Digital Image Correlation (DIC) for Plastic Deformation Assessment of High-Strength Nuclear Steel under Low-Cycle Loading

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Abstract. This research presents a novel methodology that integrates Digital Image Correlation (DIC) with strain-based fatigue theories to evaluate the low-cycle fatigue (LCF) performance of high-strength nuclear steel (SA508-G 4N) [1]. The methodology bridges experimental mechanics and theoretical modeling by applying DIC to capture full-field local strains and incorporating them into the Manson-Coffin Curve Method (MCCM) for accurate fatigue life prediction. Experimental testing using hourglass and parallel-sided specimens under strain-controlled, fully reversed uniaxial loading was conducted. The fatigue constants were derived and used to construct stabilized stress-strain and Manson-Coffin curves. Results show strong agreement between theoretical predictions and observed fatigue lifetimes, validating DIC as a reliable tool for characterizing fatigue-critical components [2].

Introduction

The assessment of fatigue life in components subjected to repeated loading is critical in aerospace, nuclear, and civil infrastructure applications. Traditional techniques such as strain gauges and extensometers provide limited spatial resolution, especially in complex geometries and under multiaxial loading. Digital Image Correlation (DIC) [3], a non-contact optical technique, offers high-resolution, full-field strain measurements. This study investigates the application of DIC in combination with strain-based fatigue models to enhance the prediction accuracy of fatigue life under low-cycle conditions [4].

Methodology

Hourglass and parallel-sided specimens were machined from SA508-G 4N steel and tested under fully reversed, strain-controlled uniaxial fatigue using an ESH 250kN servo-hydraulic test machine [5]. The DIC system (LaVision with 5M cameras) recorded local strain evolution over 15mm and 27mm gauge lengths during loading. A black-and-white speckle pattern was applied to facilitate correlation. Fatigue constants including cyclic strength coefficient (K′), cyclic strain hardening exponent (n′), fatigue strength coefficient (σ′f), and ductility coefficient (ε′f) were derived experimentally and used to construct the stabilized stress-strain and Manson-Coffin curves. The methodology is presented in Fig. 1.

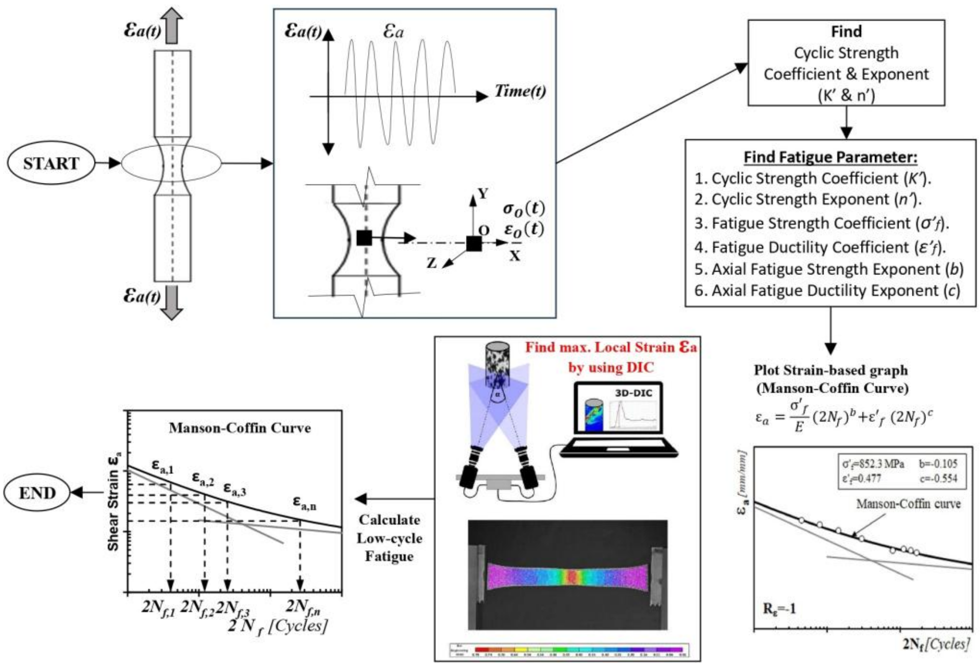

Fig. 1, Flow-chart of Estimating Low-cycle Fatigue by using DIC

Results and Discussion

DIC successfully captured localized elasto-plastic strain distributions, enabling identification of strain concentration zones responsible for crack initiation. The derived fatigue constants (σ′f, ε′f, b, c) allowed accurate plotting of Manson-Coffin curves. When the experimentally observed strain amplitudes were input into the theoretical model, the predicted cycles to failure closely matched the physical test results. For validation, three parallel-sided specimens were tested, and DIC data confirmed the reliability of the theoretical fatigue life estimations. The integration of DIC with MCCM significantly improved the precision of fatigue life predictions compared to traditional strain measurement techniques. The calculated number of cycles to failure was compared to the experimentally found $\boldsymbol{N_{f.e}}$ as shown in Fig 2.

Conclusion

This study demonstrates the effective use of Digital Image Correlation in enhancing low-cycle fatigue analysis. By integrating DIC with strain-based fatigue models, an accurate, full-field understanding of local deformation and fatigue behavior is achieved. This approach provides a validated framework for reliable fatigue life prediction in safety-critical components, with significant implications for experimental mechanics, structural integrity, and advanced material testing.

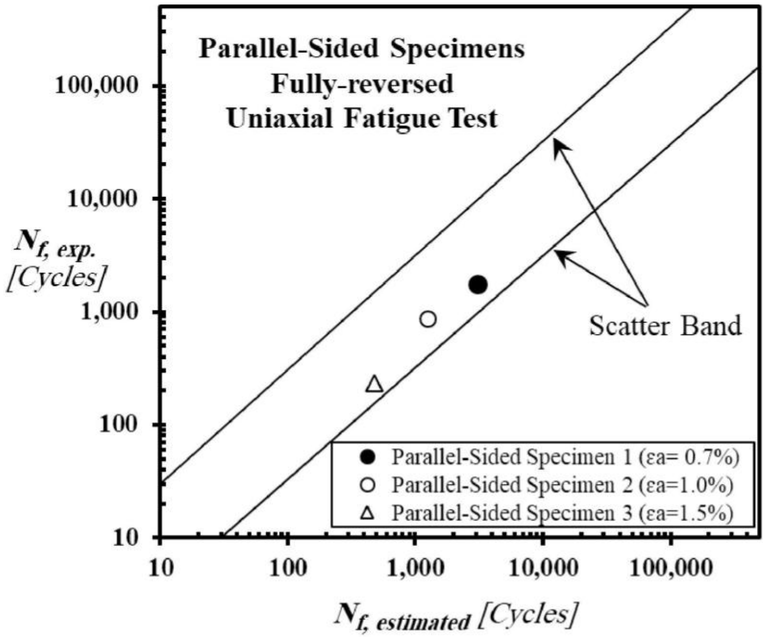

Fig. 2, The Calculated Lifetime cycles versus experimental Nf.exp

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