DDSIM: A NEXT GENERATION DAMAGE AND DURABILITY SIMULATOR

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ABSTRACT

Current state-of-practice tools for life prediction of structural components are limited in some or all of the following capabilities: geometry of and boundary conditions on the affected structural component, automation of the analysis process, stochastics of the primary variables, and physics of the damage evolution processes.

A next generation damage and durability simulator, DDSim, is being developed to address each of these limitations with a hierarchical "search and simulate" strategy. This strategy consists of two levels. The focus of this paper is on the first level analysis tool, DDSim Level I, which performs an initial, reduced order screening to determine the most dangerous intrinsic flaw locations through an automated interrogation of the structure. DDSim Level I accomplishes this using the principle of superposition to combine stress fields from an uncracked structure with analytical stress intensity factor solutions for internal, surface and corner cracks to estimate the fatigue life of the structure. The stress field information is computed using a finite element code and is transferred to DDSim Level I via the mesh and nodal stress data. Hence, any finite element code capable of outputting such data, can been used. Next, a fatigue life prediction is made assuming a crack originates in the worst possible orientation at every node in the finite element model. The result is a scalar field of predicted life on the domain of the structure and, thus, is plotted on a contour map. The contour map, titled the Damage Hazard Map (DHM), provides rapid visualization of the most critical flaw locations.

The DHM is a useful bi-product of the Level I analysis; however, the main purpose for the initial screening is to feed the second level tool, DDSim Level II. DDSim Level II is designed to intensely focus on the upper echelon of flaw location criticality with high performance, parallel computing finite element power, the best known physics, and the most advanced numerical modeling techniques. More description of DDSIM Level II will be presented during the oral presentation of this paper.

1 INTRODUCTION

The issue of aging air- and spacecraft has seen increasing attention recently and brought with it the task of damage prognosis. Damage prognosis is defined by Farrar *et al.* [1] as the estimate of a system's remaining useful life. There are many contributing elements to successful damage prognosis including quantifying the current status of the structural integrity, recording previous loading history, estimating future loading patterns and developing robust material models that account for such things as environmental effects. A next-generation tool is required to blend all of this useful information and simulate the structure's remaining life.

Current tools available for damage prognosis impose many restrictions on the engineer. They often separate the tasks of computing field data from computing material response, making them cumbersome. In addition, this decoupling often requires the damage to take a hand-book type geometrical form, hence, constricting its behavior. Furthermore, the material and life prediction models in current use usually do not account for material variability. These limitations result in a very deterministic and geometrically overly simplified approach to damage prognosis. In other words, due to the cumbersome nature of the tools, the engineer assumes damage originates at only a few, best estimate, locations in the structure, grows in some geometrically restricted manor, and necessarily has the same material properties of the average lab specimen.

Clearly, there is high demand for an automated life prediction tool that embraces the physics and recognizes the stochastic nature of the problem. To that end, a next generation damage and durability simulator, DDSim, has been developed using a hierarchical “search and simulate” strategy. This strategy consists of two separate stages, or levels. The focus of this paper is on the first level analysis tool, DDSim Level I, which performs an initial, reduced order screening to determine the most dangerous intrinsic flaw locations through an automated interrogation of the structure.

The Level I analysis is used to feed the second level tool, DDSim Level II. DDSim Level II is designed to intensely focus on the upper echelon of flaw location criticality with high performance, parallel computing finite element power, the best known physics, and the most advanced numerical modeling techniques. More description of DDSim Level II will be presented during the oral presentation of this paper.

2 DDSim LEVEL I

Figure 1 shows a flow chart describing DDSim Level I. Components were developed to read and store the finite element data, operate on the data under the assumptions of linear elastic fracture mechanics, store and organize the resulting fatigue life predictions, and post-process the data. The following discussion elaborates on these tasks and presents a case study of DDSim Level I.

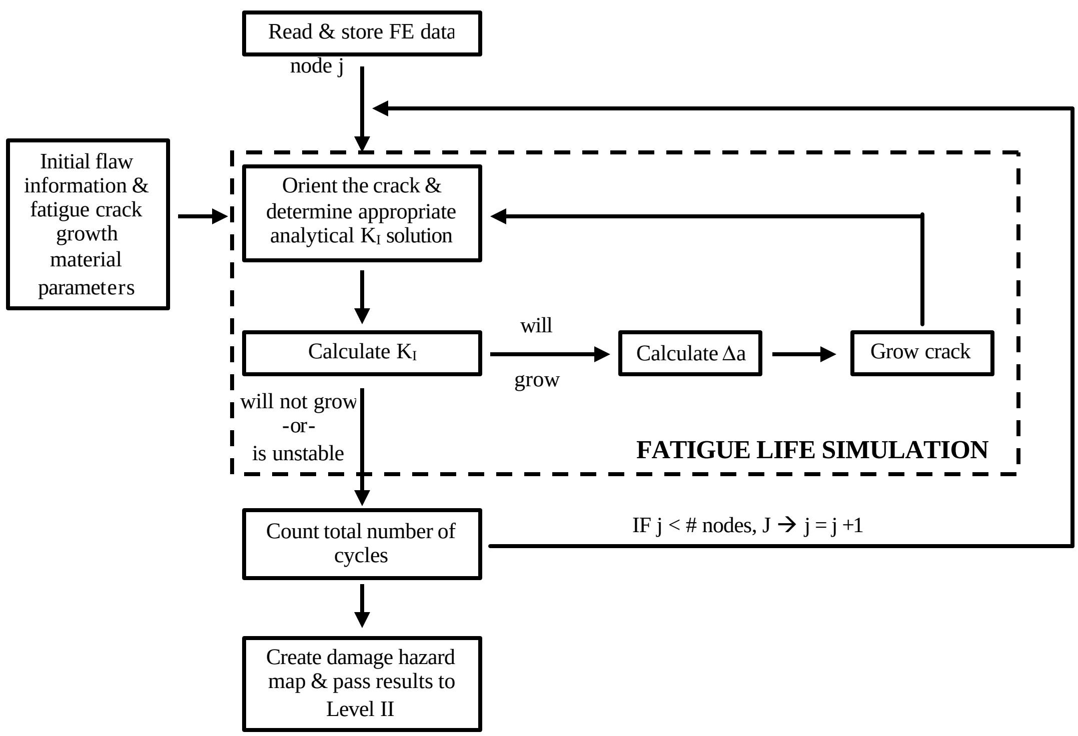

Figure 1: Flowchart for DDSim Level I

2.1 Input

As previously mentioned, DDSim Level I was designed to operate on a user-supplied finite element generated stress field. In order to do so, a robust method to read, to store and to query the finite element mesh and corresponding data was developed. The required input from the finite element analysis is the mesh and nodal stress values, and both are input from ASCII text files.

Additional user input is required in order to perform the fatigue life calculations. This input is: initial flaw size (specified as the major and minor axes of an elliptical flaw), minimum crack growth increment, maximum practical life span (in loading cycles) and the critical stress intensity factor, $K_{I,c}$.

The initial flaw size is intended to be the intrinsic characteristic material defect or the largest flaw size not detectable by testing. The minimum crack growth increment and maximum practical life span are structure/boundary condition specific. The critical stress intensity factor is a material property. Currently, these inputs are specified deterministically. However, they provide the most obvious opportunity to begin treatment of the stochastics of the problem. In the immediate future, these parameters will be specified via mean and variance, and thus take on randomly assigned quantities.

2.2 Fracture Mechanics

For initial development the Paris law was used as the crack growth rate model because of its simplicity. The Paris law gives the crack growth rate as:

$$\frac{da}{dN} = C\Delta K^{n} \tag{1}$$

where a is the crack length, N is the number of loading cycles, ΔK is the difference between the maximum and minimum mode one stress intensity factors during a loading cycle, and C and n are user-specified material constants. Forman and Mettu [2] give a crack growth rate relationship that more accurately reflects experimental data, commonly known as the NASGRO crack growth rate equation. The NASGRO equation will be added as a user option before the oral presentation of this paper.

To use eqn (1), or the NASGRO equation, for calculating a crack growth rate increment, DDSim Level I calculates ΔK using analytical stress intensity factor (SIF) solutions in conjunction with stress field data extracted from the finite element data. Three analytical solutions are used: that for a fully-elliptical flaw in an infinite body given by Roy and Saha [3], and those for a semi-elliptical flaw and a quarter-elliptical flaw, both given by Raju and Newman [4]. The solution for a full ellipse requires the stress field on the crack to be approximated by a bi-quadratic polynomial. The solutions for the semi- and quarter-elliptical cracks impose similar restrictions and require the stress field to be approximated as linearly varying over the flaw surface.

It is worth noting the shortcomings of these analytical solutions. First, as noted, they do not allow for completely arbitrary stress fields. Next, they constrict crack growth to planar, elliptical shaped growth. However, since DDSim Level I is intended to be a fast, reduced order screening tool, these limitations are acceptable. In fact, the benefits of their ease of use outweighs their limitations in the Level I analysis. Further, DDSIM Level I is a preprocessor for more rigorous life prediction in Level II.

2.3 Procedure

For illustration, presume a finite element model containing J nodes is read into DDSim Level I. The procedure to calculate the fatigue life at node number j is shown in the dashed box in Figure 1. The first task is to determine the worst-case orientation for the initial crack at node j. The default crack orientation is chosen such that the crack surface is perpendicular to the major principal stress. Then, somewhat arbitrarily, the major axis of the ellipse is oriented in the direction of the second principal stress. The only exception to these rules is made to avoid placing the crack in the plane of a structural surface. In this situation, the crack is oriented perpendicular to the second principal stress.

The next task is to determine which analytical SIF solution is most appropriate at node j. In other words, it is not known, *a priori*, if the initial fully elliptical crack is entirely contained in the domain of the structure. For example, if node j is a surface node, the semi-elliptical crack solution would be chosen.

After determining the most appropriate SIF solution, the stress field is sampled over the crack, rotated in to a basis perpendicular to the crack surface and a least squares fit to the degree polynomial required by the SIF solution is performed. With this accomplished, ΔK is calculated along the crack front centered at node j. With ΔK computed, it must be determined whether crack growth should continue or whether the loop should be exited. There are two reasons to exit the loop: 1) if the crack is unstable, or 2) if it would not grow or grows very slowly.

For sake of discussion, assume it is determined that the crack at node j would grow. The next task is to calculate the crack growth increments using eqn (1). These increments are computed keeping in mind the restrictions of the analytical solutions and the user-specified minimum crack growth increment. With the crack growth increments computed, the crack is grown and the loop restarted.

When it is determined appropriate to exit the fatigue life simulation loop, the total number of load cycles for node j is tallied. Next, the node number is updated and the entire process is repeated for node j+1. This continues until a life prediction has been made for all J nodes in the finite element model. The final task is to summarize the findings visually in the form of a contour plot of predicted life, the Damage Hazard Map (DHM).

2.4 Case Study: Flat plate with bore holes

A flat plate with two bore holes was chosen for a practical demonstration of DDSim Level I. The finite element mesh contained 46,808 nodes and is shown in Figure 2. The plate was simply supported and subjected to a tensile traction in the global x direction (refer to figure 2). In terms of commonly used fatigue crack terminology, the applied stress range, $\Delta\sigma$, was 17.1 ksi, with an R value of zero. The elastic material properties E and ν were 10,000 ksi and 0.33, respectively. The fatigue crack growth material constants C and n were 0.233e-7 (in/cycle)/(ksi$\sqrt{\text{in}}$)^n and 2.885, respectively. Finally, the initial flaw assumed by DDSim was set to be a circular crack of radius 1.0e-3 in. with a maximum practical life span specified as 50,500 load cycles.

Figure 3 shows the resulting DHM with successive zoom-ins on the area of interest near the bore holes. It is important to understand that this contour map *is not* showing a stress plot. This is a contour map that quantifies the most dangerous, or life limiting, locations for propagation from an intrinsic flaw.

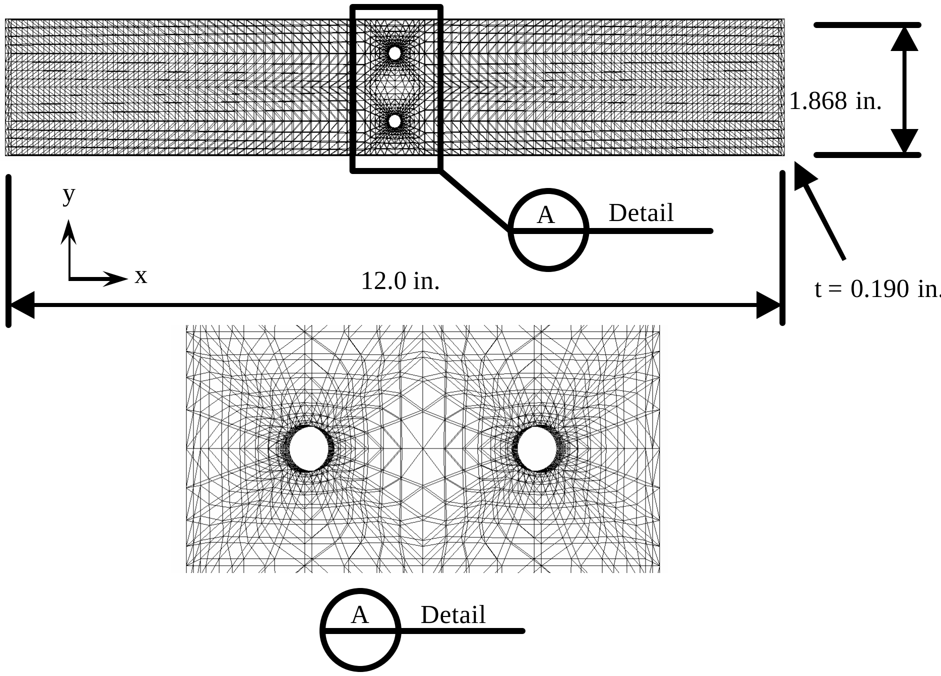

Figure 2: Finite element mesh for case study

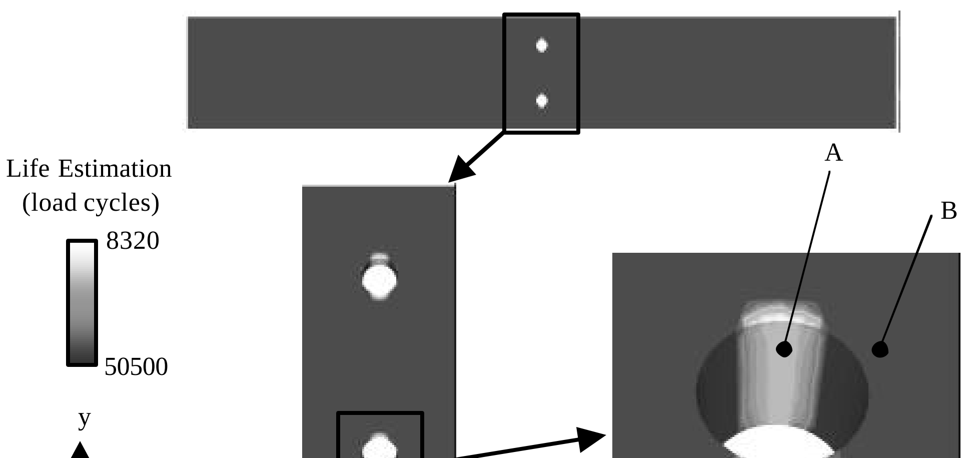

Figure 3: Damage hazard map for case study

From the DHM it can be seen that, subject to the greatly simplified and generally conservative assumptions of this first order analysis, the most dangerous initial flaw locations are adjacent to the bore holes where the predicted life is only 8,320 load cycles. In other words, if an intrinsic flaw of radius 1.0e-3 in. originated at point A (indicated in Figure 3) it would lead to an end of life event in 8,320 load cycles. However, if the same intrinsic flaw originated a point B (Figure 3) it would not lead an end of life event until, at least, 50,500 load cycles.

3 DDSim LEVEL II

With the first order life prediction from DDSim Level I in-hand, the next level of the "search and simulate" strategy, DDSim Level II, is designed to increase the accuracy of the life estimation. This tool alters the finite element mesh by inserting an actual initial crack geometry and remeshing to accommodate growth, as necessary. Crack insertion and remeshing is a well known procedure and has been successfully utilized by Carter *et al.* [5]. This allows the crack driving forces to be computed with a high degree of accuracy. At this point, Level II has the option to apply known methods for fatigue life prediction in linear elastic fracture mechanics or, if appropriate, zoom-in further to the polycrystalline length scale to determine the material response. If the user-specified initial flaw size is on the order of the intrinsic flaw size of the material, it is likely that DDSim Level II would pursue modeling at this scale using similar methods to Iesulauro *et al.* [6].

4 CONCLUSIONS

The result from using DDSim Level II, a next generation damage and durability simulator, will be a high fidelity life prediction of the structure. This life prediction can be used in design or damage prognosis with a high degree of confidence because DDSim: 1) has considered the outcome of an intrinsic flaw originating, practically, anywhere in the structure and 2) has used the best known physics and computational methods.

In the near future, to address the current lack of treatment for uncertainty, the initial crack size, orientation and the fracture mechanics material properties will be assigned stochastic values based on user-specified statistical distributions. DDSim Level I will then perform Monte Carlo type simulations to develop reliability based, first order life predictions.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] Farrar, C. R., *et al.*, Damage Prognosis: Current status and future needs, Report No. LA-14501-MS, Los Alamos National Laboratory, pp. 2-13 & 39-56, July, 2003

[2] Forman, R. G., and Mettu, S. R., Behavior of surface and corner cracks subjected to tensile and bending loads in Ti-6Al-4V alloy, Fracture Mechanics: Twenty-second symposium, Vol. 1, ASTM STP 1131, H.A. Ernst, A. Sexena, and D.L. McDowell, Eds., ASTM, Philadelphia, pp. 519-546, 1992

[3] Roy, A., and Saha, T. K., Weight function for an elliptical crack in an infinite medium. I. Normal loading, Int. J. Fract., 103, 227-241, 2000

[4] Newman, J. C., Jr., and Raju, I. S., Stress intensity factor equations for cracks in three-dimensional finite bodies subjected to tension and bending loads, Ch. 9 of Comp. Meth. in Mech. Fract., Atluri, S. N., Ed., Elsevier Science Publishers, pp. 312-334, 1986

[5] Carter, B. J., Wawrzynek, P. A., and Ingraffea, A. R., Automated 3-D crack growth simulation, Int. J. Numer. Meth. Engng., 47, 229-253, 2000

[6] Iesulauro, E., Ingraffea, A.R., Arwade, S. and Wawrzynek, P. A., Simulation of grain boundary decohesion and crack initiation in aluminum microstructure models, Fatigue and Fracture Mechanics: 33rd Volume, ASTM STP 1417, W.G. Reuter and R.S. Piascik, Eds., ASTM, West Conshohocken, PA, 715-728, 2002.