Chapter 2
Multi-Scale, Multi-Mode Damage Simulation for Miter Gates

Guofeng Qian, Haiwei Lin, Zhen Hu, and Michael D. Todd

Abstract Different failure modes can evolve simultaneously in large civil infrastructure systems like miter gates throughout their service life. However, most physics-based prognostic models focus solely on the evolution of a single damage mode, neglecting the significant interactions between different damage modes. This paper proposes a physics-based, multi-scale, multi-mode damage prognostic model applied to miter gate structures important to the inland waterways navigation corridor. The model simulates four common types of damage: two global damage modes (contact loss between the wall and gate and regional uniform corrosion), and two local damage modes (pitting corrosion and cracking). First, the two global damage modes are simulated using the finite element method by modifying the boundary conditions and element dimensions. Next, pitting corrosion is modeled at the local scale with a phase-field method, using the stress response from the global structural analysis model. A pit-to-crack transition is identified, incorporating information from both the corrosion simulation and the structural analysis models to indicate the transition process. Subsequently, the extended finite element method (XFEM) is applied to simulate localized crack growth. Finally, the growth of the local crack is used to update the global structural analysis through an iterative local-global model. The interactions between contact loss, regional uniform corrosion, pitting corrosion, and cracking are simulated in a holistic simulation framework, with the global and local models updated iteratively. This allows for the development of a systematic failure prognostic framework for large civil structural systems using physics-based analysis. The proposed method is demonstrated using a miter gate structural example to showcase its effectiveness.

Keywords Multi-Scale Simulation · Multi-Mode Damage Prognostics · Structural Health Monitoring · Local-Global Model

Introduction

Multiple types of deterioration can occur simultaneously in civil structures throughout their decadal service lives [1, 2]. Taking the miter gate structure used in inland navigational lock systems as an example, multiple studies have been conducted on various deterioration types associated with the aging of these structures, including wall/boundary contact loss [3, 4], localized corrosion [5], and cracking [6, 7]. It is crucial to note that the evolution of different damage types influence each other. For instance, stress corrosion cracking can initiate from localized corrosion [8], and uniform corrosion can lead to stress redistribution within the gate, impacting gaps and crack formation [9]. Despite these interactions, the influence between different damage types has not been sufficiently studied to fully understand their interdependencies [10]. This study investigates a multi-scale, multi-mode damage simulation framework to capture the inter-damage influence on damage evolution. In the following sections, we introduce the simulation framework, detailing each component, including macro structural analysis, meso-scale corrosion evolution, and local-global crack propagation.

Guofeng Qian · Haiwei Lin · Michael D. Todd
Department of Structural Engineering, University of California San Diego, La Jolla, CA 92037
e-mail: g4qian@ucsd.edu; hal145@ucsd.edu; mdtodd@ucsd.edu

Zhen Hu
Department of Industrial and Manufacturing Systems Engineering, University of Michigan-Dearborn, Dearborn, MI 48128
e-mail: zhennhu@umich.edu

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Multi-Scale Multi-Mode Damage Simulation Framework

Fig. 1 illustrates the overall framework. Due to the length scale differences between the structure and the localized crack and corrosion damage, maintaining the same level of fidelity in the simulation is computationally prohibitive. To address this challenge, we implemented a multi-scale approach.

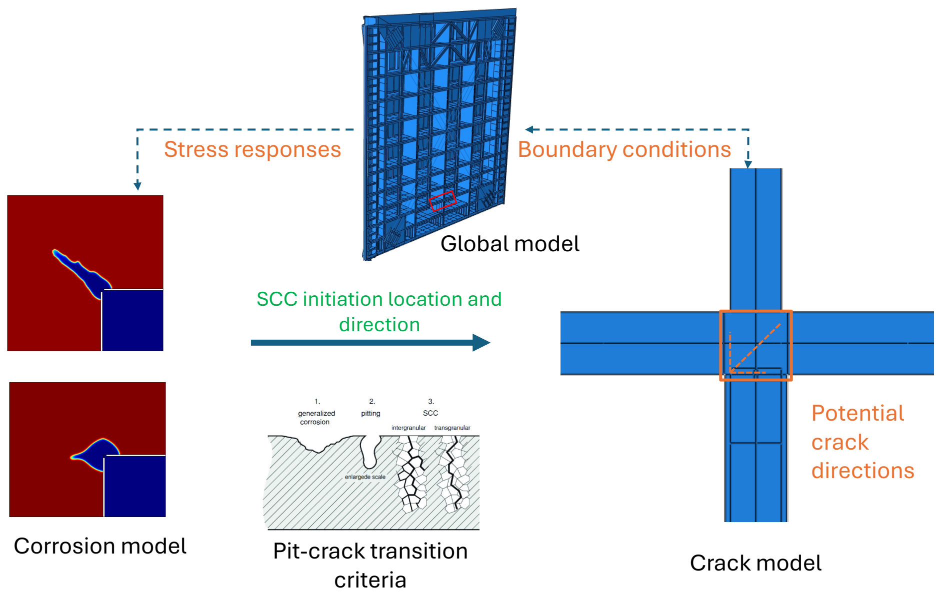

Fig. 1 Overall framework for multi-mode damage simulation

The framework consists of a macroscale structural analysis finite element model that serves as the global model. This global model simulates the strain response of the structure under operational loads and accounts for global damage, including structural thickness loss due to uniform corrosion and contact loss between the quoin block and the wall.

On one hand, the global model provides the local strain response, which acts as the mechanical load input to the meso-scale corrosion evolution model. On the other hand, the global model interacts with the local crack model by iteratively adjusting the boundary conditions until convergence is achieved. The corrosion model also informs the crack model by identifying the stress corrosion cracking (SCC) initiation location and direction.

Macro-Scale Structural Analysis

To provide the correct strain response to the local model, it is essential to simulate both gap damage and uniform corrosion in the global model. In the finite element (FE) model, the gap is represented by a free boundary condition, simulating the loss of contact between the gate and the wall quoin block near the bottom of the gate [4].

For uniform corrosion, we simulate its impact on the structure by reducing the thickness of the structural components in the FE model. Given that different areas of the structure experience varying degrees of corrosion, we divided the structure into three distinct zones: the upper zone exposed to air, the middle zone subject to fluctuating water level exposure, and the lower zone always submerged in water. The corresponding mass losses in these zones are denoted as t_1, t_2, and t_3, where $t_2 > t_3 > t_1$. By simulating these varying thickness losses, we can effectively analyze effects of uniform corrosion on different regions of the structure.

Meso-Scale Corrosion Evolution and Crack Initiation

As most SCC initiates from the corner of the intersection of webs, as shown on the left side of Fig. 2, we further perform a phase-field corrosion simulation for the corner area. This model is capable of predicting SCC initiation [5] as well as determining the initial direction of SCC propagation when subjected to different mechanical loads from the top surface and the right surface. The simulation utilizes a 2D model since the flange is a thin plate and is therefore represented using two-dimensional shell elements. Once SCC initiates at a specific time and propagates in a particular direction, the crack progression will be further analyzed using the crack model described in the next section.

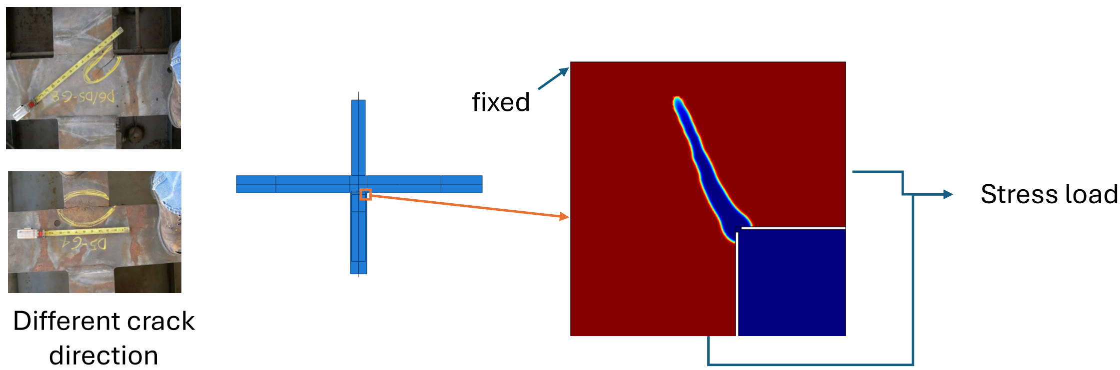

Fig. 2 Localized corrosion simulation and crack initiation direction.

SCC and stress intensity factor Simulation

Based on the different directions induced by corrosion, we conducted simulations of crack propagation under various conditions and calculated the stress intensity factor (SIF) at the crack tip by iteratively coupling the global model and the local model, exchanging boundary conditions between them [7]. For illustration, we present two SCC directions initiating from the same location with the same crack length.

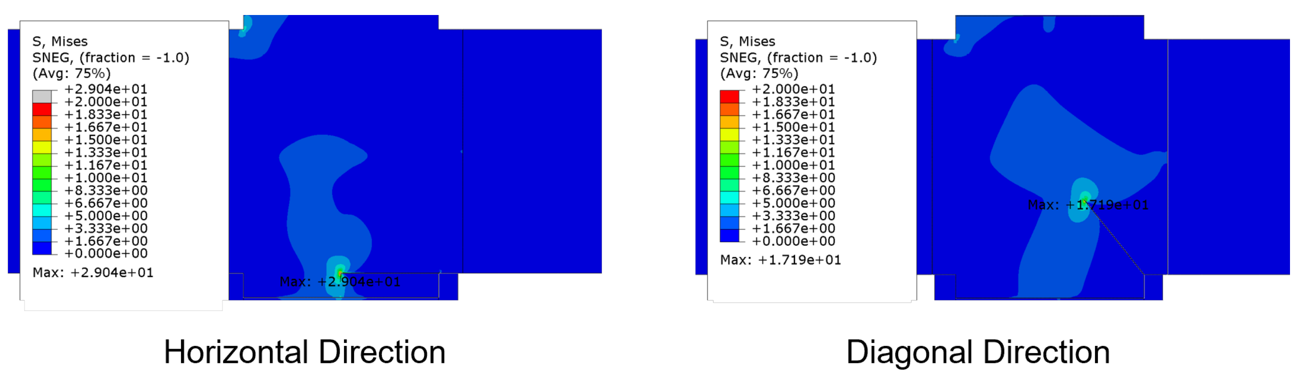

Fig. 3 Stress Distribution around Tip from Two Different Initiation Directions

Figure 3 displays the von Mises stress distribution maps for SCC in horizontal and vertical directions. We observe that the horizontal direction exhibits higher stress values as the depth increases, while the diagonal direction shows lower stress values under these conditions. Additionally, Fig. 4 presents the maximum SIF values along the depth near the crack tip. Consistent with the stress results, SCC in the horizontal direction has higher SIF values, whereas SCC in the diagonal direction has lower SIF values. These findings indicate that SCC in different directions results in varying propagation velocities, even when the initiation location and crack length are identical.

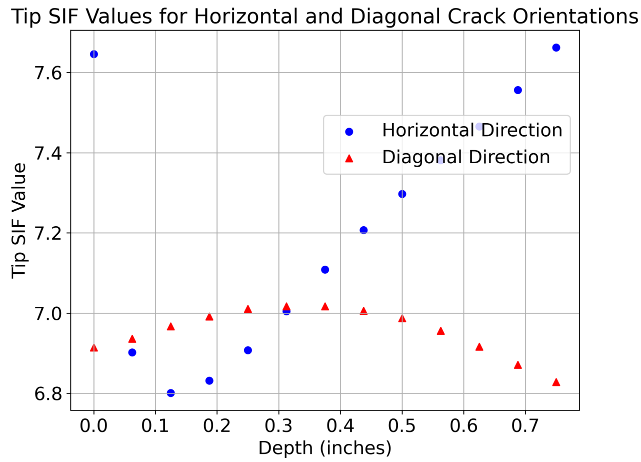

Fig. 4 Tip SIF Values for Different Cracks

Conclusions

This paper proposes a systematic framework to simulate four interdependent damage models in the miter gate structure. The studied damage modes include contact loss, thickness loss due to uniform corrosion, localized corrosion, and cracking. The interactions between these different damage types were effectively captured using a multi-scale simulation. The developed framework will be used for failure prognostics of miter gates considering various uncertainty sources.

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