Simulation of Discrete-source Damage Propagation and Residual Strength of Aircraft Structures

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1. Introduction

In an effort to advance the state of aircraft flight control, NASA has initiated the Integrated Resilient Aircraft Control (IRAC) project. The long-term goal of the project is to arrive at a set of validated, integrated aircraft control design tools that enable safe landing in the presence of adverse conditions. Adverse conditions include point-source damage events such as that experienced in 2003 when an Airbus A300 operated by DHL was struck by a surface-to-air missile shortly after take-off from Baghdad, resulting in severe damage to both the aileron and rear spar of one wing. A more recent example occurred in July of 2008 when a Boeing 747-438 operated by Qantas Airways incurred significant fuselage damage due to the explosion of an on-board oxygen tank. In light of these kinds of serious adverse flight conditions, the Cornell Fracture Group (CFG) is developing a finite element-based fracture mechanics analysis methodology to predict growth of point-source damage within airframe structures under realistic conditions and in real-time.

The purpose of this paper is to discuss a methodology for predicting residual strength of damaged airframe structures in real-time based on three-dimensional crack growth simulations in finite element models. The paper includes a brief discussion of relevant work related to characterizing point-source damage in aircraft wing structures. A description of the presently employed software system used for simulating crack growth in three-dimensional finite element models is also provided. Proof-of-concept simulations are described, and the paper concludes with a look to the future of the CFG's continued role on the IRAC project.

2. Methodology

The methodology employed for predicting residual strength of damaged airframe structures is shown in Fig. 1. First, a global finite element model of, say, a wing structure, is subject to some original allowable aerodynamic loading spectrum. This original load spectrum corresponds to the structure's design limit load. From this global finite element model, boundary conditions are extracted in order to build a local finite element model of, say, a stiffened wing panel section. Parameterized initial damage configurations are then imposed on the local finite element model, and explicit crack growth simulations are subsequently performed. From these crack growth simulations, it is determined whether or not the structure will experience catastrophic failure given the loading conditions and particular damage configurations. If catastrophic failure is predicted to occur, then the allowable load must be decreased and the simulation process repeats. Once the allowable load has been decreased such that catastrophic failure is predicted not to occur, the applied load is stored in a response surface of damage parameters versus allowable load. The response surface is to be integrated into the control system feedback loop such that damage characterization information provided by on-board sensors will be used to query the response surface in real-time and yield a reduced, damage-dependent flight envelope.

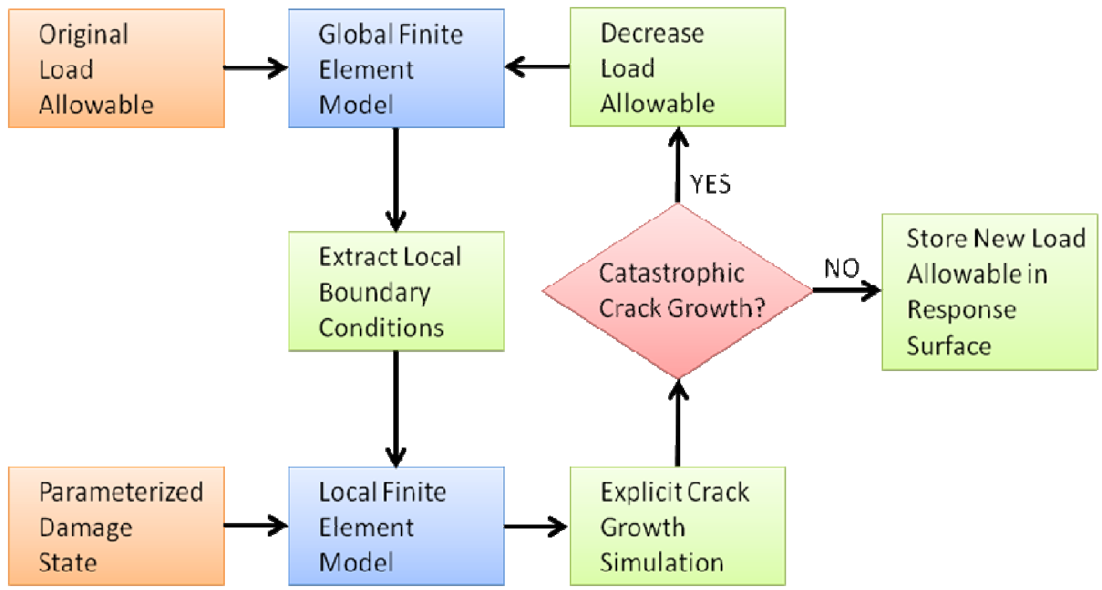

Fig.1 Response surface methodology for residual strength prediction of damaged airframe structure.

2.1 Damage Parameterization

As mentioned above, explicit crack growth simulations are performed based on parameterized damage configurations. Such damage parameters include size, shape (*e.g.*, an n-sided star), and location of damage. In order to quantify point-source damage, researchers from NASA Langley Research Center have performed computational simulations of projectile impact on aircraft wing structures [1]. As shown in Fig. 2, the angle and location of projectile impact, among other factors, affect the damage characterization in stiffened wing panels. Results from these simulations will be used to parameterize initial damage states. Presently, however, the focus is on the development of a methodology for performing three-dimensional crack growth simulations to predict residual strength of aircraft structural components. Once proper physics and modeling techniques have been incorporated, focus will be placed on populating a response surface with results based on various parameterized initial damage states.

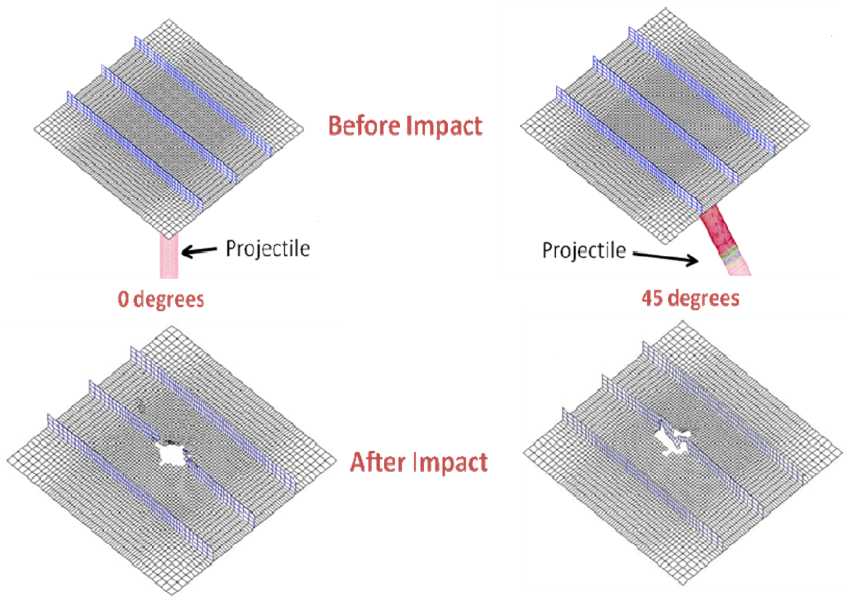

Fig. 2 Models showing damage caused by generic projectiles impacting a stiffened wing panel at angles of 0^{o} and 45^{o} [1].

2.2 ABAQUS/F3DNG Software System

The computational modeling and analysis process is shown schematically in Fig. 3. Model geometries, materials, and boundary conditions are defined using the commercial finite element code, ABAQUS. The finite element model is then read into the CFG's in-house three-dimensional fracture analysis code, FRacture ANalysis Code 3D / Next Generation (FRANC3D/NG or F3DNG for short). Within the F3DNG environment, crack growth analysis is performed. This analysis process entails explicitly defining the crack(s) in the model, incrementally propagating the crack(s) using an adaptive remeshing technique, calling ABAQUS to analyze the model at each crack growth step, and computing fracture growth parameters, which is performed automatically.

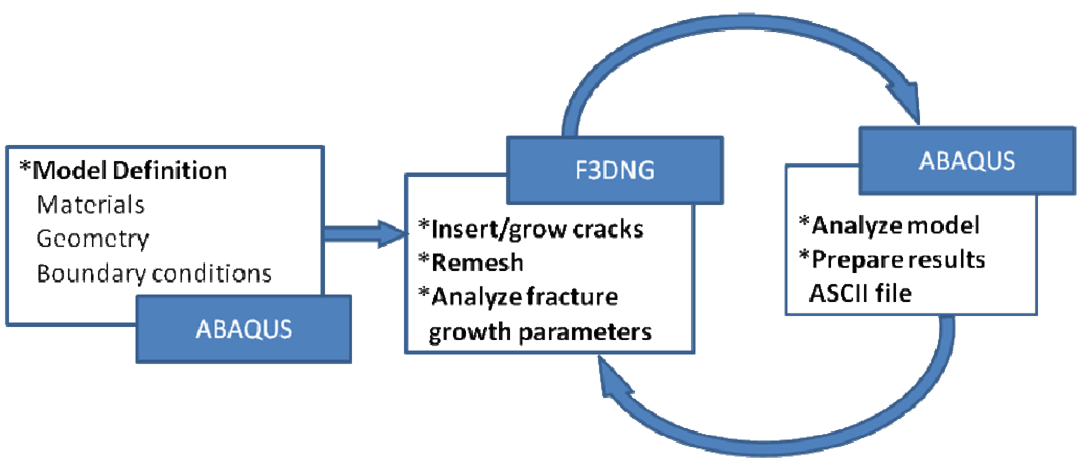

Fig. 3 Simulation flowchart for modeling and analyzing damage propagation.

For the purpose of developing the finite element-based fracture mechanics analysis methodology described above, an LEFM approach is presently assumed in performing crack growth simulations. The analysis invokes the conservative M-integral for computation of stress intensity factors [2,3]. Based on stress intensity factor history and appropriate empirical constants, the Forman-Newman-de Koning model is used to model fatigue crack growth rate beyond the Paris regime, i.e. Region III of the da/dN versus ΔK curve [4]. Because significant amounts of damage have likely accumulated due to point-source damage, we are primarily concerned with predicting residual strength of the structure based on remaining cycles necessary to enable safe landing of the damaged aircraft.

3. Proof-of-concept

Proof-of-concept simulations have been performed, demonstrating the capabilities of the fracture analysis software developed by the CFG. Fig. 4 shows images from a simulation performed by Chen *et al.* of curvilinear crack growth in a damaged fuselage panel subject to internal pressurized loading [5]. In this particular example, the fuselage panel was modeled using shell elements. The computational simulation was carried out using a STAGS/FRANC3D analysis environment rather than the presently described ABAQUS/F3DNG environment. A critical CTOA was used to characterize elastic-plastic crack growth and to predict residual strength. In Fig. 4, contours represent out-of-plane displacements on the deformed mesh model.

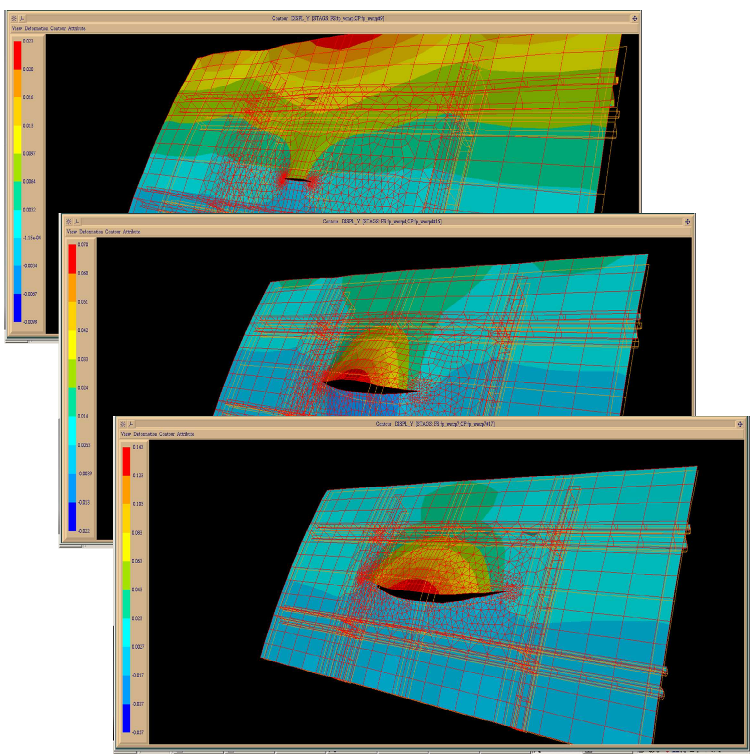

Fig. 4 Curvilinear crack growth simulation of pressurized fuselage panel (exterior view of panel). Contours indicate out of plane displacement [5].

For illustrative purposes, a shell-to-solid coupled model was created using the same fuselage panel used by Chen *et al*. This was done by importing the original fuselage panel shell model into ABAQUS and replacing shell elements with solid elements for a region of the model surrounding the crack front. Using F3DNG, a new crack was then inserted into the local solid region. Multi-point constraints were invoked to couple the local solid region to the global shell region. The simulation result is shown in Fig. 5, where the contours indicate the maximum principal tensile stress near the crack front.

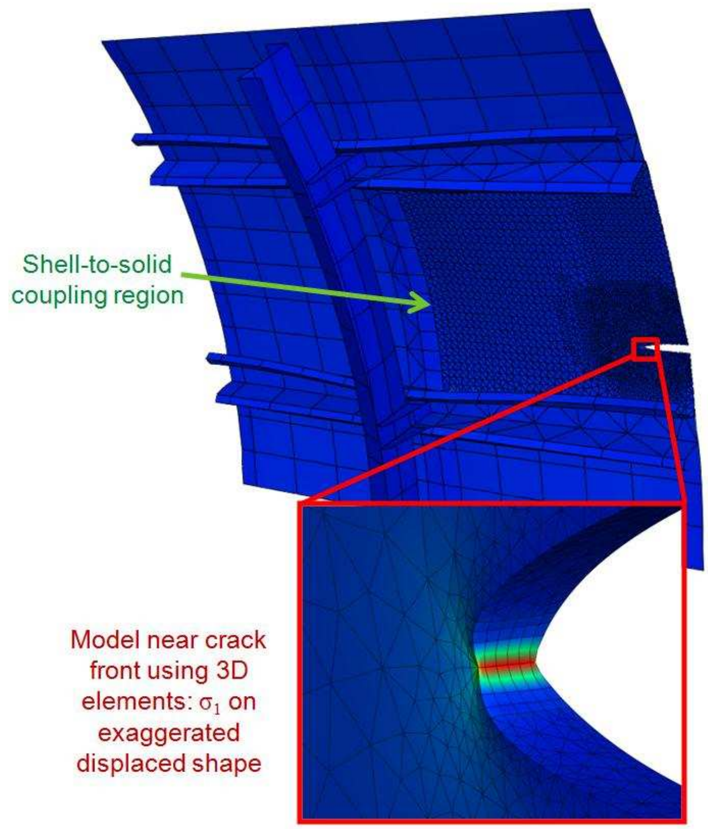

Fig. 5 Shell-to-solid coupled sub-model of pressurized fuselage panel with detail of crack front deformation (interior view of panel). Contours indicate maximum principal tensile stress.

4. Future Work

The immediate focus of the CFG on the current project is to continue developing and refining a finite element-based methodology for predicting residual strength of damaged airframe structures in real-time using three-dimensional crack growth simulations. Once the physical and modeling details of the methodology have been sufficiently considered, future work will focus on performing simulations of damage propagation based on parameterized damage sets. A response surface methodology will then be employed using the results from these simulations. Finally, collaboration with other members of the IRAC project will be necessary to integrate the response surface with the control system such that a damage-dependent flight envelope can be achieved.

5. Acknowledgements

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6. References

[1] R.L. Hinrichsen, A.G. Kurtz, J.T. Wang, C.M. Belcastro, J.L. Parks, Modeling projectile damage in transport aircraft wing structures, AIAA J. 46 (2) (2008) 328-335

[2] L.Banks-Sills, I. Hershkovitz, P.A. Wawrzynek, R. Eliasi, A.R. Ingraffea, Methods for calculating stress intensity factors in anisotropic materials: Part I—z=0 is a symmetric plane, Eng. Fract. Mech. 72 (2005) 2328-2358

[3] L. Banks-Sills, P.A. Wawrzynek, B. Carter, A.R. Ingraffea, I. Hershkovitz, Methods for calculating stress intensity factors in anisotropic materials: Part II—Arbitrary geometry, Eng. Fract. Mech. 74 (2007) 1293-1307

[4] J.C. Newman Jr, A crack opening stress equation for fatigue crack growth, Int. J. Fract. 24 (4) (1984) R131-R135

[5] C.S. Chen, P.A. Wawrzynek, A.R. Ingraffea, Prediction of residual strength and curvilinear crack growth in aircraft fuselages, AIAA J. 40 (8) (2002) 1644-1652