A SOFTWARE FRAMEWORK FOR PROBABILISTIC FATIGUE CRACK GROWTH ANALYSIS OF METALLIC COMPONENTS

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Abstract
A comprehensive software framework has been developed for probabilistic fatigue crack growth (FCG) analysis of safety-critical metallic components. The framework has been implemented in a computer code called DARWIN® (Design Assessment of Reliability With INspection). DARWIN determines the probability of fracture for a component as a function of operating cycles, with and without inspection, by integrating finite element (FE) geometries, stress, and temperature analysis results; fracture mechanics models; material anomaly data; probability of anomaly detection; and uncertain inspection schedules with a user-friendly graphical user interface (GUI). The framework can accommodate anomalies occurring anywhere in the volume of the component (such as material voids or inclusions) or anomalies occurring only on the surface of the component (such as manufacturing or maintenance damage).

1. Threats Addressed

This framework is particularly well-suited for addressing fracture risk arising from populations of anomalies, including inherent material anomalies such as inclusions or voids that can occur anywhere in the volume of the component; manufacturing- or maintenance-induced anomalies that can occur on the component surface; naturally-occurring fatigue cracks from service loading; or corrosion pits from environmental damage. Multiple anomaly types can also be included. Assumed initial anomaly geometries can be simple (e.g., equivalent spheres) or complex (e.g., ellipsoids with variable size/shape/orientation).

The framework and the DARWIN software were initially developed with funding from the U.S. Federal Aviation Administration (FAA) in order to address the threat of rare hard alpha anomalies in titanium rotors for commercial aircraft engines. The resulting capabilities for volumetric anomalies are also applicable to components produced using additive manufacturing (AM). Additional FAA funding developed specific capabilities to address surface damage at machined holes or broached slots.

2. Deterministic Life Calculations

This framework is suitable for both axisymmetric and general 3D components. DARWIN has a direct interface with 2D and 3D FE component models (geometry as well as stress and temperature results) from standard commercial tools such as ANSYS and Abaqus. The DARWIN GUI enables users to visualize and to manipulate the component models as the analyses are performed, and then can superimpose life and risk results on the FE models. HDF5 binary data files support the computationally efficient use of extremely large FE models with multiple time steps. Complex stress histories can be built up from multiple time steps in the FE analysis with various scaling factors and mission mixing capabilities.

DARWIN incorporates a state-of-the-art engineering FCG analysis module, including advanced weight function stress intensity factor (SIF) solutions that use either univariant or fully bivariant stress gradients extracted directly from the FE analysis of the uncracked component. The SIF solutions may include residual stress (RS), both local RS profiles from surface treatments such as peening and bulk RS fields from forging or heat treating. Novel algorithms automatically generate suitable engineering fracture models (simple rectangular plate models with appropriate dimensions and orientation) at any arbitrary initial crack location in the 2D or 3D model. This capability can also be used to generate FCG life contour plots for the entire component, or critical initial crack size contours (the initial crack size that would just grow to failure in a given service lifetime). An interface is also available to link a user-supplied crack formation module, and crack formation lifetime can be summed with crack growth lifetime to provide a total fatigue life.

3. Probabilistic Calculations

DARWIN employs a zone-based methodology in which the fracture risk is calculated as the product of (1) the probability of occurrence of an anomaly in a given zone and (2) the probability of fracture assuming that an anomaly does exist in the zone. Initial zones within a component are identified by grouping finite elements with similar properties (material properties, anomaly distributions, inspections) and then refining the zones based on approximate risk values. Final conditional risk calculations are performed at the highest-risk location within each zone, and the results are assigned to the entire zone. As zones are refined (more zones, smaller zones), the total component risk (summing all zones) converges to a final value from above. Automatic algorithms are used to identify optimum zone groupings for maximum accuracy and computational efficiency, and to ensure a conservative risk value.

The effects of non-destructive evaluation (NDE) inspections during manufacture or service may be incorporated into the fracture risk calculations. NDE inspections for anomalies or resulting cracks are characterized by probability-of-detection (POD) curves and statistical descriptions of uncertain inspection times. Location-specific POD curves can be imported from from physics-based simulations of the NDE inspection method on the component of interest.

The framework here considers five major random variables: the size and frequency of anomalies, material property scatter, stress scatter, NDE POD, and time of inspection. Additional optional random variables are associated with 3D anomalies, crack formation lifetime, and residual stress. In addition to regular Monte Carlo (MC), the probabilistic methods in DARWIN include several tailored MC methods (including response surface importance sampling) that substantially reduce computation time without loss of accuracy. The software framework is summarized in Figure 1.

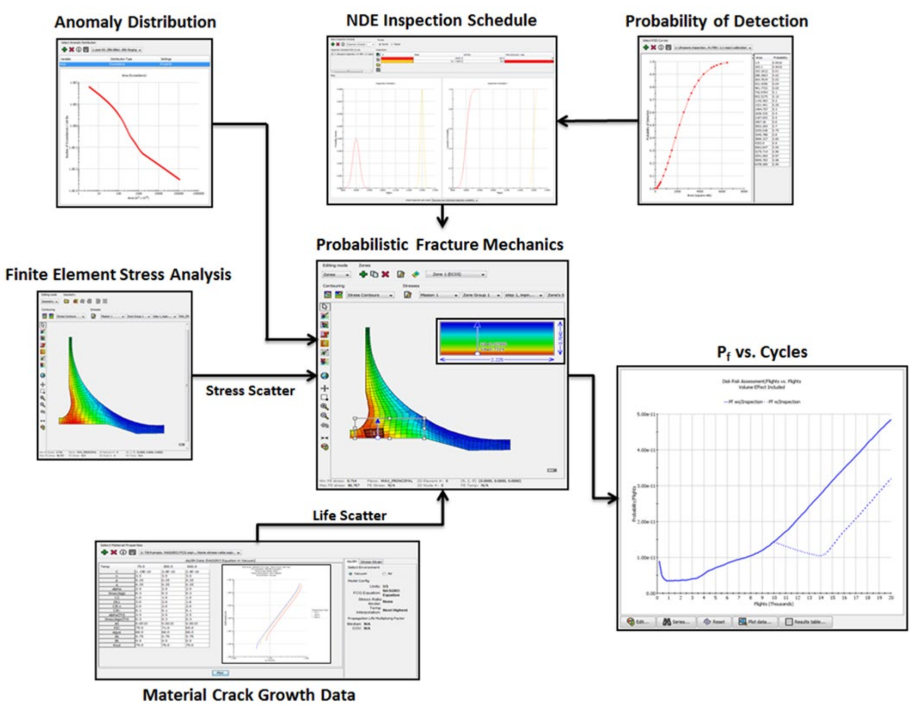

Fig.1 – DARWIN framework for probabilistic damage tolerance analysis

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