Investigating the Long-Term Durability of CFRP Repairs for Bridges Under Environmental Conditions

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16 Abstract

Carbon fiber-reinforced polymers (CFRP) have been widely used for bridge repair and strengthening because of their high strength-to-weight ratio, corrosion resistance, and ease of installation. However, the long-term durability of CFRP repairs under harsh environmental conditions remains unclear. Accumulated damage resulting from mechanical loading and environmental degradation, such as moisture, freezing, and thermal aging, may cause unpredictable damage to the infrastructure. To address this issue, this project aims to investigate the combined effects of fatigue and environmental aging on the durability of CFRP. The project employs a range of theoretical and computational methods to explore the impact of these factors on the mechanical properties of CFRP repairs. These methods multi-scale modeling of environmentally and mechanically conditioned samples to simulate the effects of moisture and temperature changes. The project results are expected to provide valuable insights into the long- term durability of CFRP repairs, which can help ensure the safety and reliability of bridges that have been repaired with CFRP. The project outcomes may have practical implications for bridge design and maintenance as well as for the wider adoption of CFRP as a repair and strengthening material in civil infrastructure.

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Contents

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Chapter 1: Introduction and Background

1.1 Project Motivation

- The literature review focusing on environmental degradation factors affecting CFRP performance, such as freeze-thaw cycles, moisture exposure, and hygrothermal conditions, provided critical insights into durability concerns that will inform our modeling approach and guide the development of durable repair solutions for New England's aging bridge infrastructure.
- The final results of the project will facilitate the design of CFRP components and repairs by considering the weather conditions at the New England area and predict their lifetime. Moreover, it can evaluate the current practices and design specifications by New England DOTs using CFRP wraps.

1.2 Research, Objectives, and Tasks

- A literature review was conducted on environmental degradation factors affecting CFRP performance in bridge strengthening applications, including freeze-thaw cycling, moisture exposure, and hygrothermal conditions, with particular attention to implementation cases in New England's railroad and highway bridge infrastructure such as Maine's Rices Bridge underwater pile repair and Vermont's mechanically fastened FRP systems.
- Review the past practices and projects on the use of CFRP at New England DOTs.
- Collaboration with TIDC advisory committee from New England DOTs.
- Developed a constitutive model of carbon fibers embedded in epoxy CFRP to accurately predict its mechanical degradation (Figs. 3 and 4).
- Developed a preliminary computational micromechanical model of CFRP laminates using ABAQUS finite element software to accurately predict its mechanical behavior and performance degradation under tensile loading conditions (Figs. 3 and 4).

1.3 Report Overview

- The literature review focusing on environmental degradation factors affecting CFRP performance, such as freeze-thaw cycles, moisture exposure, and hygrothermal conditions, provided critical insights into durability concerns that will inform our modeling approach and guide the development of durable repair solutions for New England's aging railroad bridge infrastructure.

- The design data will be compared to a computational model of the bridge, which predicts its behavior under the same conditions. By correlating the environmental information with the computational model, engineers can better understand the actual behavior of the bridge and ensure that the model accurately reflects the bridge's true behavior. This is important for ensuring the safety and longevity of the bridge, as well as for making informed decisions about any necessary maintenance or repairs. Field data validation, design manuals, and experimental findings will be considered in this process.

- This research will provide valuable insights into the long-term durability of CFRP repairs for bridges under various environmental conditions. The results will help bridge owners make more informed decisions about repair methods, potentially leading to significant cost savings through more efficient use of resources. By improving our understanding of CFRP performance over time, this project will contribute to safer and more resilient transportation infrastructure, benefiting both the economy and public safety.

Chapter 3: Results and Discussion

3.1 Data must be included

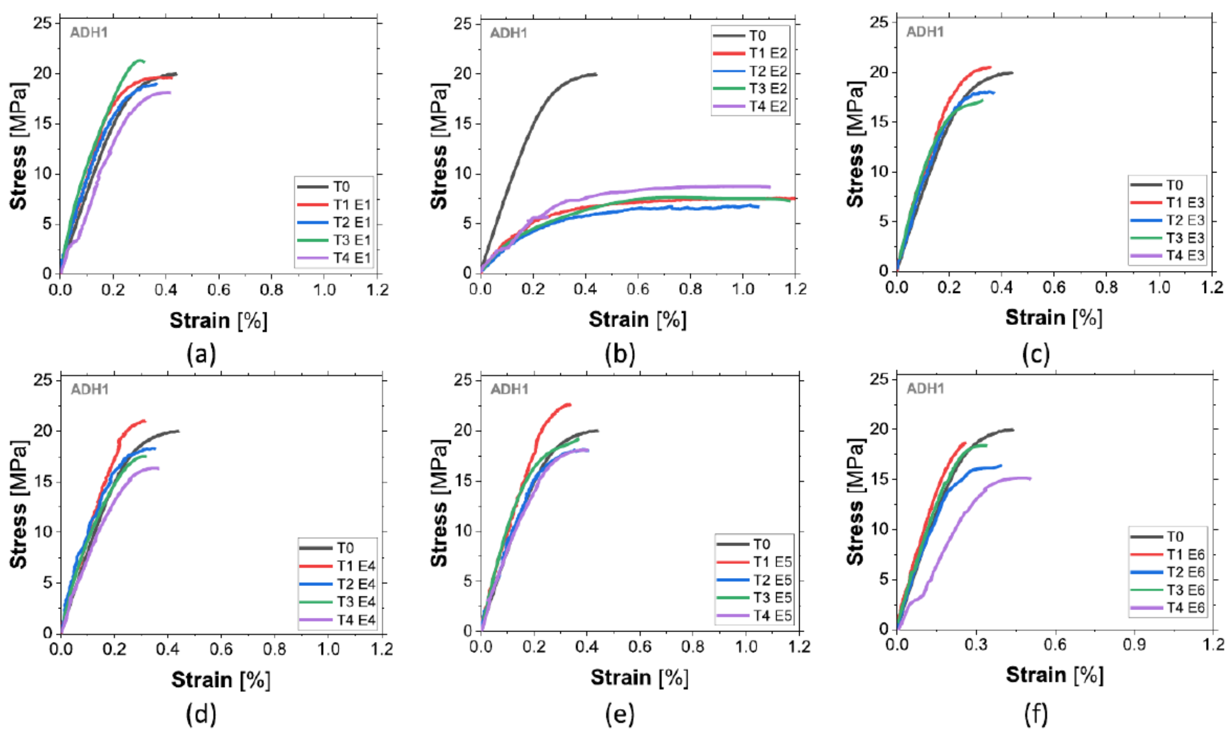

Figure 1. Stress-strain curves of epoxy adhesive dog-bone coupons under tension. Environmental Exposure Classifications: E1 (laboratory-controlled reference, 20°C, 55% RH), E2 (continuous water immersion, 20°C), E3 (outdoor carbonation-induced aging), E4 (outdoor elevated temperatures), E5 (outdoor freeze-thaw cycles), and E6 (coastal airborne chlorides)1.

1 A. Dushimimana et al., "Behavior of CFRP Composites and Epoxy Adhesives After Long-Term Exposure to Outdoor and Laboratory-Controlled Environments," *Construction and Building Materials*, vol. 438, p. 137201, 2024, doi: 10.1016/j.conbuildmat.2024.137201.

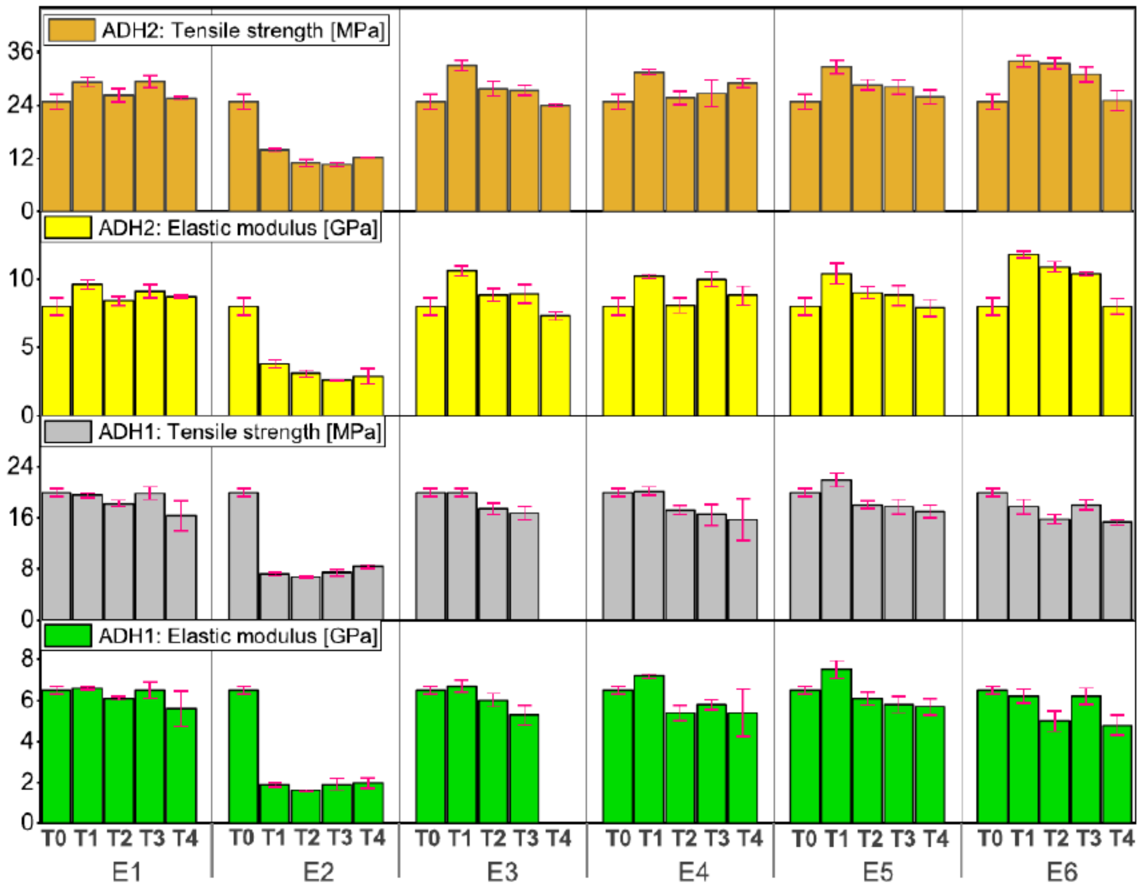

Figure 2. Comparative tensile property retention of epoxy adhesives after 1-4 years of exposure (T1 – T4) across all environmental conditions (E1–E6). Environmental Exposure Classifications: E1 (laboratory-controlled reference, 20°C, 55% RH), E2 (continuous water immersion, 20°C), E3 (outdoor carbonation-induced aging), E4 (outdoor elevated temperatures), E5 (outdoor freeze-thaw cycles), and E6 (coastal airborne chlorides). ADH2 demonstrates superior post-curing resilience in E3–E6 environments, while ADH1 shows vulnerability to degradation agents2.

2 A. Dushimimana et al., "Behavior of CFRP Composites and Epoxy Adhesives After Long-Term Exposure to Outdoor and Laboratory-Controlled Environments," *Construction and Building Materials*, vol. 438, p. 137201, 2024, doi: 10.1016/j.conbuildmat.2024.137201.

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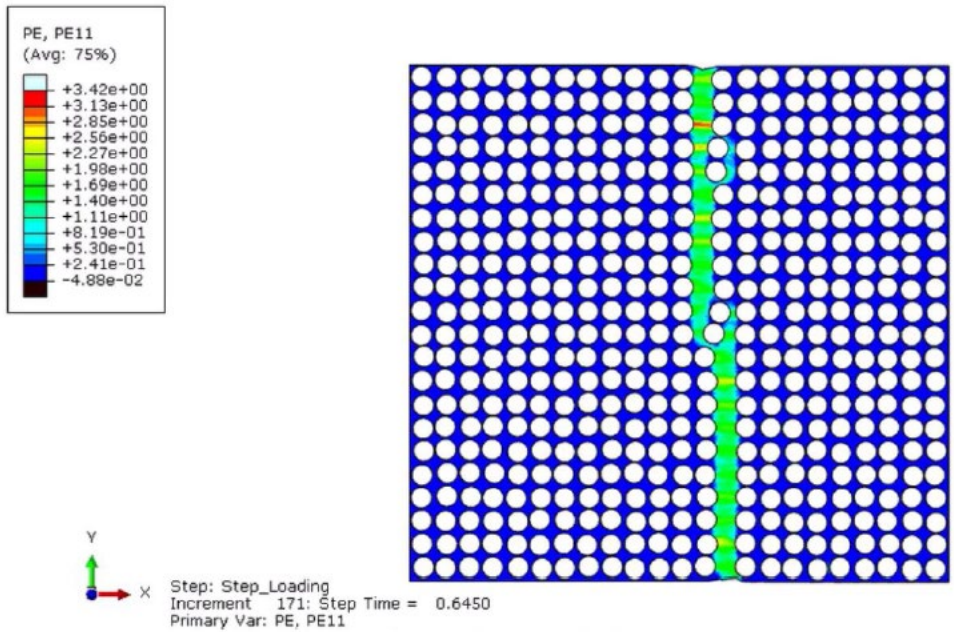

Figure 3. Plastic strain in the composite due to tension resulting in separation and failure in the epoxy matrix

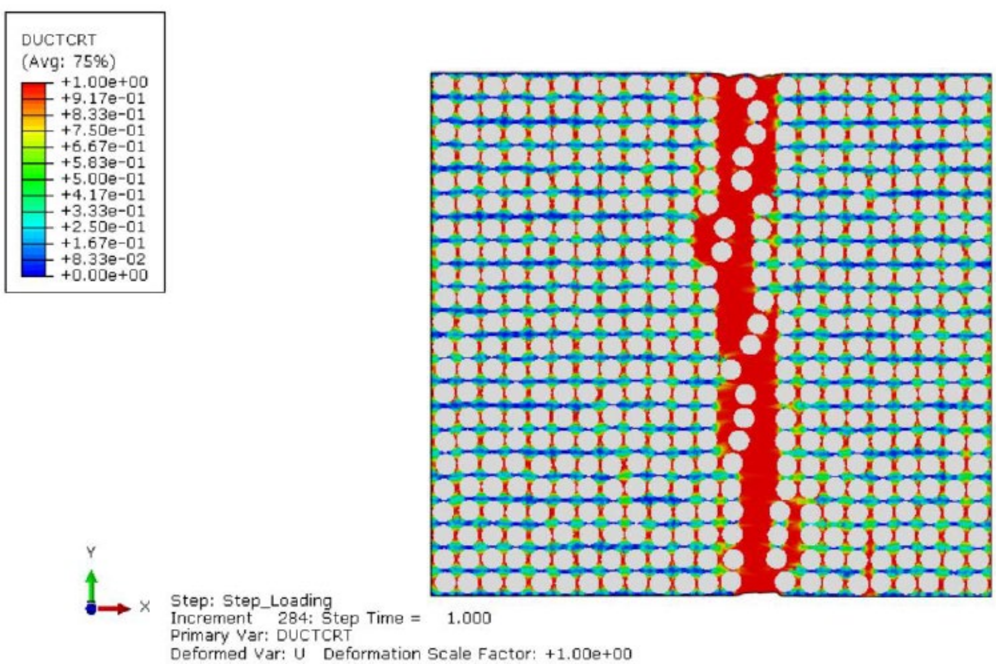

Figure 4. Damage development in the composite due to tension resulting in separation and failure in the epoxy matrix

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