

Abstract

Cracks in engineering structures pose a significant threat to their integrity, leading to the propagation of the cracks and potentially catastrophic failure. These cracks, often originating from stress concentrations or material defects, weaken the structure, reduce its load-bearing capacity, and accelerate fatigue failure. Consequently, effective crack repair and structural health monitoring are crucial for ensuring the safety and longevity of critical components.

Previous research has primarily focused on static crack repair using piezoelectric materials, demonstrating their ability to reduce stress intensity factors (SIF) under static loading. However, a comprehensive analysis of fatigue life enhancement, incorporating both the active and passive effects of piezoelectric patches, remains largely unexplored. Specifically, the passive stiffening effect of the patch and the combined "hybrid" repair effect have not been analytically modeled and validated against finite element (FE) solutions. Additionally, these repair techniques are not yet utilized for complex structures like cracked I-beams, cracks emanating from the elliptical hole, arc-shaped cracked specimens, cracked plates under bending, etc.

This thesis aims to develop and validate analytical models for passive, active, and hybrid crack repair using piezoelectric materials to enhance fatigue life under cyclic loading. The primary objectives are to develop analytical models that accurately predict the SIF and fatigue crack growth rate (FCGR) in cracked plates and beams repaired with piezoelectric patches under various loading conditions. Additionally, this thesis aims to investigate the individual and combined effects of passive stiffening and active actuation on crack behavior and to conduct a parametric study to determine the optimal thickness and voltage application to the piezoelectric actuators for maximum crack mitigation and fatigue life extension. At last, the developed analytical model is validated against finite element (FE) simulations using ABAQUS.

The methodology employed in this thesis is based on linear elastic fracture mechanics (LEFM) principles. The SIF is calculated using established solutions for cracked structures, and the weight function method (WFM) and crack surface widening energy release rate are used to determine the SIF induced by piezoelectric actuation. The passive effect of the piezoelectric patch is determined using Rose's equations. The superposition principle combines the effects of mechanical loading and piezoelectric actuation. Fatigue crack growth is predicted using the standard crack growth model, considering various stress and voltage ratios.

The analytical models developed in this thesis were rigorously validated against FE solutions obtained using ABAQUS software. This validation process involved comparing the calculated SIF and fatigue life predictions with the FE results under various loading conditions and repair configurations. The consistency between the analytical and FE results confirms the accuracy and reliability of the proposed models.

The main findings of this research demonstrate that piezoelectric patches, particularly in hybrid repair configurations, significantly reduce SIF and extend fatigue life. Hybrid repair, combining passive stiffening and active actuation, consistently outperformed individual passive or active repair methods. Active repair using strategically placed piezoelectric actuators mitigates crack propagation in various structural geometries, including plates with elliptical holes, arc-shaped specimens, and I-beams. The parametric studies revealed that thin actuators are optimal for low mechanical loads, while thick actuators perform better under higher loads as they are prone to mechanical failure. Furthermore, applying external voltages to piezoelectric actuators induces controlled deformations, significantly reducing FCGR and enhancing structural integrity. This research provides a robust context for designing and implementing effective piezoelectric-based crack repair strategies, contributing to developing safer and more durable engineering structures.