15th International Conference on Fracture (ICF15)
June 11-16, 2023 Atlanta, GA USA

ADVANCED CRACK TIP FIELD QUANTIFICATION USING DIGITAL IMAGE CORRELATION, MACHINE LEARNING, AND INTEGRAL EVALUATION

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Abstract
We use higher-order Williams coefficients from full-field displacement data obtained by digital image correlation (DIC) to approximate complex crack tip fields with simpler expressions. The methodology is based on invariant path integrals and machine-learned crack detection. We demonstrate the framework for fatigue crack growth experiments of aluminium alloys and compare the results to matching finite element simulations.

1. Introduction
Quantifying fatigue crack growth (FCG) is of significant importance for evaluating the service life and damage tolerance of critical engineering structures and components subjected to non-constant loads.

In recent years, digital image correlation (DIC) has become instrumental for contactless generation of full field surface displacements and strains during FCG experiments. Coupled with suitable material models, the DIC data can be used to determine important fracture parameters like stress intensity factors (SIFs).

FCG mechanics is mainly driven by the crack tip field which can be described by the famous Williams series who's first order term relates to the $r^{-1/2}$ stress singularity and is used to determine K_I and K_{II}. Although the potential influence of higher order terms on crack growth and stability is known, classical studies solely rely on first order terms.

The so-called T-stress, related to the second-order, mode-I Williams coefficient, acts parallel to the crack and is related to crack path stability, plastic zone shape, and constraint parameters of the plastic zone size. Its sign determines shielding or anti-shielding behaviour of the plastic zone at the crack tip. A positive T-stress leads to directional instability associated with the possibility of crack path deflection.

Well-known integral techniques like the J- or interaction integrals are reliable methods for calculating K_I and K_{II} based on displacement and stress fields. However, Bueckner proposed a more general *conjugate work integral* and Chen proved that it can be used to determine *all* coefficients of Williams' series. Nevertheless, all these methods require profound knowledge of the crack configuration - especially the crack path and crack tip position.

2. Methods and Results
In this work, we present a framework for the advanced numerical characterization of crack tip fields with a modern, data-centric approach. The framework is based on the following consecutive steps:

1. Fatigue crack growth experiments accompanied by DIC
2. Automatic crack detection using deep learning
3. Determination of Williams coefficients using integral evaluation

We analysed fatigue crack propagation experiments with middle tension (MT) and compact tension (CT) specimens of aluminium AA2024 and AA7010 alloys.

To allow efficient evaluation of large amounts of DIC data, cracks need to be determined fully automatically. In recent years, machine learning and especially deep learning based on convolutional neural networks (CNNs) led to enormous breakthroughs in several computer vision tasks. Our crack detection is based on CNNs trained with labeled DIC displacement data to predict crack path and crack tip position by segmentation. The neural networks are monitored by eXplainable AI (X-AI) tools in order to guarantee correct functioning.

We implemented Bueckner's conjugate work integral to calculate Williams coefficients. By comparison of stress field approximation errors for simulations by finite element analysis (FEA), we find that the integral method outperforms state-of-the-art fitting methods. We carried out a parameter study for the higher-order Williams coefficients varying crack lengths, external forces, and sizes for widely used MT, SECT, and CT specimen. Finally, we compare Williams coefficients from DIC to corresponding Williams coefficients from FEA integral evaluation. The goal is a dimensional reduction of complex crack tip fields by simpler expressions which can be correlated later with other descriptive attributes like the shape of the plastic zone, the stress state or the microstructure.

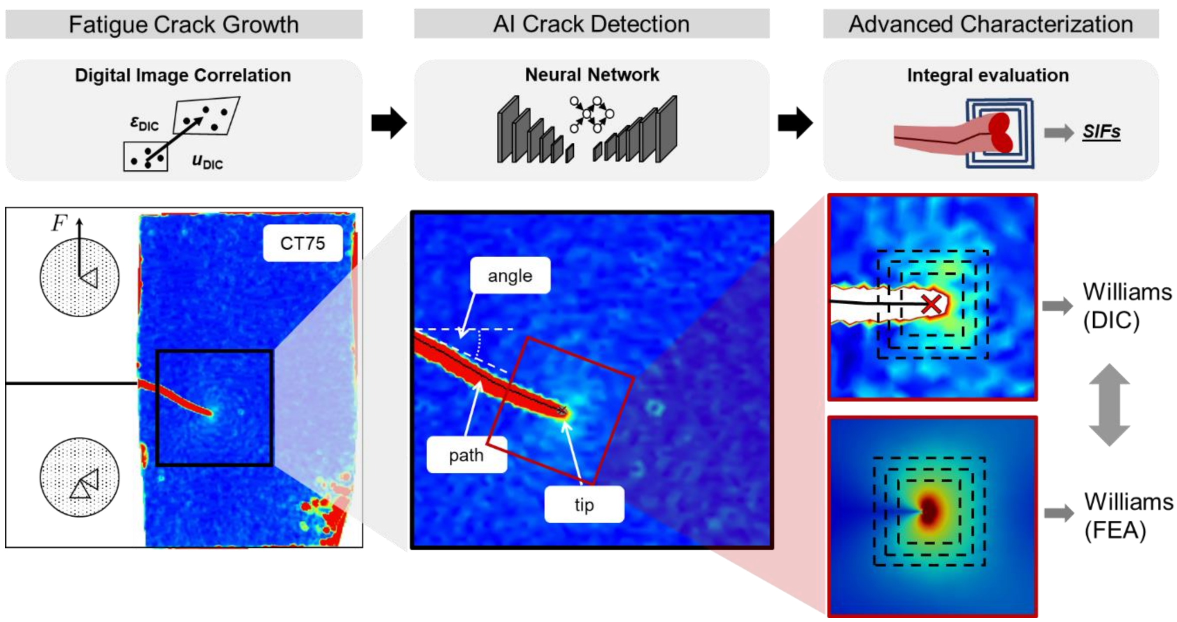

Fig.1 – Advanced crack tip field characterization framework: FCG experiments (e.g. with CT75 specimen) are accompanied by DIC (left). The measured displacement data is fed into a trained CNN which detects the crack's path, angle, and tip (middle). This information is used for the integral evaluation method in order to calculate Williams coefficients for the DIC-data or corresponding FEA (right).

3. Conclusions

From a data scientific standpoint, the precise calculation of Williams coefficients is a dimension reduction similar to the mathematical approximation theory. It gives an efficient way to represent the high-dimensional nodal displacement data ($\approx 10^5$ D) in the much lower dimensional space of coefficients ($\approx$ 10 D). Thus, this approach opens the data science toolbox in the field of fracture mechanics. In particular, it allows to cluster large amounts of DIC data and search for patterns connected to crack path and crack propagation stability and to analyze deviations between experiments and matching simulations more thoroughly.

Acknowledgements
We acknowledge the financial support of the DLR-Directorate Aeronautics and would like to thank E. Dietrich for supporting and conducting the FCG experiments.