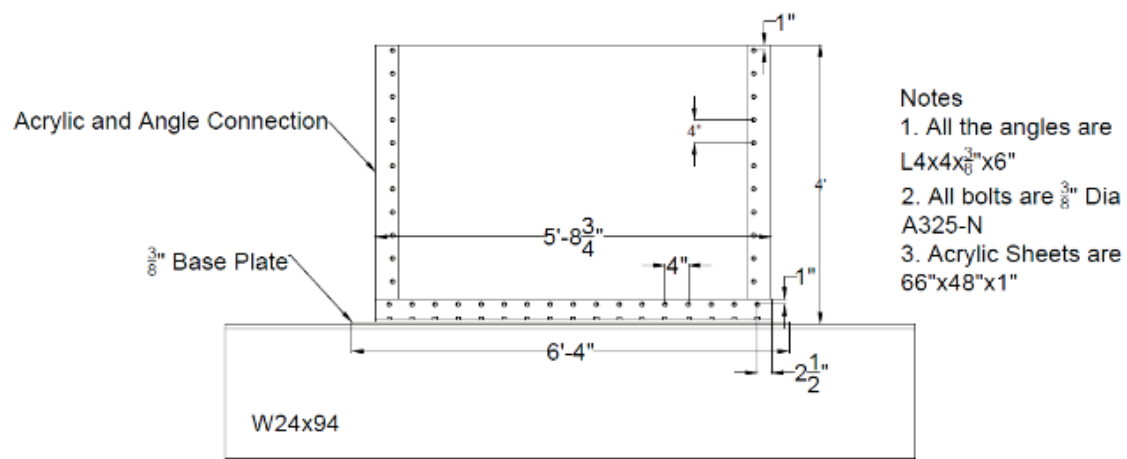


Figure B10. Bottom W24 x 94 beam and acrylic tank connections.



Appendix C: Calculations for Paris' Law Constants for Specimen 1

British Standards (BS 7910:1999) give an equation for ΔK for CCT as follows:

$$\Delta K = Y \Delta \sigma \sqrt{\pi a} \quad C1$$

And

$$Y \Delta \sigma = M \times F_W \times M_m \times \sigma_{max} \quad C2$$

Where for through-thickness center crack,

$$M = M_m = 1 \text{ and}$$

$$F_w = \left(\sec \frac{\pi a}{W} \right)^{0.5} \text{ here } W \text{ is the width of the plate (1 m)}$$

Paris law is only applicable to cracks obeying linear elastic fracture mechanics laws. Crack showed stable propagation until 250 mm. The first few data points were neglected as the tensile residual stresses from the tack welds are affecting this data.

A da/dN versus ΔK scatter was generated for both half-crack lengths and linear trendlines along with their equations were obtained for this scatter. As mentioned before, Paris' law constant C is the y-intercept of these linear trendlines and m is the slope.

Sample calculations for this study are tabulated in Table C1.

Table C1. Sample calculations for ΔK for west half crack length of specimen 1.

$\Delta \sigma$ (MPa)	Number of cycles 'N'	Change in number of cycles 'dN'	Half crack length 'a' (m)	Change in half crack length 'da'	da/dN	F_w	ΔK (MPa $m^{1/2}$)
55.15	146623	-	0.0908	-	-		
55.15	181118	34495	0.0938	0.003	8.6969×10^{-8}	1.022	30.61036672

List of Abbreviations

ΔK_{eff} = Effective range of stress intensity factors

ΔK_{th} = Change in Stress intensity factor Threshold

ΔK = Range of stress intensity factor

a = Half the crack length

C = Material constants

da = Change in crack length

dN = Change in Number of Cycles

E = Modulus of Elasticity

F_c = Crack shape factor

F_g = Non-uniform stress factor

F_s = Crack surface factor

F_w = Finite width factor

G = Energy Release Rate

K = Stress intensity factor

K_c = Fracture Toughness

K_{max} = Maximum Stress Intensity Factor

K_R = Residual stress intensity factor

m = Material constants

N = Number of cycles

N_T = total number of cycles

R = Minimum load to maximum load ratio

R^{eff} = Effective stress ratio

R_y = Extent of yield zone

y = Wheeler shape factor

Z_{OL} = Overload plastic zone size

γ_W = Walker's Parameter

ΔK_i = stress intensity factor range for i^{th} cycle

ΔK_{rms} = Root mean square value of stress intensity factor range

σ = Nominal stress

σ_{max} = Maximum Nominal Stress

σ_{min} = Minimum Nomi

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14. ABSTRACT Steel hydraulic structures (SHS) are deteriorating day by day whether it is from corrosion due to harsh environmental conditions or because of the fatigue cracks developed in the components due to daily wear. Repairing these fatigue cracks is not only time consuming but also expensive with available repair methods. Recent advances with the use of carbon fiber reinforced polymers (CFRP) to retrofit structures has proven helpful to increase the fatigue life of structures made of different types of metals. Although a large number of studies have been conducted for structures retrofitted with CFRP, very few have been conducted for underwater metal structures. The purpose of this experimental study is to evaluate the fatigue crack growth in SHS retrofitted with CFRP. Four specimens were tested with different types of CFRP and adhesive with different environmental conditions. The main focus is on the crack growth rate. As the river waters contain fluvial sediments as well as salt, the effect of both of these factors are taken into account. The results showed the increase in fatigue life with the use of CFRP but the effect of fluvial sediments and salts showed accelerated fatigue crack growth.					
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