UNCERTAINTY QUANTIFICATION IN RESIDUAL STRESS AFFECTED FATIGUE CRACK GROWTH LIFE

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Abstract

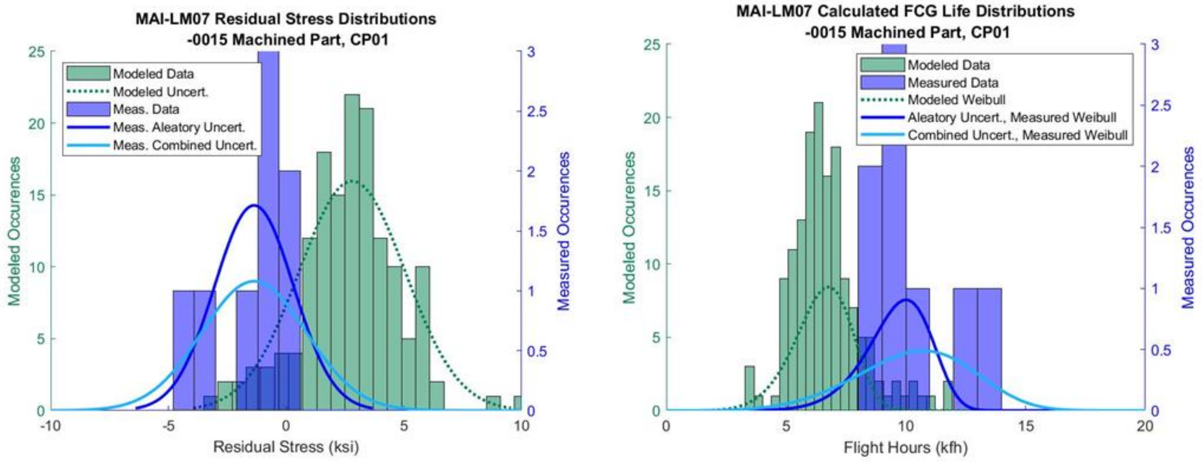
In recent years a number of studies have been performed in which the impact of residual stress on structural performance, especially fatigue performance, has been evaluated both experimentally and analytically. These efforts are leading to an emerging paradigm in which residual stresses are represented explicitly in structural design, analysis, manufacturing and sustainment calculations. In order for this new approach to be become minimally viable, it is necessary to be able to quantify both the residual stresses in the structural component in question, and the impact that those residual stresses have on component strength and life. However, to achieve general acceptance, especially for critical applications in which the presence of the residual stress directly impacts whether or not the component will meet its design requirements, deterministic quantification alone may not be sufficient; it may be necessary to quantify the uncertainties in both the residual stresses and the resulting fatigue lives.

1. Introduction

In several recent studies sponsored by the US Air Force Research Laboratories (AFRL), the variability in forging process induced residual stresses in 7000-series aluminum machined parts was quantified using both computational simulation and replicate measurements [1]. The experimental data were taken using several methods, including the contour method [2], which allows the characterization of one component of stress over a full, two-dimensional plane. The variability in the measurement data was combined with an estimate of the measurement error to determine the overall uncertainty. At the same time, forging process modeling was used to simulate both the expected mean and uncertainty in residual stress at the same locations where measurement data were available. In the work presented here, the uncertainties in both the measured and modeled residual stresses were propagated through fatigue analyses in order to predict the dependence of fatigue life variability on residual stress variability.

2. Results

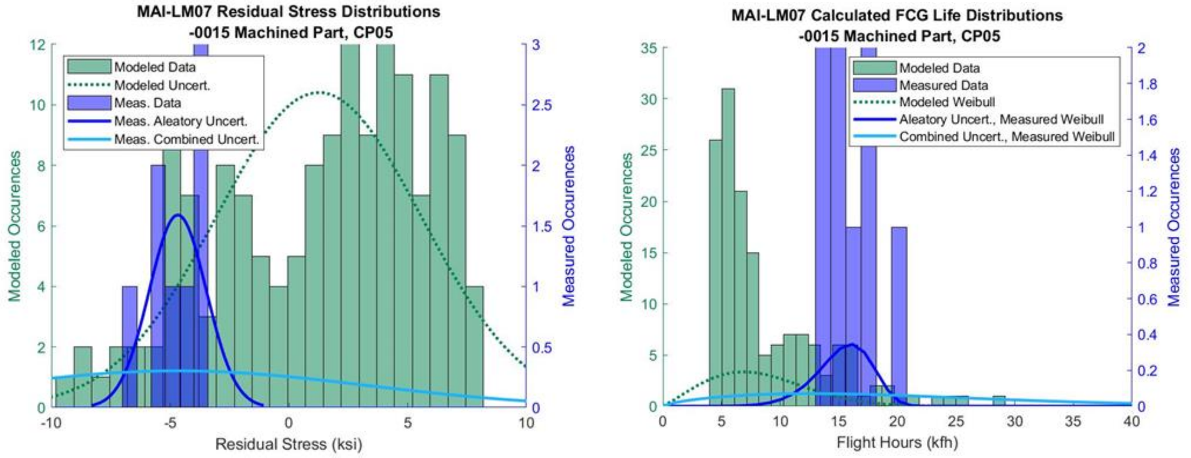
LEFM-based fatigue crack growth (FCG) analyses were performed based on the assumption that separate stress intensity factors (SIF) for the applied fatigue stresses and the residual stress can be superimposed to define a total SF. In both cases, SIF was calculated using either the applied or the residual stress distribution on the critical plane, in conjunction with the appropriate weight function or Green's function [3] for the body / crack configuration. FCG lives were computed for a fixed material and fatigue loading spectrum (fighter aircraft wing bending moment). Separate lives were computed for each of the replicate residual stress measurements and for each of the modeled residual stress permutations. Examples of the modeled and measured variability in residual stress at two selected locations in the structural component are shown in Figures 1(a) and 2(a). Statistical evaluation (T-test) of these data indicated that the measured and modeled residual stresses were loosely correlated at location 1 (Figure 1(a)), but that they were un-correlated at location 5 (Figure 2(a)). The impact that this variability had on computed FCG life is shown in Figures 1(b) and 2(b). The projected variability in FCG life at location 1 (Figure 1(b)) appears to be manageable in that the 95% confidence bounds fall within the 2X life scatter factor which is standard for FCG analysis. However, for location 5 (Figure 2(b)), the computed 95% confidence bounds fall outside the standard life scatter factor. In both cases, quantification of the residual stress affected uncertainty in the FCG lives would be critical to any design, manufacturing or sustainment decision making if this were a real structural application.



(a) Modeled and measured RS data with normal probability distributions.

(b) Calculated FCG lives based on modeled and measured RS distributions. Weibull distributions are fitted to FCG life results.

Fig.1 – Calculated variability in fatigue crack growth (FCG) life due to variability in bulk residual stress for location with loose correlation between measured and modeled residual stress.



(a) Modeled and measured RS data with normal probability distributions.

(b) Calculated FCG lives based on modeled and measured RS distributions. Weibull distributions are fitted to FCG life results.

Fig.2 – Calculated variability in fatigue crack growth (FCG) life due to variability in bulk residual stress for location with no correlation between measured and modeled residual stress..

3. Conclusions

For the conditions studied in this project, it was shown that the use of MEASURED residual stress data resulted in conservative FCG life prediction (compared to analysis with no residual stress) 81% of the time when aleatory uncertainty alone was considered, and 100% of the time when combined uncertainty was considered. When using MODELED residual stress data, the FCG life predictions were conservative 56% of the time when considering aleatory uncertainty alone, and only 38% of the time when combined uncertainty was considered.

The results demonstrate the critical importance of FCG life uncertainty quantification for structural applications in which residual stress is going to be explicitly managed, and in which that residual stress may impact of the ability of that structure to meet its performance requirements.

Acknowledgements

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