Welcome to the Monthly Webinar on

Innovative Bridge Technologies / Accelerated Bridge Construction

Condition Assessment of In-Service Bridge Cables Using the Innovative BTC Method

Sponsored by

Innovative Bridge Technologies / Accelerated Bridge Construction - University Transportation Center (IBT/ABC-UTC) at Florida International University

FIU | FLORIDA INTERNATIONAL UNIVERSITY

Website: abc-utc.fiu.edu
Email: abc@fiu.edu

BRIDGE TECHNOLOGY CONSULTING

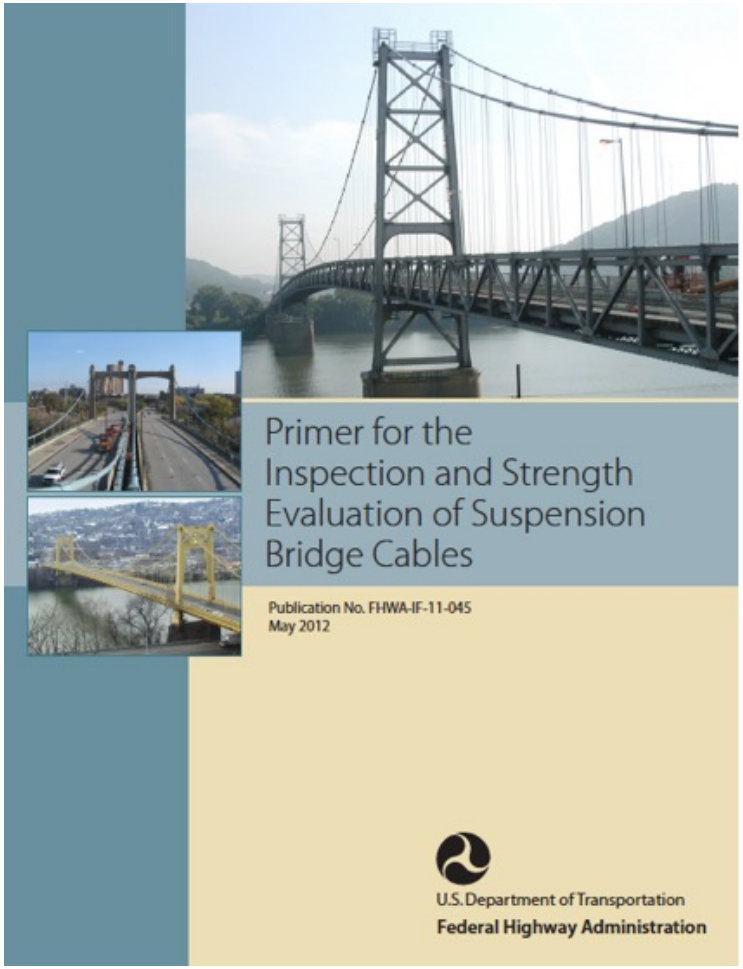
May 16, 2024 – 1:00 p.m. to 2:15 p.m. Eastern

ABC UTC IBT

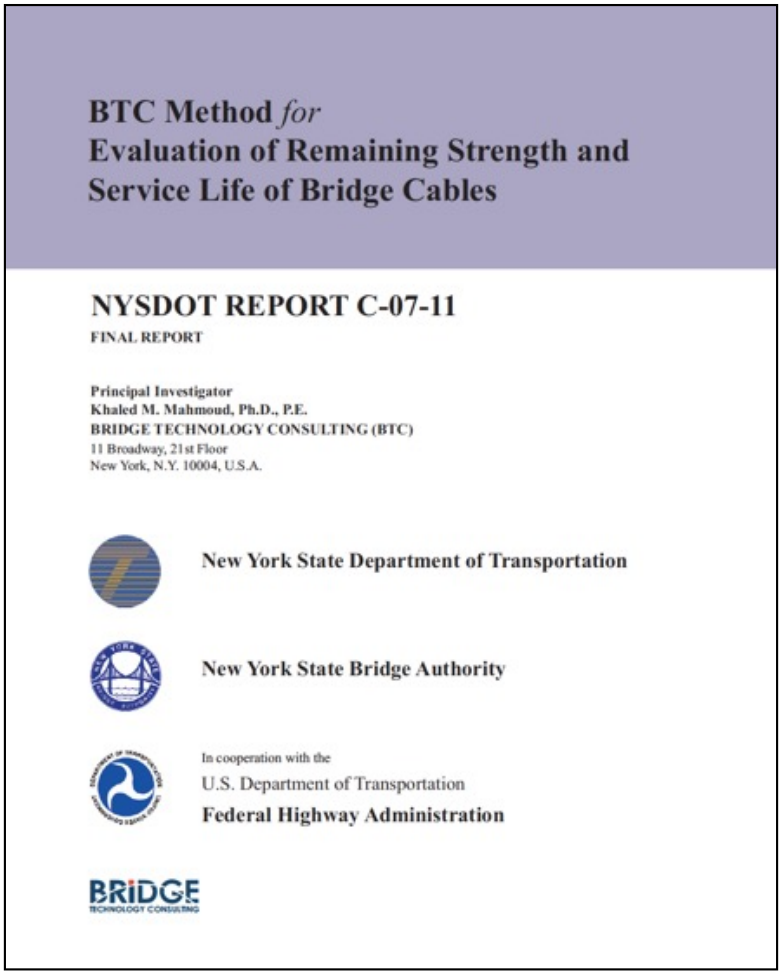
Outline

- Why inspect bridge cables?
- Methods of strength evaluation of bridge cables:
  - BTC method
  - NCHRP 534 - Visual corrosion-based approach – 2004
  - NCHRP 12-115 (Web ONLY Document NCHRP 353), October 2022
- Risk Matrix considered in the BTC method
- Inspection, Sampling & Wire Tests for the BTC method
- Inputs for Cable Strength Evaluation per the BTC method
  - Broken Wires
  - Cracked Wires
  - Mechanical Properties of Wire Samples
  - Inclusion of Ultimate Strength & Ultimate Strain Data
- Forecast of Cable Life per the BTC method
- Conclusions

BTC Method for Evaluation of Cable Strength



BTC Method for Evaluation of Cable Strength



BTC Method *for*
Evaluation of Remaining Strength and
Service Life of Bridge Cables

NYSDOT REPORT C-07-11

FINAL REPORT

Principal Investigator
Khaled M. Mahmoud, Ph.D., P.E.
BRIDGE TECHNOLOGY CONSULTING (BTC)
11 Broadway, 21st Floor
New York, N.Y. 10004, U.S.A.

New York State Department of Transportation

New York State Bridge Authority

In cooperation with the
U.S. Department of Transportation
Federal Highway Administration

BRIDGE
TECHNOLOGY CONSULTING

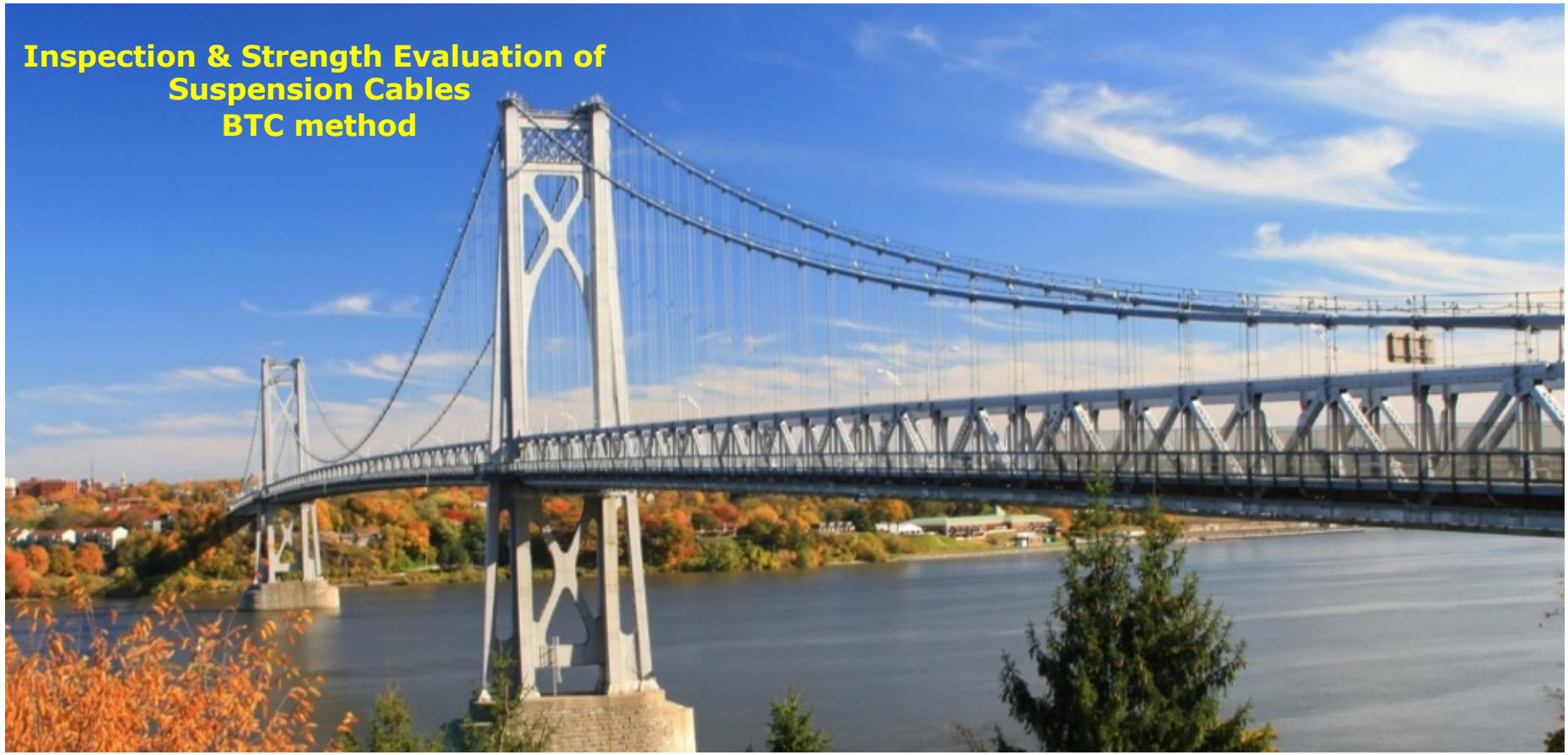
Williamsburg Bridge, New York City

Pierre-Laporte Bridge, Quebec City, Canada

Forth Road Bridge, Edinburgh, Scotland

Bronx-Whitestone Bridge, New York City

Mid-Hudson Bridge, Poughkeepsie, New York



Yavuz Selim (3rd Bosphorus) Bridge İstanbul, Turkey

1915 Çanakkale Bridge, Çanakkale, Turkey

Why Inspect Bridge Cables?

Risk Matrix considered in the BTC method

Risk Factors for Degradation of Bridge Cable Wire:

- **Fatigue Damage coupled with Environmental Degradation**
- **Embrittlement of Wire (reduction in ultimate elongation)**
- **Growth of Cracks**
- **Breakage of Wires**

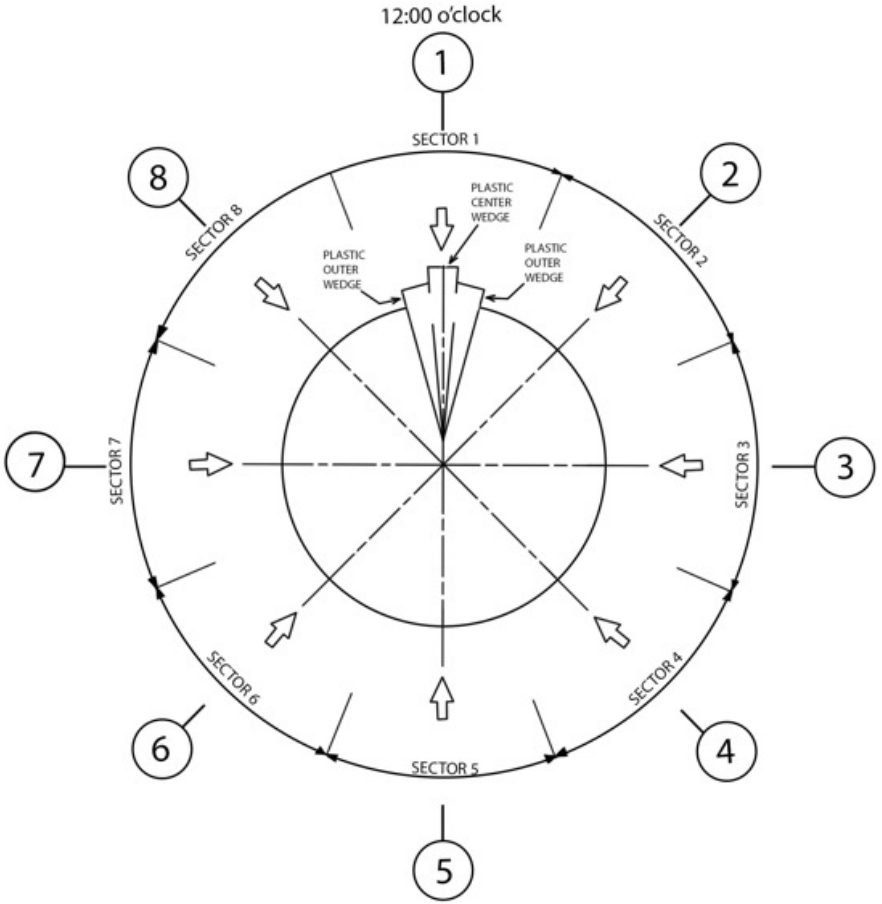
All these Factors of Risk are at play under the combined effect of loads and the environment.

BTC method Process

- Cable Wedging & Inspection
- Wire Sampling
- Wire Tests
- Evaluation of Cable Strength (Based on Inspection Findings & Analysis of Test Data)
- Forecast of Cable Life

Inspection of Wedged Suspension Cables

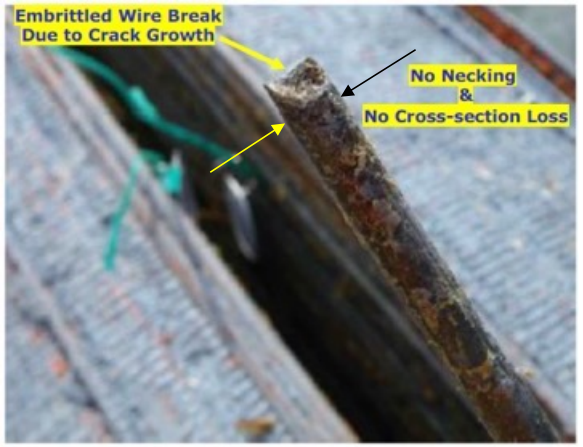
Wedge Pattern for Inspection



Wedged Suspension Cable – Interior Broken Wires

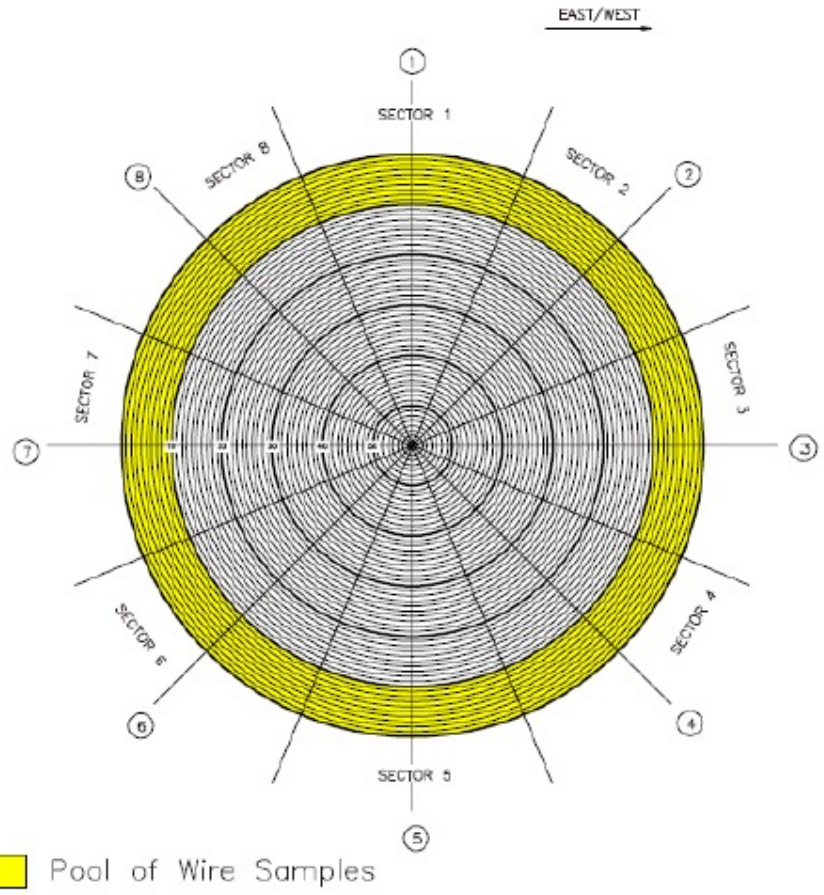
Embrittled Broken Wires

Wedged Suspension Cable – Interior Broken Wires



Embrittled Broken Wire

Wire Sampling – BTC method

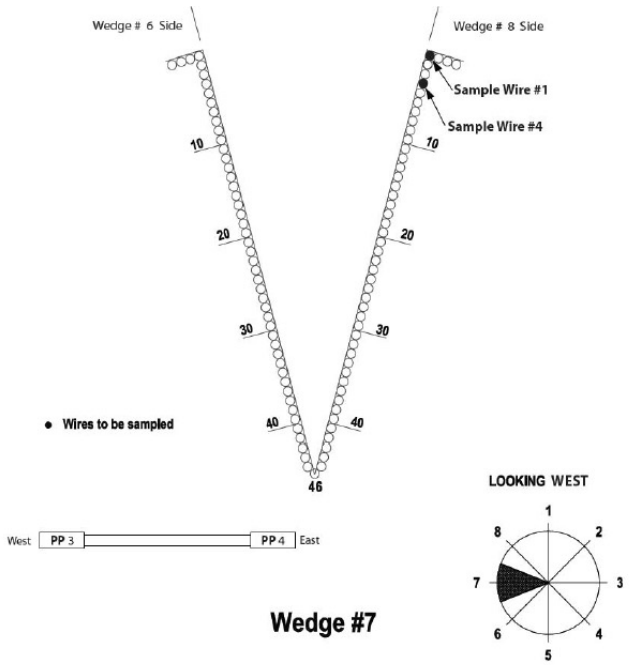


Ref.: NYSDOT Report C-07-11, BTC Method for Evaluation of Remaining Strength and Service Life of Bridge Cables, 2011.

Wire Sampling – BTC method

Bridge Name:	Nice Bridge	Prepared by:	K. Mahmoud
South Cable	West Side Span	Date of Sampling:	
Panel Opening	3-4	Weather Condition:	Sunny, 76°F

RANDOM SAMPLE OF WIRES FROM WEDGE # 7



Ref.: NYSDOT Report C-07-11, BTC Method for Evaluation of Remaining Strength and Service Life of Bridge Cables, 2011.

Replacement of Wire Samples

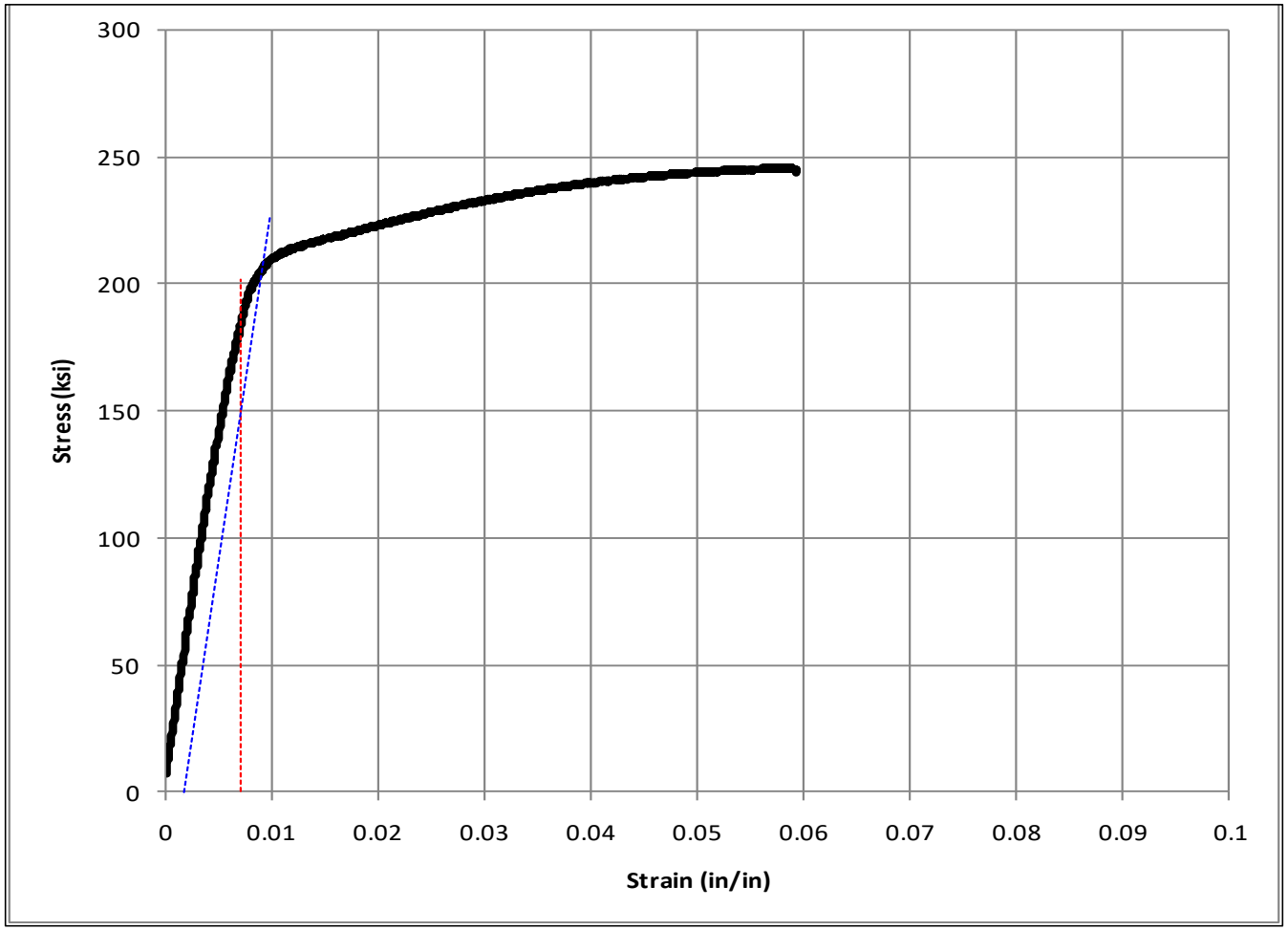
Replacement of Wire Samples

Replacement of Wire Samples

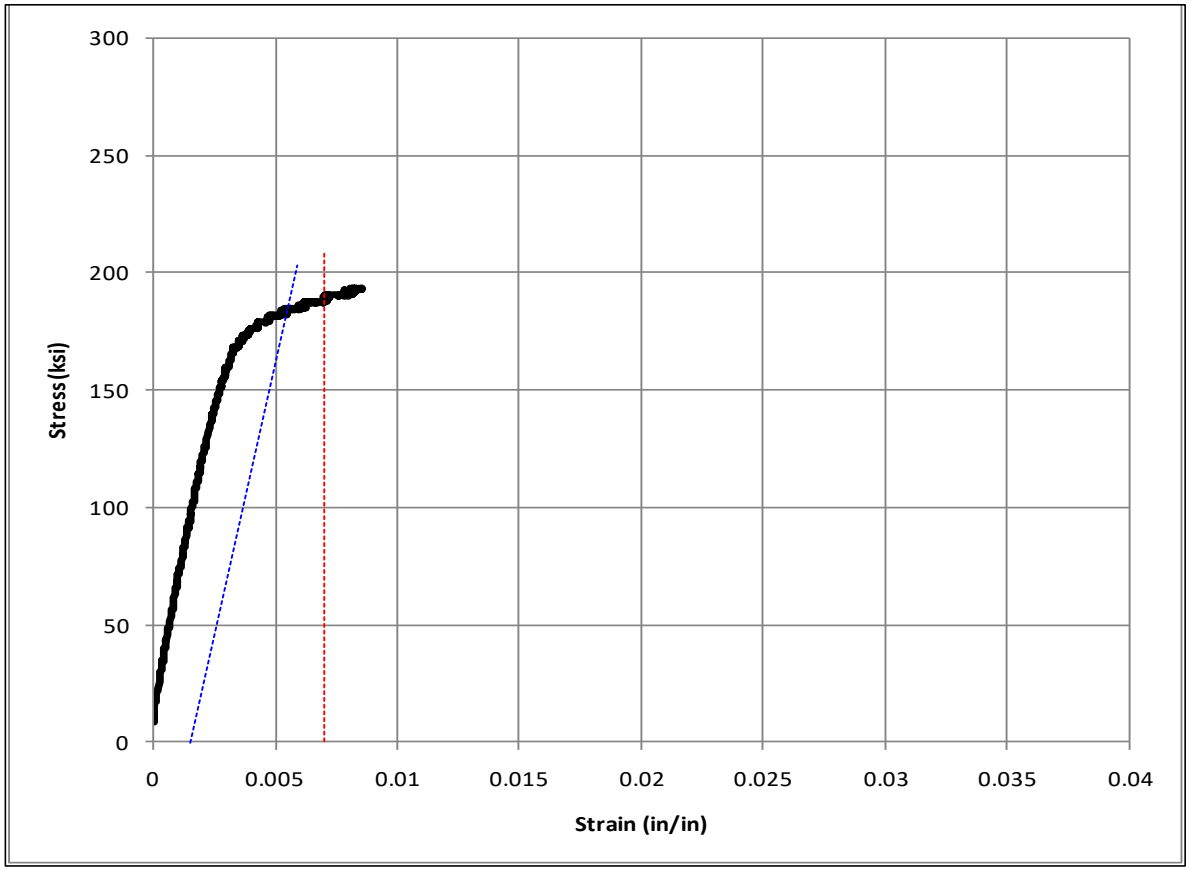
Wire Tests for the BTC method

- **Tension Test**
- **Fatigue Test**
- **Fractographic Examination of Fracture Surfaces via Scanning Electron Microscope (SEM)**
- **Hydrogen Content Test (ppm)**

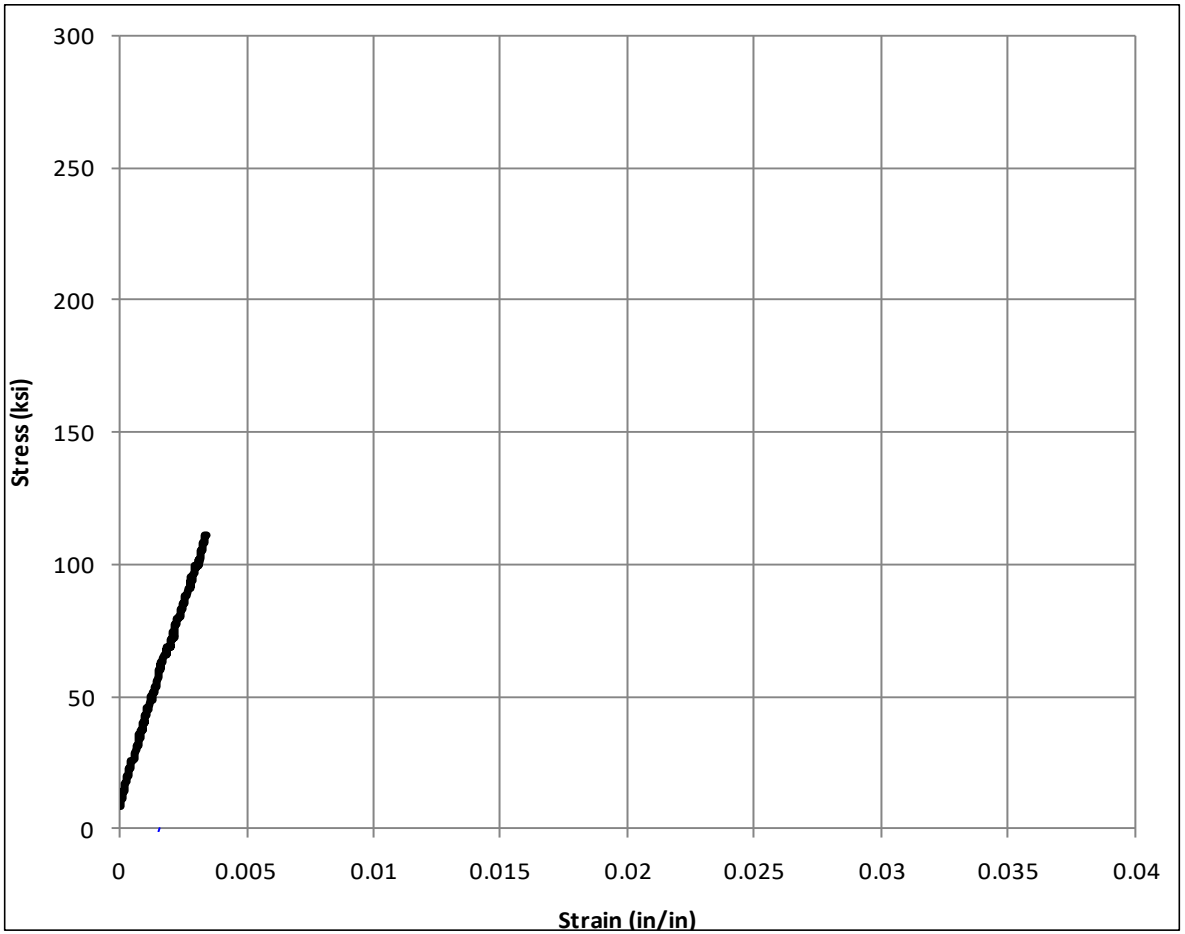
Tensile Test – Typical New Wire



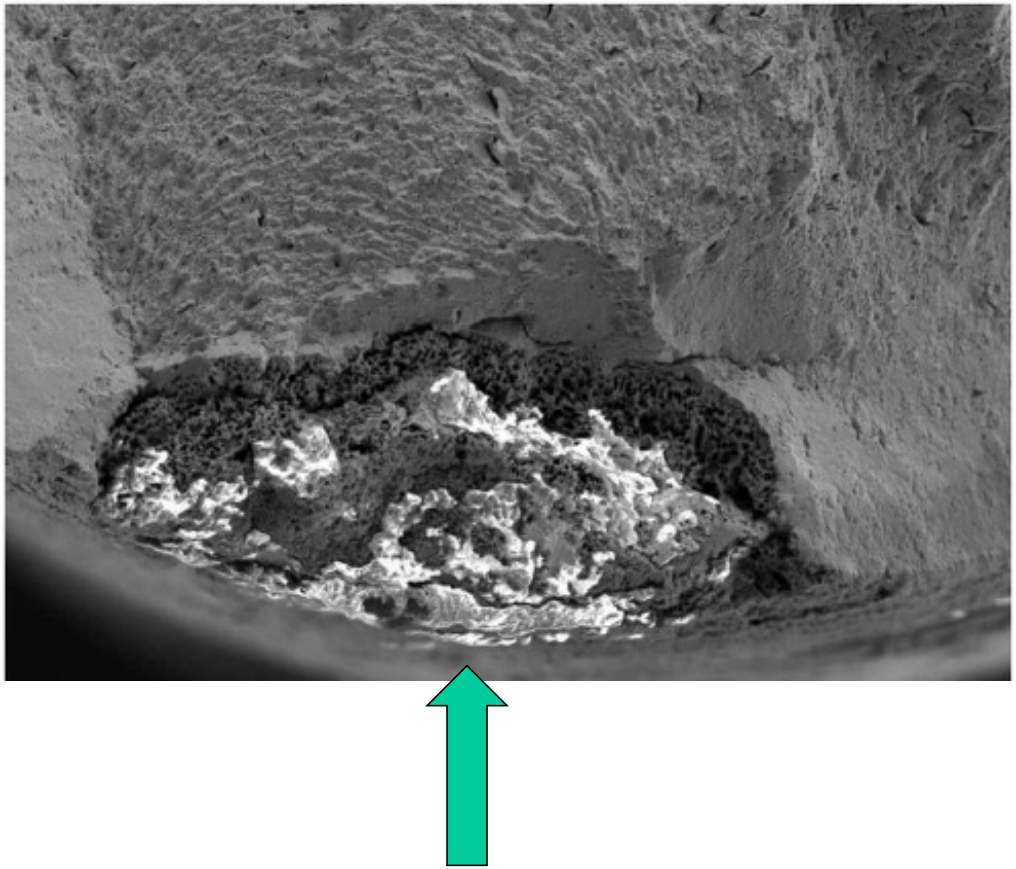
Tensile Test – Degraded Embrittled Wire



Tensile Test – Degraded Embrittled Wire



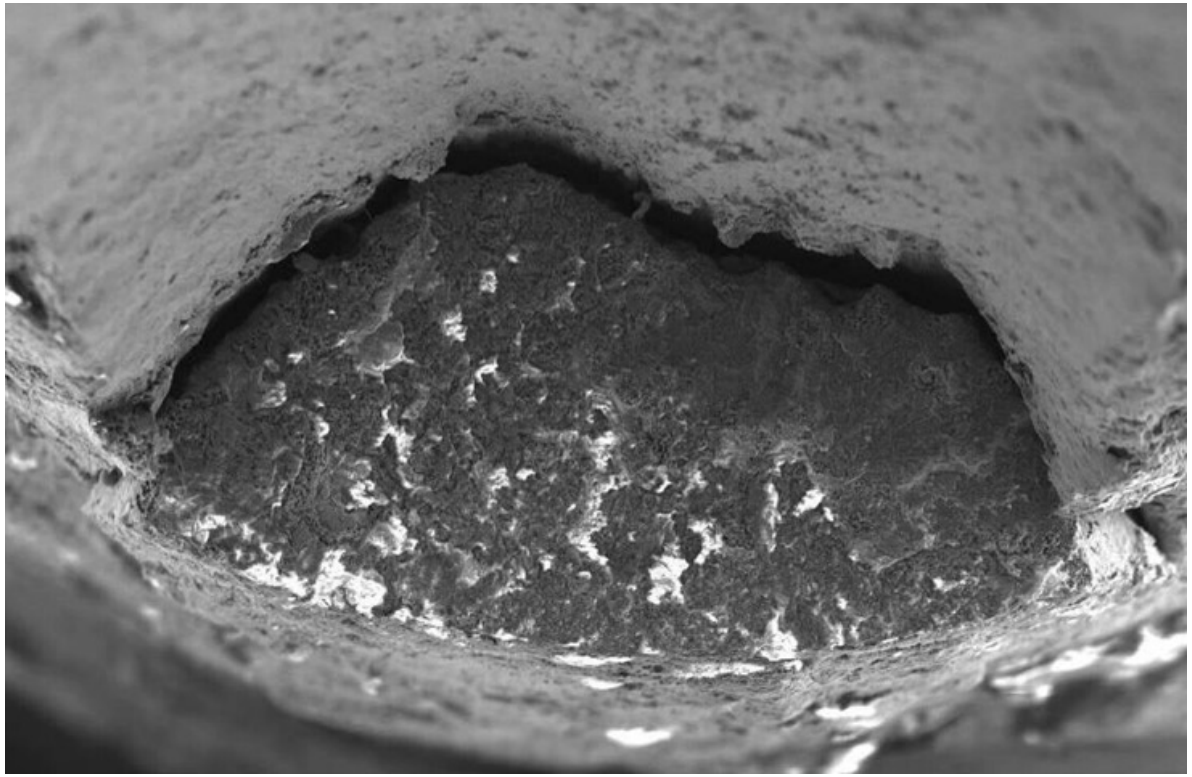
Fractographic Examination-Preexisting Cracks



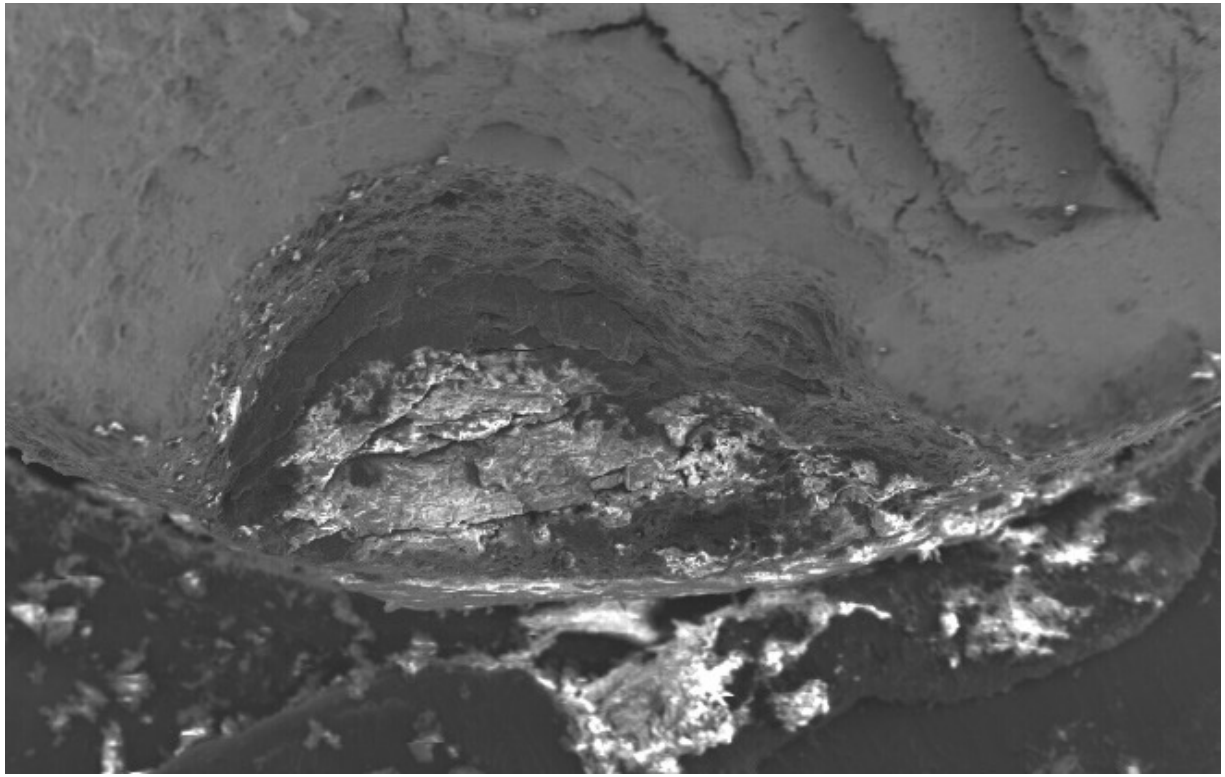
Preexisting Crack

Fractographic Examination-Preexisting Cracks

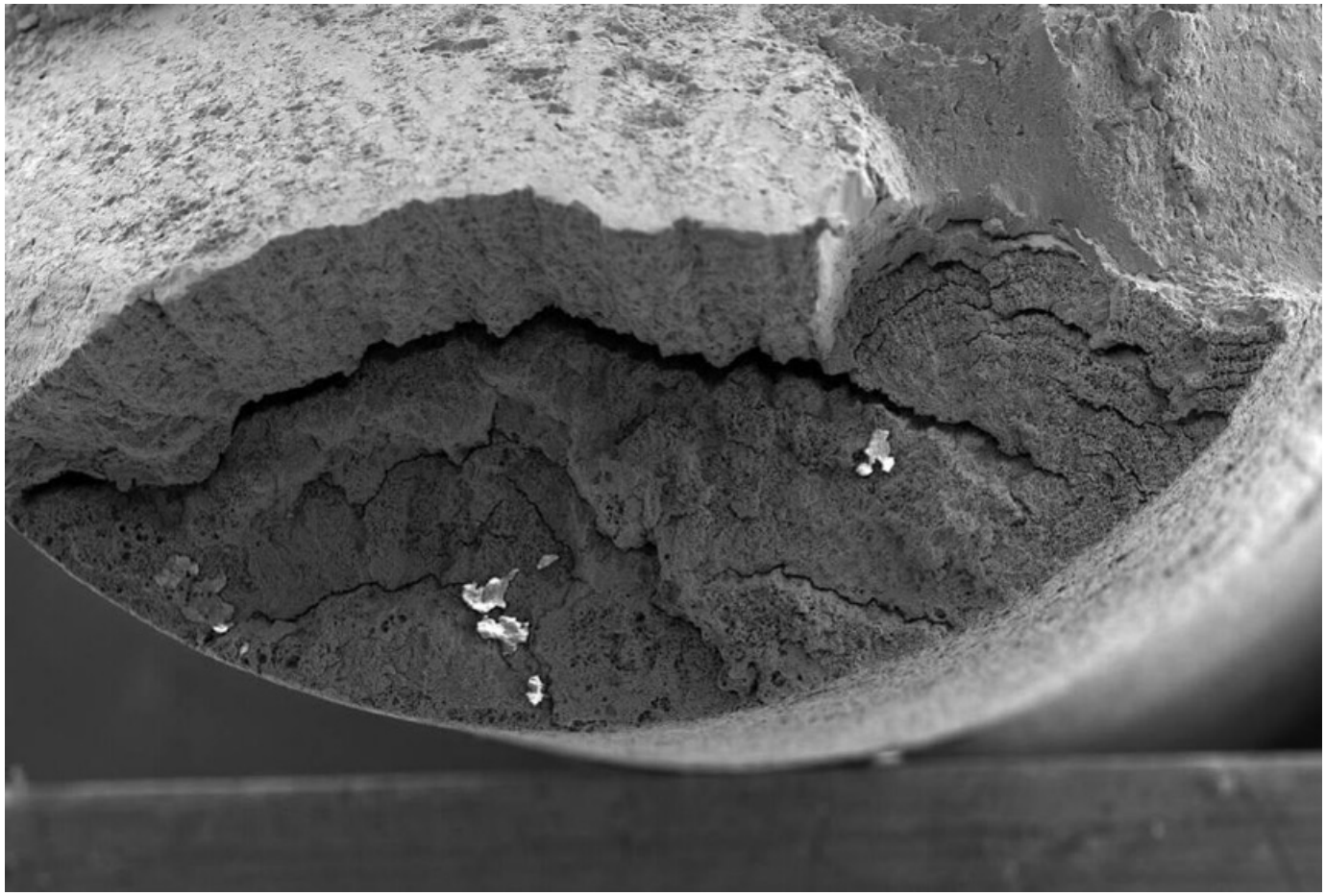
Fractographic Examination-Preexisting Cracks



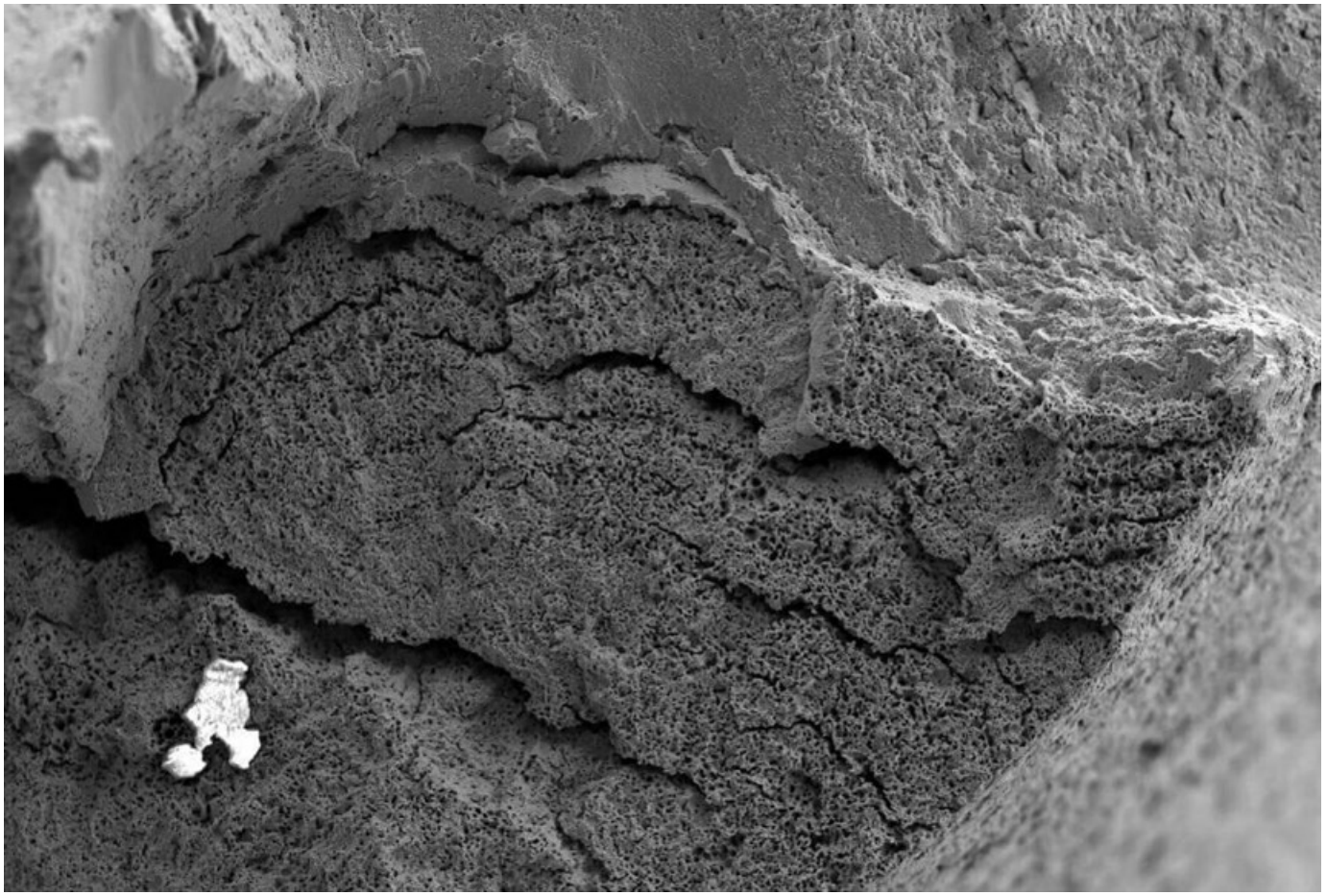
Fractographic Examination-Preexisting Cracks



Fatigue Damage in Fracture Surface of Wire



Fatigue Damage in Fracture Surface of Wire

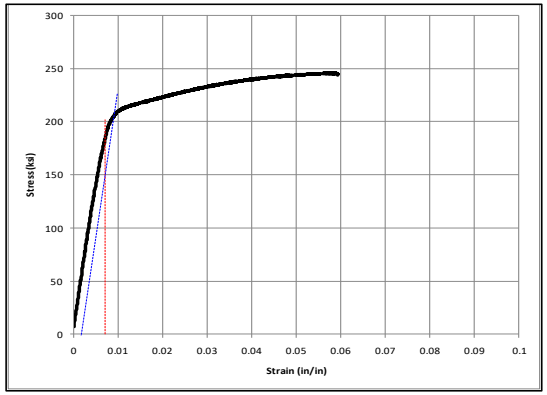


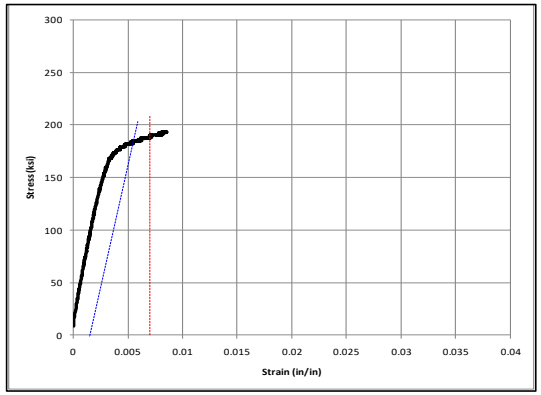
Hydrogen Embrittlement of Cable Wire

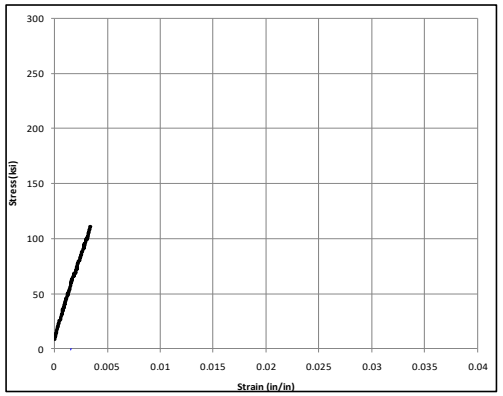
Heavy corrosion and rusted thru holes in the web

Cracked, embrittled wire, without necking or section loss

Reduction in Ultimate Elongation (Embrittlement)







Inspection of Wedged Suspension Cables

Fracture-based Analysis of Cracked Wires per the BTC method

- For a cracked wire, Fracture Mechanics analysis refers to establishing a quantitative relation between the crack depth, the material's inherent resistance to crack growth, and the stress at which the crack propagates at high speed to cause failure of the wire.

$$\sigma_{cracked} = \frac{K_c}{Y(\frac{a}{D})\sqrt{\pi a_c}}$$

BTC method

$K_{c,}$ = fracture toughness of the wire determined from test data,

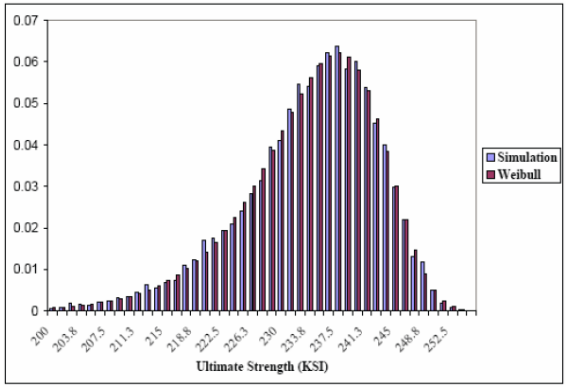
a_c = critical crack depth measured in specimens with preexisting cracks, and

$Y(\frac{a}{D})$ = crack geometry factor

Steps for Evaluation of Cable Strength-BTC method

The BTC method utilizes the following inputs to estimate cable strength:

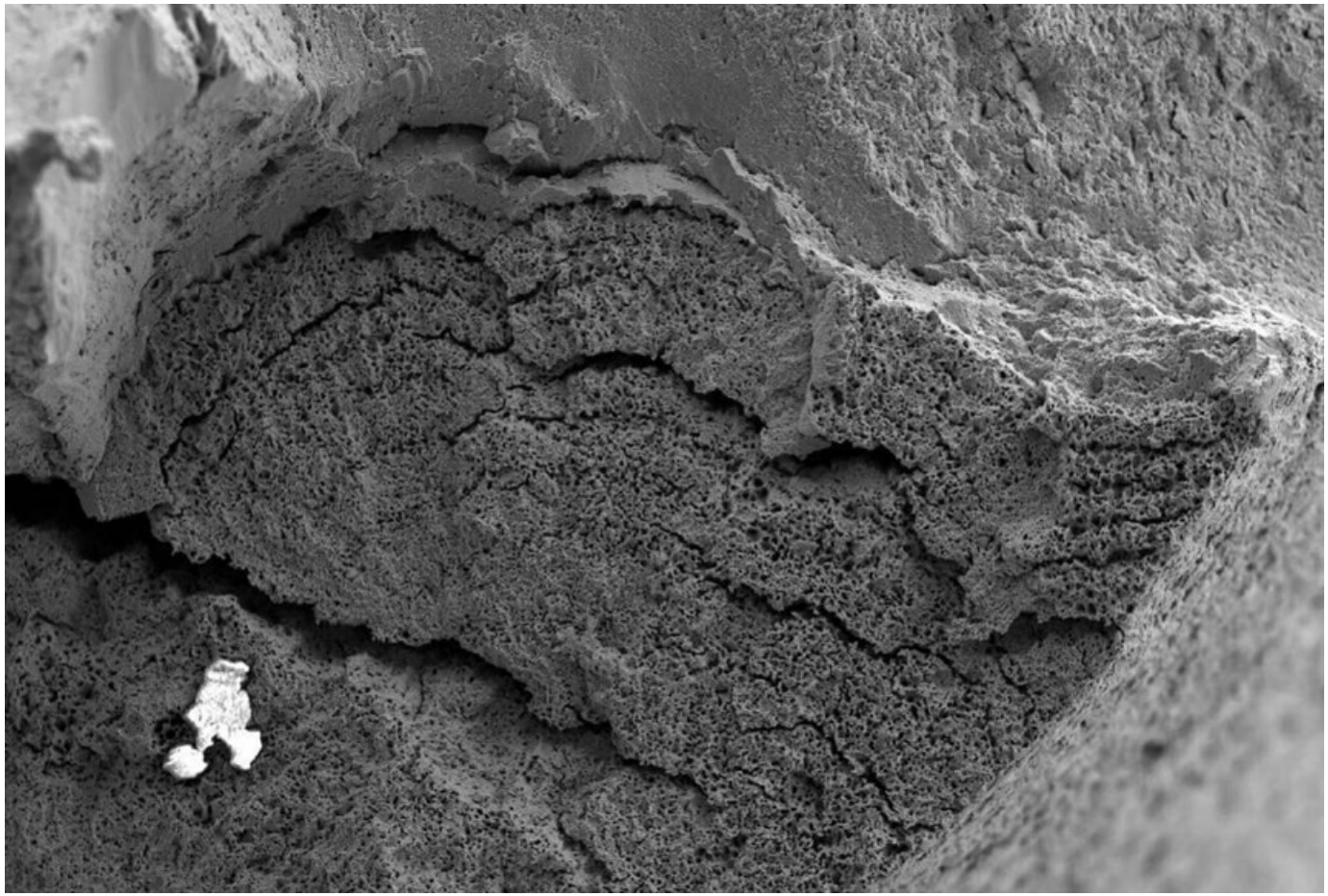
- Wire Properties are described with appropriate Probability Distributions.
- Probability of Broken wires
- Probability of cracked wires
- Utilizing Monte Carlo simulation, and probability distributions of mechanical properties, a failure mechanism of the cable is developed.



Probability Distribution for ultimate strength

- The load carrying capacity for the cable reaches zero at maximum elongation.
- The estimated cable strength is the maximum load calculated.

Crack Growth under Fatigue Loading

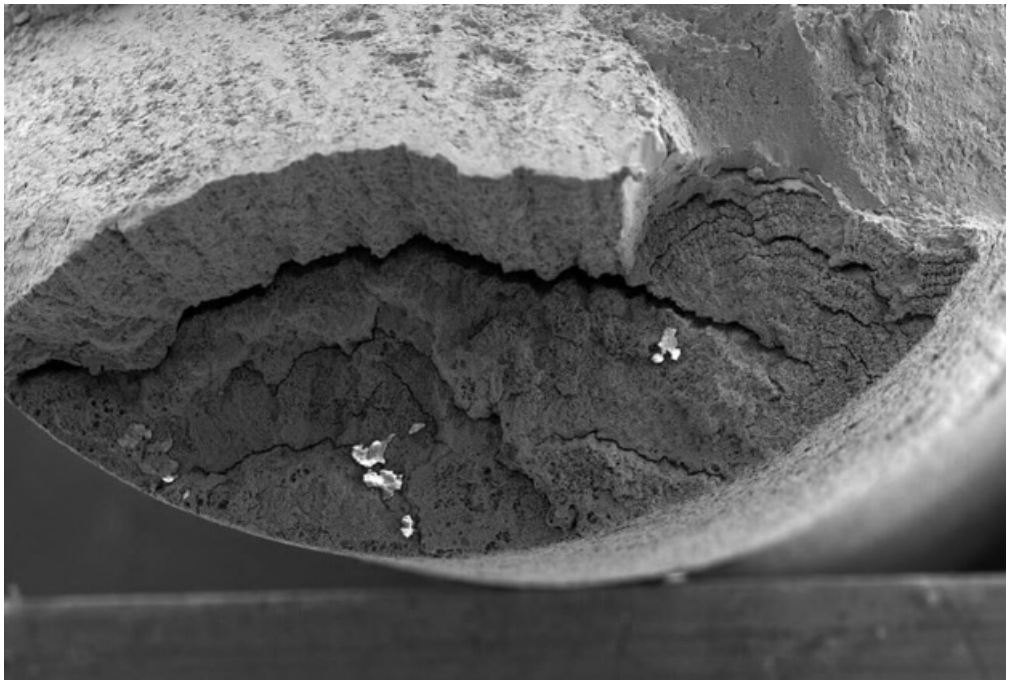


Forecast of Cable Strength-BTC method

- Wire deterioration progresses via crack growth.
- Crack growth takes place due to application of Live Load.
- Until Crack reaches critical crack depth, a_c, leading to wire fracture, Paris Law.

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

$$\Delta K = \mathrm{f}\ (\Delta\sigma, \mathrm{a}, \mathrm{Y})$$



C & m are Paris law constants, $\Delta\sigma$ is live load stress range, a is crack depth and Y is crack shape parameter.

Discussion on Risk of missing Wire Cracks

The cracked wire shown in Figure (a) displays, very clearly, beach marks which articulate the fatigue damage in the fracture surface. Figure (b) shows a cracked beam from bottom flange through full height of web.

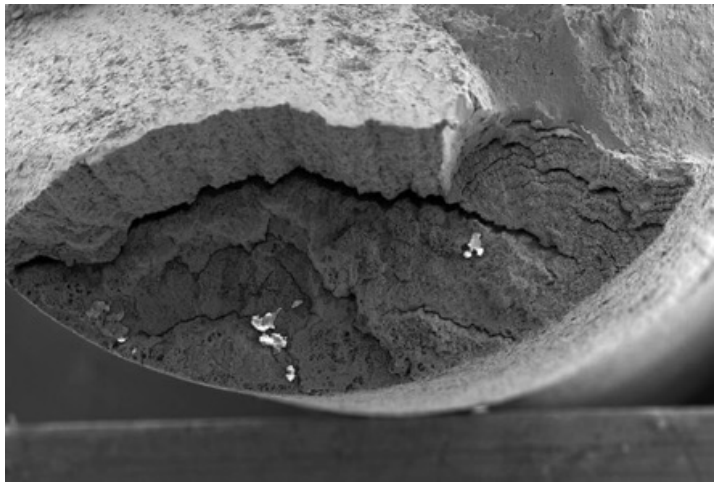


Figure (a). Cracked wire displaying fatigue beach marks

Figure (b). Cracked beam from bottom flange through full height of web

Would it be acceptable to just be concerned with only the bending capacity of the cracked beam in Figure (b), without consideration of the crack? This would defy every tenet of engineering mechanics, let alone structural common sense.

Interstate 40 bridge linking Arkansas and Tennessee

Interstate 40 bridge linking Arkansas and Tennessee

Crack in a Coped Beam

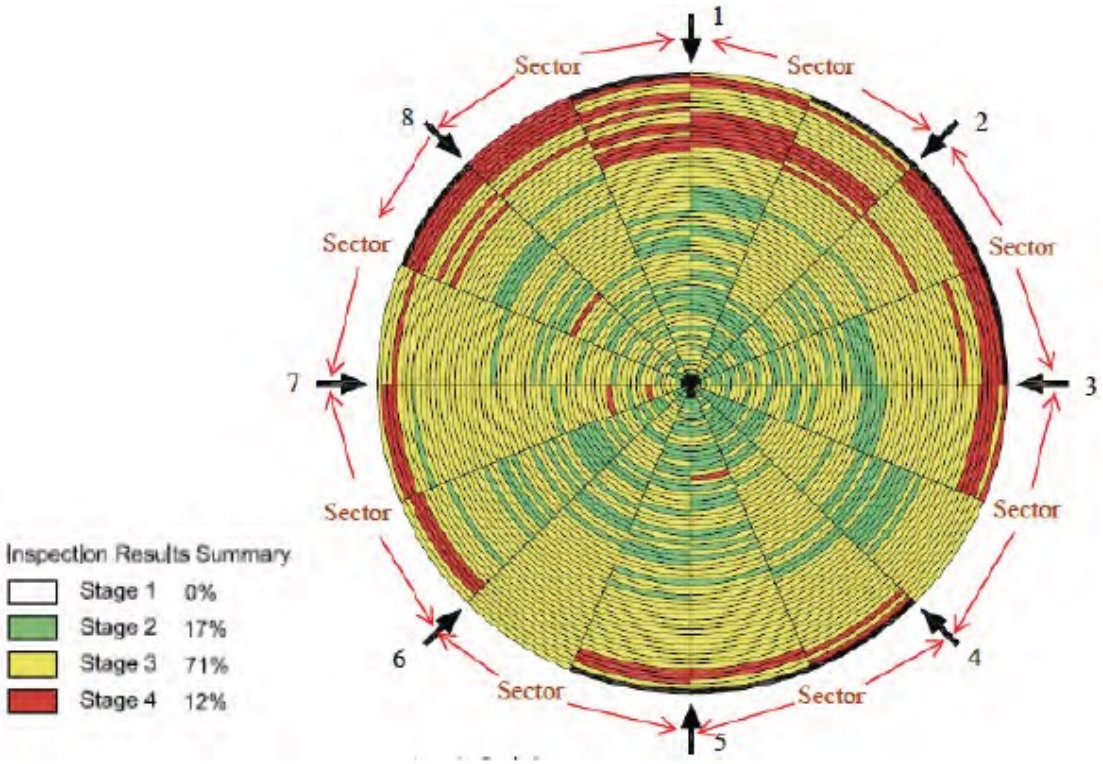
Visual Corrosion - NCHRP

- Stage 1: the zinc coating of wires is oxidized to form zinc hydroxide, known as “white rust”.
- Stage 2: the wire cross-section is completely covered by white rust, resulting from zinc oxidation.
- Stage 3: appearance of a small amount of (20-30% of wire surface area) of ferrous corrosion.
- Stage 4: the wire cross-section is completely covered with ferrous corrosion.

Footnote: The BTC method does not utilize the visual stages of corrosion, which are showed only to point out discrepancy between these visual stages of corrosion and measured mechanical properties.

Ref.: NCHRP 534, Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables, 2004.

Cable Wedging & Inspection



NCHRP
Visual-Corrosion Approach

Footnote: The BTC method does not utilize the visual stages of corrosion, which are shown only to point out discrepancy between these visual stages of corrosion and measured mechanical properties.

Ref.: NCHRP 534, Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables, 2004.

Visual Evaluation of Stages of Corrosion vs Measured Mechanical Properties

Corrosion Stage	Avg. Ult. Strength (ksi)	Avg. Ult. Strain (%)
Stage 2	223.2	4.44
Stage 3	238.3	4.96
Stage 4	245.6	5.41

(1) Mechanical Properties are taken from Testing Laboratory Test Results, while the Stages of Corrosion are assigned by inspectors utilizing NCHRP 534 Guidelines.
(2) The noted discrepancy between the visual evaluation of stages and corrosion and measured mechanical properties is for the entire set of wire samples taken from the panel opening.
(3) This noted discrepancy is noted for all eight (8) investigated panels, for the case study bridge, as detailed in NYSDOT Report C-07-11, referenced below.
(4) The BTC method does not utilize the visual stages of corrosion, which are shown only to point out the noted discrepancy between the visual stages of corrosion and measured mechanical properties.

Ref.: NYSDOT Report C-07-11, BTC Method for Evaluation of Remaining Strength and Service Life of Bridge Cables, 2011.

Study between Corrosion Level & Fatigue Strength

Summary of Conclusions

- In the specimens obtained from the corrosion levels set in this study, fatigue strength showed results that were equivalent to or higher than those of new wires. The tensile strength also showed similar results. Therefore, it is consid-

Bridge Structures 19 (2023) 79–90
DOI 10.3233/BIRS-230214
IOS Press

Correlation between corrosion level and fatigue strength of high-strength galvanized steel wires used for suspension bridge cables

Kazuhiro Miyachi*, Shoya Saimoto and Yusuke Oki
Division of Architectural, Civil and Environmental Engineering, Tokyo Denki University, Saitama, Japan

Abstract. This study investigated the relationship between "rust color distribution ratio," "corrosion surface shape," and "fatigue strength" of high-strength galvanized steel wires used in cable supported bridges. The study utilized a digital image color analysis system to classify the rust color distribution rate and categorize corrosion levels based on the distribution ratio. The relationship between cross-sectional loss rate and corrosion depth tendency was visually and quantitatively comprehended from the categorized corrosion levels. The study found that fatigue and tensile strengths of the specimens from the corrosion levels set in this study were equivalent to or higher than those of new wires. However, the possibility of variations due to the small number of specimens or insufficient corrosion progress cannot be ruled out.

Keywords: Bridge cables, cable supported bridges, corroded wires, corrosion evaluation criteria

1. Introduction

In cable supported bridges such as suspension bridges and cable-stayed bridges, cables serve as life-lines and are the most important structural elements. Bridge cables consist of numerous high-strength steel wires but have a weakness that is susceptible to corrosion. Therefore, usually, galvanization is applied to the steel wires to improve their corrosion resistance. However, cables are often exposed to harsh corrosion environments, and many cases of corrosion, breakage, and even bridge collapses have been reported all over the world [1] through [8]. Preventative maintenance for corrosion and breakage of suspension-type bridge cables is essential, but effective measures have not yet been established, and it is necessary to advance inspection and repair techniques to prevent impending bridge collapse accidents [8].

The purpose of this study is to clarify the potential correlation between the "rust color distribution rate," "corrosion surface shape," and "fatigue strength" of high-strength galvanized steel wires used in suspension-type bridge cables.

This study is structured as follows: In Chapter 2, the specifications and testing methods used in this study to create high-strength galvanized steel wires corroded in a laboratory environment are described. Additionally, an explanation is provided for the rust color distribution rate analysis and corrosion level evaluation conducted. Chapter 3 describes the surface shape measurement conducted and its measurement method. Chapter 4 explains the testing method for the fatigue strength testing conducted. Chapter 5 summarizes the main findings obtained in this study.

2. Rust color distribution rate

2.1. Specimen

The specimens used in the test were high-strength galvanized steel wires used for cable-stayed bridges. The specimens were high-strength galvanized steel wires (hereinafter referred to as "wire") with a diam-

*Corresponding author. Kazuhiro Miyachi, Associate Professor, Division of Architectural, Civil and Environmental Engineering, Tokyo Denki University, Saitama, Japan. E-mail: miyachi@g.dendai.ac.jp.

Ref.: Correlation between corrosion level and fatigue strength of high-strength galvanized steel wires used for suspension bridge cables, K. Miyachi, S. Saimoto and Y. Oki, *Bridge Structures*, 19 (2023) 79–90.

Lessons Learned

- **Cable-supported bridges are strategic assets with a significant value to the economy and society enabling social and business connectivity.**
- **Therefore, the assessment of residual strength and service life of bridge cables is of paramount importance.**
- **Only conducting in-depth inspection, sampling, and testing of wire samples from different openings along the cable length can provide the inputs needed for strength evaluation and forecast of the service life of the cable.**
- **A successful strategy for the preservation of bridge cables has many traits, some of which are:**
  - **Performance periodic inspection, sampling, testing and strength evaluation.**
  - **This allows the bridge owner to intervene with corrective measures to slow down degradation.**
  - **With several successive cable investigations, the forecast estimates of cable service life is more accurate.**
  - **Any suspension cable investigation must include removal of cable bands to conduct inspection under the cable bands.**
- **Experience shows that reliance only on the visual-corrosion approach could lead to unnecessary and costly measures.**

Lessons Learned

- **Cables are the most critical elements of a of cable-supported bridge. Therefore, it would be sensible and logical to use a condition assessment method that provides confidence and reliable results regarding the strength evaluation and forecast of service life.**
- **With vast expertise and successful applications on numerous major cable-supported bridges around the world, the BTC method presents a reliable alternative methodology and independent checking mechanism rather than just relying on the NCHRP visual corrosion-based approach alone.**
- **This would provide owners with greater assurances when dealing with decisions they may face regarding the results of an internal inspection and strength evaluation of the bridge cables.**
- **The BTC method's unique Forecast of Life capability provides unparalleled feature that provides the bridge owner with preservation strategies and measures to prolong the service life of the cable.**
- **Further, with BTC's thorough knowledge of the high strength steel material of bridge cables, the BTC method contributes to the development of Project Specifications, as was done on new major cable-supported bridges, to delay wire degradation and prolong the cable life.**

Conclusions

- **The BTC method has been applied to evaluate the strength and forecast the service life of main suspension cables on the Bronx-Whitestone Bridge, Mid-Hudson Bridge and Williamsburg Bridge in the state of New York, Forth Road Bridge in Scotland, and the Pierre-Laporte Bridge in Canada.**
- **On the Pierre-Laporte Bridge, the BTC method has been applied to evaluate the strength and forecast service life of the main cables, provide condition assessment and forecast service life of suspender ropes, prioritize the replacement of entire set of suspender ropes.**
- **Wire cracking is a major driver of cable strength degradation. Therefore, application of principles of fracture mechanics is essential for accurate assessment of cable strength and remaining service life.**
- **Fractographic Examination is therefore, a crucial step for identification of preexisting cracks.**

Conclusions

- **The BTC method is the ONLY methodology that provides:**
  - **Identification of cracks via Fractographic Examination**
  - **Fracture-based analysis of cracked wires using Fracture Mechanics**
  - **Forecast of Cable Life**
  - **Strength Evaluation and condition assessment of Parallel & Helical Wire Strand Cables**
- **The BTC method provides condition assessment of suspension cables, stay cables of cable-stayed bridges and prestressing steel strands of prestressed and segmental bridges, including forecast of service life.**
- **The BTC method presents an overall risk management strategy to estimate the cable strength at high level of confidence.**

For questions, contact:
Khaled Mahmoud
Khaled@kmbtc.com
Tel: +1-917-371-4601
For more details on application of the BTC method, visit:
www.kmbtc.com

Thank you!

Condition Assessment of In-Service Bridge Cables Using the Innovative BTC Method

May 16, 2024

BRIDGE TECHNOLOGY CONSULTING