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## Fatigue Crack Growth Life Assessment for Industrial Applications using Re-meshing and Bayesian Hybrid Techniques

Adrian Loghin\*, Balajee Ananthasayanam, Jeff LeMonds, Arun Subramaniyan,  
Felipe Viana

*General Electric Global Research Center, Niskayuna, NY, USA*

### Abstract

In this study, two different techniques are outlined for assessment of fatigue crack growth life of industrial components: i) a finite element based approach (3DFAS, GE proprietary) using re-meshing techniques that allows automatic propagation of cracks under realistic loading conditions and ii) novel approach using Bayesian hybrid methods (BHM) that significantly improves the efficiency of life assessment computation of the former approach. Parallel processing of a set of three dimensional crack geometries using 3DFAS and Ansys™ is used to create a crack propagation space that is further used to build metamodels required to assess propagation life for an asymmetrically grown planar crack. Verification of the 3DFAS-BHM procedure against automatic (serial mode) finite element crack propagation simulation (using 3DFAS) is provided.

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*Keywords:* crack propagation, fracture mechanics, finite element, 3DFAS, life assessment

### Nomenclature

3DFAS Three Dimensional Fracture Analysis System

BHM Bayesian Hybrid Modelling

a crack depth dimension (minor semi-axis length of the elliptical crack surface)

\* Corresponding author: Tel.: 01-518-387-4337; fax: 01-518-387-7006.

*E-mail address:* [loghin@ge.com](mailto:loghin@ge.com)

|          |  |
|----------|--|
| $2c$     | Crack length at the free boundary of the model (major axis length of the elliptical crack surface) |
| $dc_1$   | Crack advancement increment at “ $c_1$ ” location  |
| $dc_2$   | Crack advancement increment at “ $c_2$ ” location  |
| $da$     | Crack advancement increment at “ $a$ ” location  |
| $K_{Ia}$ | Stress intensity factor at the crack depth (“ $a$ ” length) location                               |
| $K_{Ic}$ | Stress intensity factor at “ $c$ ” location  |
| $Y_c$    | Center of the elliptical crack surface   |
| $\mu$    | Mean value   |
| $\sigma$ | Standard deviation   |
| DOE      | Design of experiment   |

## 1. Introduction

In a very recent review on remeshing techniques in three dimensional fracture mechanics, Branco et al. (2015) captures state-of-art capabilities and lays out further challenges to improve current meshing and geometry representation procedures for models containing cracks, enhance criteria for mix-mode and non-proportional loading crack propagation and validate the modelling framework against experimental measurements. The intent of this study is to add to general knowledge the crack propagation capabilities developed at General Electric in the recent years. The development, 3DFAS [Loghin et al. (2009, 2010)], uses meshing capabilities developed by Simmetrix Inc. [Klass et al (2011)] in a Graphical User Interface (GUI) that is GE proprietary. The goal of the development is to provide a streamlined capability to perform crack propagation simulation using existing CAD or FEM models, and to eliminate most of the tedious modelling development that was associated in the past with crack insertion or propagation. The 3DFAS implementation was intended to satisfy several industry level requirements: accuracy, efficiency, ease of use, and robustness.

Two main procedures were implemented in the development: first starts with a Parasolid model while the second uses and orphan mesh as an input. Independent of the native model (CAD or orphan mesh model), 3DFAS provides capabilities to insert a crack or multiple cracks, mesh the new model, assign loading and boundary conditions, perform the simulation using Ansys™ and post-process the solution to compute stress intensity factors at each node along the crack front. The process is repeated automatically for each crack advancement considered in the simulation. Independent of the native model (CAD or orphan mesh) the GUI follows the same process to provide a simple interface to all the users. Any initial crack shape can be considered by using a Parasolid representation of the crack surface which basically removes the usage of a predefined crack surface library.

For the orphan mesh procedure, the mesh that is created after crack insertion blends with the initial mesh and enforces compatibility between elements by using pyramids for tetrahedron to brick transitions and quadratic elements with linear faces or edges for linear-quadratic interfaces. Since in most cases only a small mesh region is removed from the orphan mesh (to have it replaced with a new mesh containing the desired crack), 3DFAS maintains the rest of the orphan mesh (elements and node numbers) to easily assign boundary conditions and loading from a previous static analysis and therefore recycle any existing model. There is no need for multiple point constraint or submodels to control the region where crack is inserted.

If a Parasolid model is used for crack insertion, the crack is inserted in the geometry and the mesh process is performed for the entire model containing the crack. Even though 3DFAS was designed to use Ansys™ and Unigraphics™, other orphan meshes and CAD geometries can be used by simply converting them into an Ansys™ or Parasolid format respectively.

Validation of predictions made with 3DFAS was presented before [Loghin et al. (2009, 2010)] and for completeness of this paper one of the validation cases is included in Fig. 1.

One aspect that would define the efficiency of the overall process is the run time ratio between the crack insertion procedure and the Ansys™ solution. For the generic models presented in Fig. 2, crack insertion and remeshing procedure take less than one minute while the solution runtime in Ansys™ might take hours. Another efficiency criterion consists in letting the crack surface adapt to the shape of the solid geometry/mesh during propagation and

allow a crack shape transition without any input from the user. The crack advancement is therefore controlled only by stress intensity factor magnitude and not by constraints associated with input model or mesh.

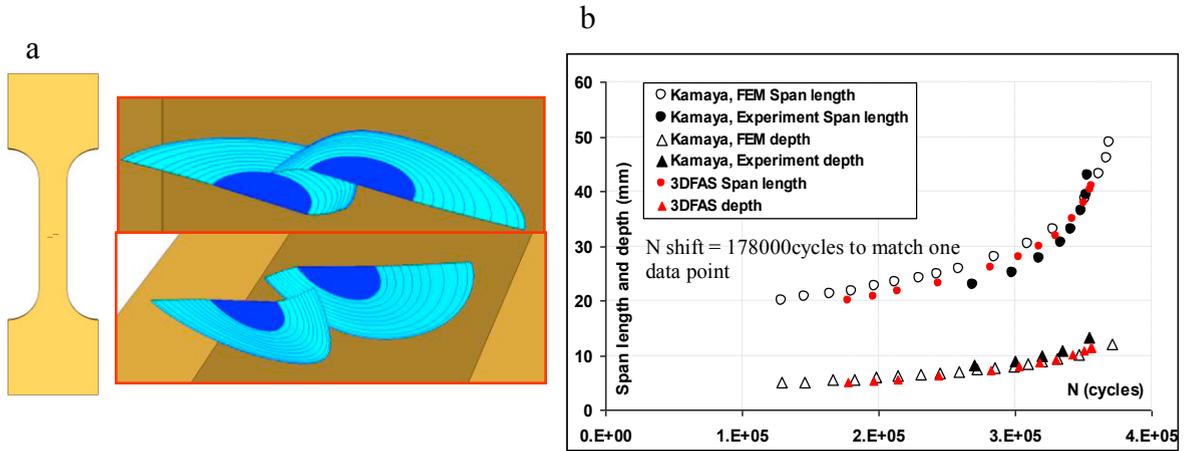


Fig. 1. Example of validation of the crack propagation procedure in 3DFAS. (a) 3D model used in the simulation and (b) comparison with the measurement and modelling provided by Kamaya (2008)

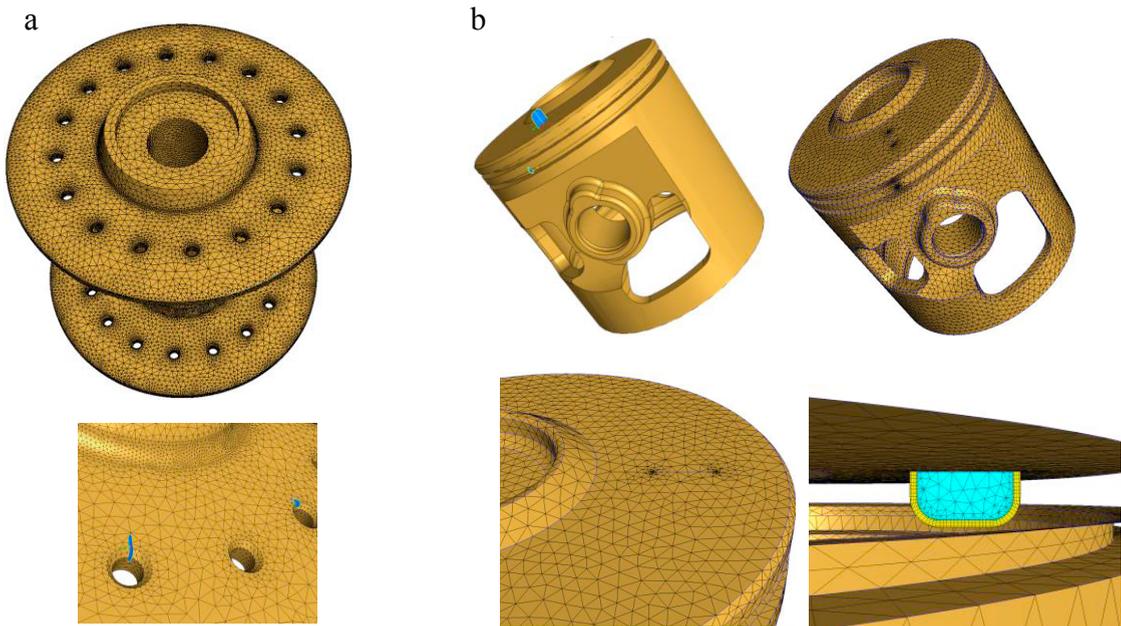


Fig. 2. Two generic examples for typical applications. (a) overall mesh of a flange and two crack locations at the bolt holes and (b) piston geometry along with the mesh containing a crack on the crown.

## 2. Three dimensional fracture mechanics using Bayesian Hybrid Modeling

Alternative approaches were considered to reduce the three dimensional fracture mechanics simulation runtime and bring 3D accurate solutions closer to a probabilistic life assessment type. Bayesian Hybrid Modeling [Srivastava (2015)] was considered as an alternative to classical transfer functions designed for simple geometries and crack configurations using finite element method [Newman and Raju (1984)]. Steps involved in this novel approach along with accuracy and efficiency of the 3DFAS-BHM method for a generic fracture mechanics is presented.

### 2.1. Problem Definition

The propagation of an initial semicircular surface crack of 0.02” on the side face of a four-point bend specimen was considered for this study. The reason for selecting this example is the crack growth asymmetry due to a bending stress gradient and, secondly, the shape transition of the crack surface during propagation i.e. from a surface to a corner and finally to an edge shape.

Concentrated force of 5000 lbf was applied along the edges as indicated in Fig. 3. From the bottom face, the crack center ( $Y_c$ ) is located at 0.5” on the side face (Fig. 4a). The width and thickness of the considered geometry are 2” and 1.5” respectively while the length is 10”. At maximum load of a total of 10 kips, the crack is subjected to linearly varying far field stress in the width direction. This causes the crack to grow faster towards the bottom surface than the top surface. The crack growth is simulated automatically using 3DFAS considering a loading cycle of 0 to 10 kips to further provide a reference for the 3DFAS-BHM coupled approach. Fig. 4 shows the crack front evolution during simulation along with the transition of the crack front shape through the edges of the solid model. The mesh used in analysis of the initial model containing the 0.02” semicircular crack is shown in Fig. 5. The stress intensity factors are computed using displacement correlation technique [Ozkan (2006)].

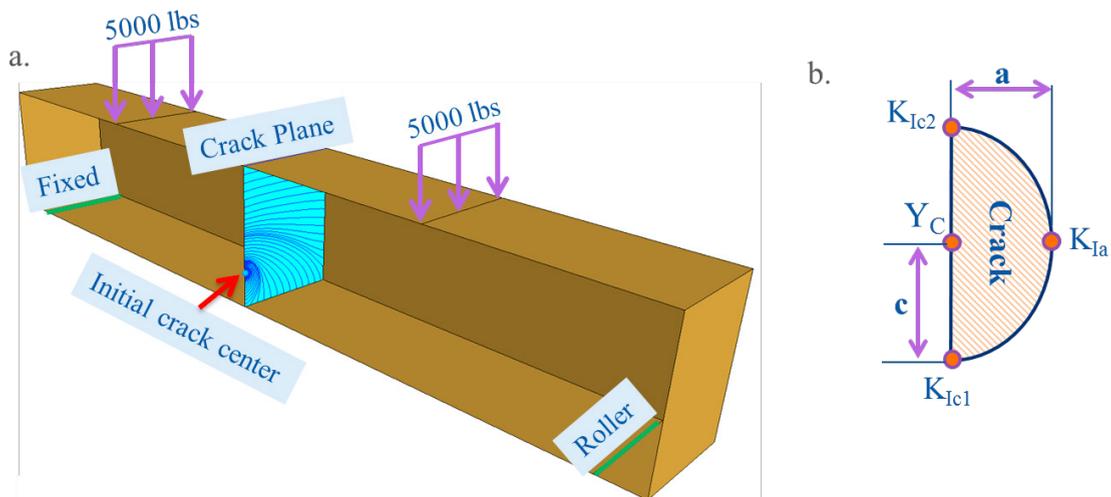


Fig. 3. (a) Four point bend specimen geometry, loading and boundary conditions, initial crack location and predicted propagation path; (b) Nomenclature used in crack definition.

### 2.2. BHM Approach for Asymmetric Surface Crack Growth

Since the crack tip on the surface near the bottom side grows faster, keeping track of the crack size becomes a challenge. One possibility is to keep the center of the crack fixed and track the growing crack tip individually on each side ( $K_{Ic1}$ ,  $K_{Ic2}$  locations) of the crack. Another possibility is to move the center of the crack as the crack is growing such that the center of the semi-elliptical crack is always at the mid-point of the surface crack tips. This

approach is based on the assumption that the crack face is always semi-elliptical in nature which is a typical assumption in most planar crack growth problems. The latter approach is used in the current study to keep the number of variables governing propagation to a minimum. An example of three cracks considered for simulation is shown in Fig. 6. Each crack has a different center and size defined by crack depth “a” and a length of “2\*c”.

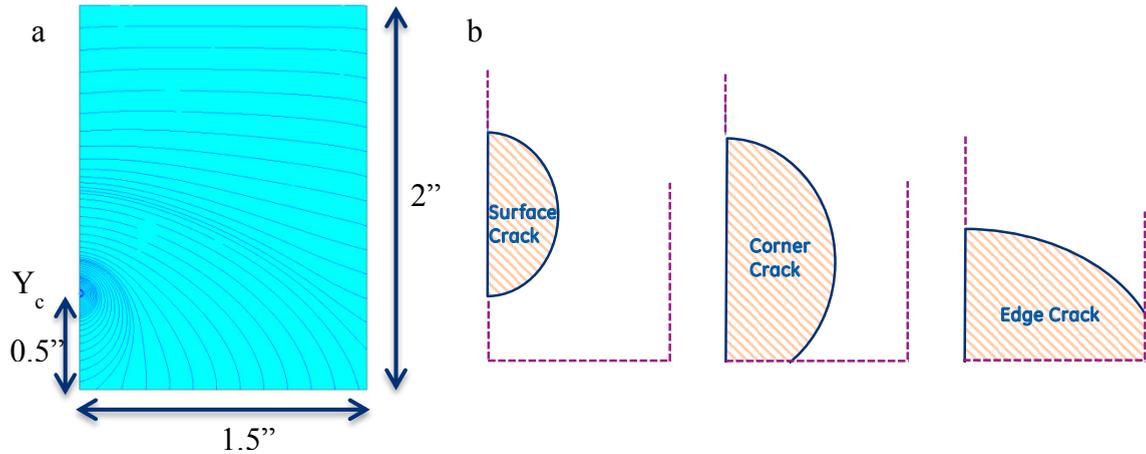


Fig. 4. (a) Predicted crack front evolution; (b) Crack shape transition.

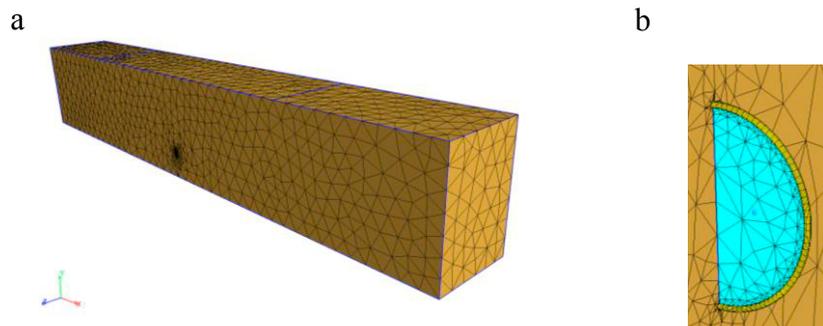


Fig. 5. (a) Overall mesh of the model and, (b) crack surface and crack front mesh used for the initial crack FE simulation

In order to develop BHM models [Srivatsava (2015)] for this crack propagation model, a set of 39 optimally spaced design points were generated in 3-parameter crack propagation space ( $c$ ,  $a$ ,  $Y_c$ ) as shown in Fig. 7. The 3-parameters were defined as follows:

- $\log(a)$  – Uniform Distribution ( $0.02'' < a < 1.5''$ )
- $c/a$  – Exponential Distribution ( $\mu = 0.7$ )
- $Y_c$  – Normal Distribution ( $\mu = 0.5$ ,  $\sigma = 0.25$ )

The parameter ‘ $c/a$ ’ was chosen because the crack aspect ratio is usually known through experience while  $\log(a)$  was chosen (instead of ‘ $a$ ’) because more design points are required for smaller size cracks since the majority of life is spent when the crack is small and hence more accurate stress intensity factors are required to reduce the error in the predicted life.

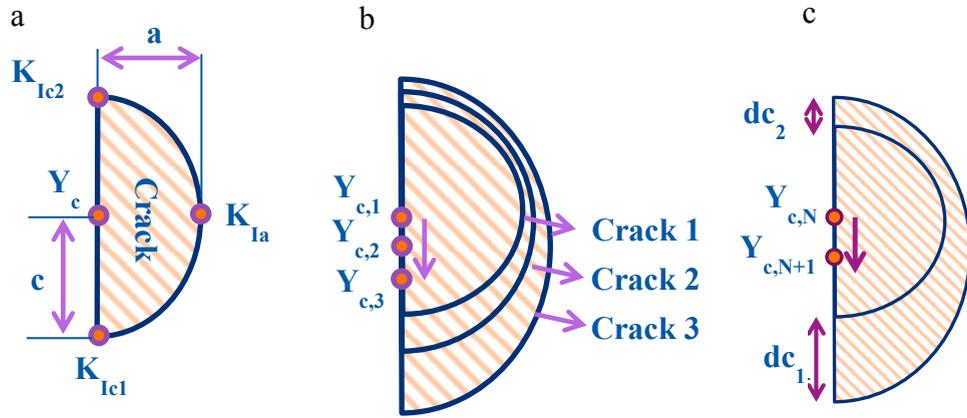


Fig. 6. (a) Definition of crack location ( $Y_c$ ) and size (“a” and “c”); (b) Crack locations and shapes simulated by 3DFAS to create a crack propagation space for 3DFAS-BHM approach; (c) Advancement procedure using BHM to simulate an asymmetric surface crack evolution.

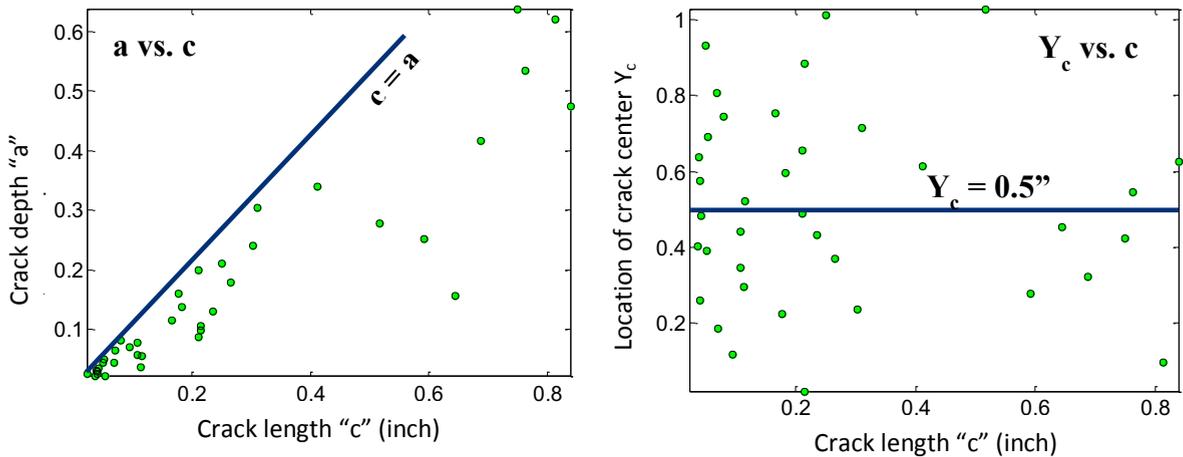


Fig. 7. Optimal Latin Hyper Cube Design Points in 3-parameter crack propagation design space ( $c, a, Y_c$ )

For all these elliptical crack sizes and locations shown in Fig. 7, stress intensity factors at ( $K_{Ic1}, K_{Ic2}, K_{Ia}$ ) are computed by generating all the meshes using 3DFAS and processing them in Ansys™. Since all these models run in parallel, the runtime for generating stress intensity factor solutions for all the design points was less than 10 minutes in high performance parallel computing environment. After the DOE runs are complete, the following three BHM model models were developed:

$$K_{Ic1} = BHM(c, a, Y_c); K_{Ic2} = BHM(c, a, Y_c); K_{Ia} = BHM(c, a, Y_c); \tag{1}$$

To confirm the accuracy of the stress intensity factors computed with the BHM model, an error assessment is shown in Fig. 8. The reference data is given by the stress intensity factors computed using finite element representation of the model containing the crack.

The error is less than 10% for the fitted data. After the BHM models were developed, the final step is to solve the initial value problem stated below using the stress intensity factor solutions from the BHM models:

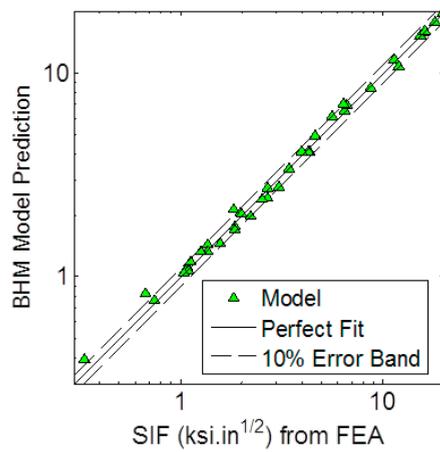


Fig. 8. Comparison between predicted stress intensity factor using BHM and direct computation using the finite element model (log scale).

$$\frac{da}{dN} = C \cdot (\Delta K_{Ia})^n; \frac{dc_1}{dN} = C \cdot (\Delta K_{Ic1})^n; \frac{dc_2}{dN} = C \cdot (\Delta K_{Ic2})^n \tag{2}$$

with initial conditions,  $c_1(0) = c_2(0) = a(0) = 0.02''$ ,  $Y_c(0) = 0.5''$ .

The crack propagation increment was calculated using  $c_1$ ,  $c_2$  and  $a$  instead of  $c$ ,  $a$ ,  $Y_c$ . Finally from  $c_1$ ,  $c_2$ , an average  $c$  is calculated and the center of crack is adjusted as follows:

$$c_{1,N+1} = c_{1,N} + dc_1; c_{2,N+1} = c_{2,N} + dc_2; a_{N+1} = a_N + da; Y_{c,N+1} = Y_{c,N} + \frac{c_{2,N+1} - c_{1,N+1}}{2} \tag{3}$$

3DFAS can run the entire crack growth simulation in about 6 hours capturing surface crack asymmetry and transition to corner and edge shape by advancing the crack front in a series of finite element solutions. In comparison, the computational time reduces to about 1/10 since the 3DFAS-BHM method uses parallel computation and solves 39 cases all together. For reference, fatigue crack growth rate is captured using  $C=3.6e-19$  and  $n=3$  in (2) (unit system: psi, in). Direct comparison between the two procedures is shown in Fig. 9.

### 3. Conclusions

Within 3DFAS framework, planar and non-planar cracks can be inserted in any CAD representation or in an existing orphan mesh of a component allowing an easy recycling of modeling development. 3DFAS allows transition to arbitrary planar and out-of-plane shape, crack surface intersection with component internal features, modeling of non-symmetrical cracks or it accounts for the effect of multiple cracks making the tool suitable for a broad of fracture mechanics applications. The procedure can be computationally intensive since each crack front increment is captured in a finite element model.

With the proposed 3DFAS-BHM approach, the efficiency of life assessment computation can be significantly improved for planar cracks. Steps involved in this novel approach are presented for an asymmetric crack growth to demonstrate the accuracy and efficiency of the method. In this approach, the crack propagation space with different crack locations, shapes and sizes is designed using an optimal Latin-hypercube sampling. Each of these DOE points is simulated (parallel computation of the entire set) using finite element models to construct the relationship between simulated cracks and stress intensity factors ( $K_I$  only). BHM techniques are employed to create metamodels to relate crack geometries to  $K_I$  values ( $K_{Ia}$ ,  $K_{Ic1}$ ,  $K_{Ic2}$ ) which are further used in the assessment of crack propagation life. For

the example provided herein, this novel approach captures crack propagation life accurately in a tenth of the runtime of a full finite element crack propagation simulation.

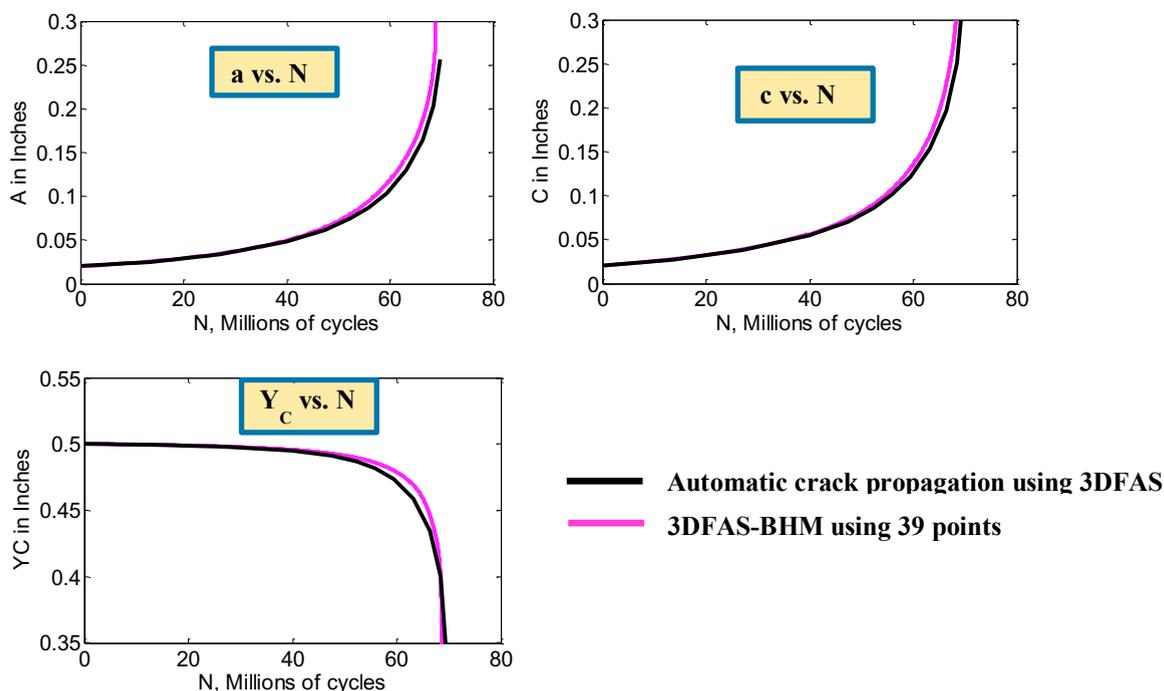


Fig. 9. Comparison between predicted crack size (“a” and “c1+c2” span) using automatic crack propagation in 3DFAS and reduced order 3DFAS-BHM methodology using 39 points in crack propagation space.

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