Fracture & Crack Propagation Analysis System (FCPAS) – Phase 2

A. O. Ayhan*, C. Kurtiş, H. Dündar, M. Derya, O. Demir, E. Nart, S. İriç, H. Lekesiz

*Sakarya University, Faculty of Engineering, Department of Mechanical Engineering

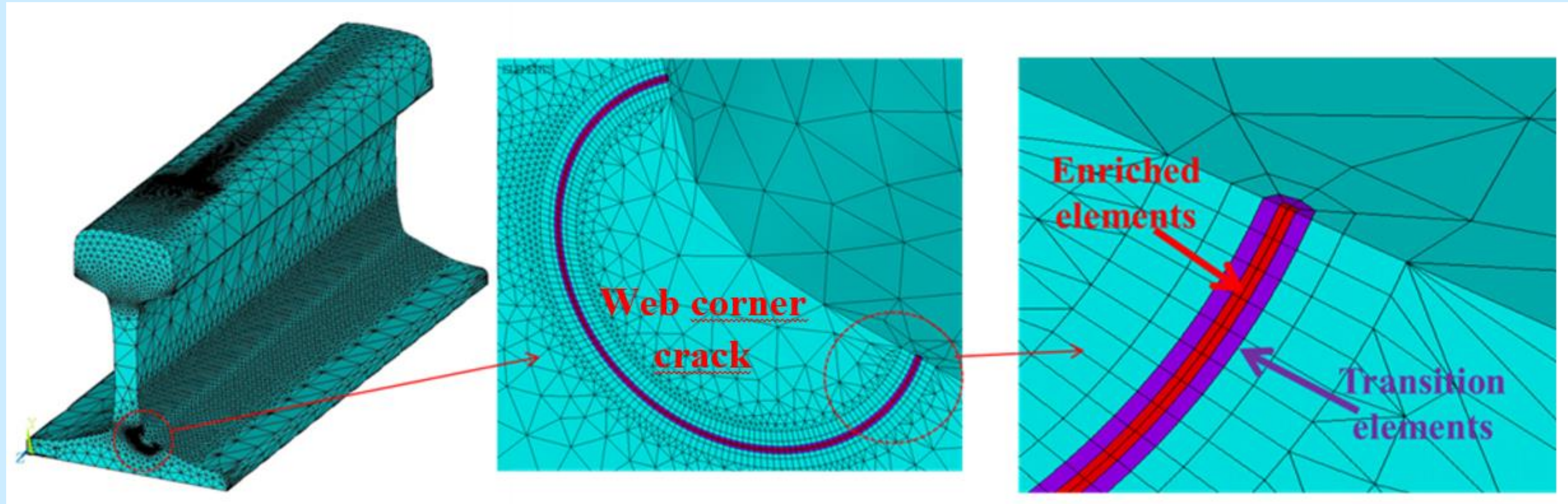
ayhan@sakarya.edu.tr

Modeling of Mode-I Fatigue Crack Propagation Problems Using FCPAS: Applications on Practical Problems

Abstract

Although some cracks seen in engineering structures can be approximated by two dimensional modeling and analysis techniques, most of them are three dimensional in nature and they appear in the form of surface, corner or an embedded crack. Furthermore, in many engineering problems involving cracks and cyclic loads, the fatigue crack propagation life of the component under consideration can be significant part of its overall mechanical life. Though some crack propagation problems are truly three-dimensional, i.e., crack faces evolve into non-planar surfaces, there are many structural problems that involve planar fatigue crack propagation under mode-I stress intensity factor as a crack driving force. In this study, some practical case studies with real part geometry are presented. In these analyses, the mode-I fatigue crack propagation capability, which had been previously developed and applied to basic and simple geometry problems such as surface crack in plates, is employed. The presented practical cases serve as additional sources for the validation of the methodology, which makes use of three-dimensional enriched finite elements to compute stress intensity factors along the three-dimensional crack front. The examples presented are; surface crack in a tubular structure and web corner crack in a UIC 60 rail, both of which are under cyclic four-point bending load conditions as described in the literature. Having compared the results, it is concluded that the predictions from the simulations show very good agreement with the experimental data from the literature in terms of predicted failure point/crack configuration, evolving crack surfaces and crack propagation life. Thus, the presented methodology can be used to assess the remaining fatigue crack propagation life of a structure with a mode-I crack under linear elastic fracture conditions.

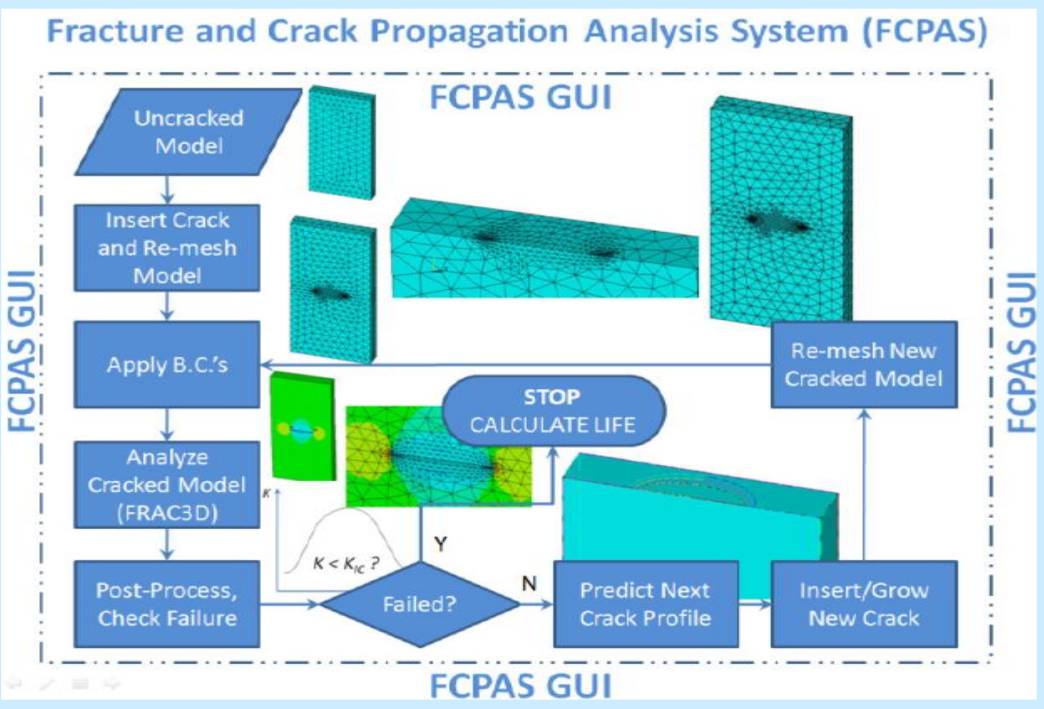
Three-Dimensional Enriched Crack Tip Elements on 3-D Mode-I Crack

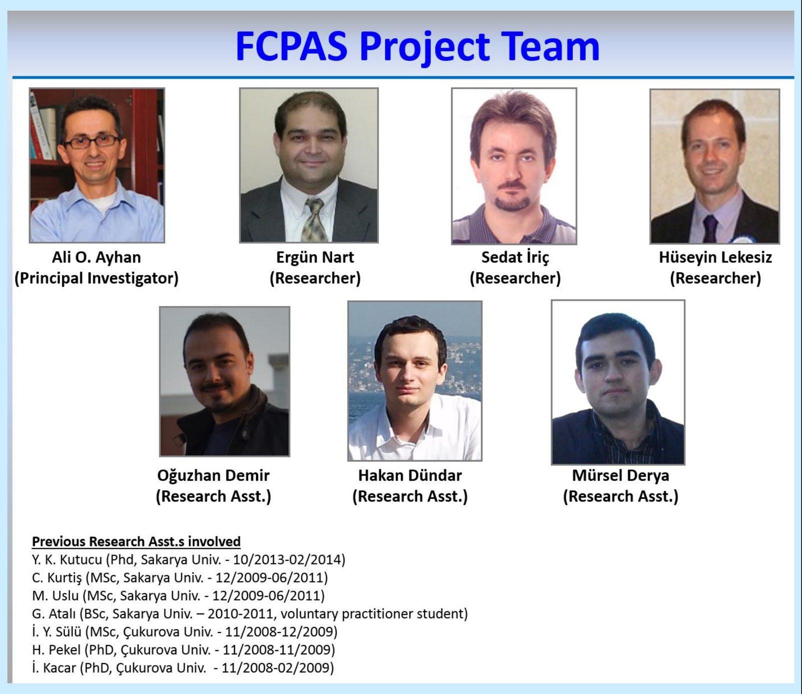


Introduction

The engineering designs that ease our daily lives, continue to gain increasing importance and their safety is the most important parameter which affects people's lives and properties. Fracture analysis and crack propagation life prediction are very important in such areas as transportation, aviation, energy and defense applications. In this study, some applications are presented that demonstrate simulation of fatigue crack propagation: web corner crack in a UIC60 rail [1], multiple cracks propagating from holes on a plate [2], corner crack on a helicopter lift frame [3, 4,] and fatigue crack propagation simulation on a plate under bending [5] using the crack insertion technique.

Results of these simulations (stress intensity factors, crack propagation profiles and life prediction graphs) are compared to literature data. For these simulations, finite element models are generated using ANSYS™ [6], fracture analyses and propagations are calculated by FRAC3D solver of FCPAS software. Having computed the stress intensity factor distribution along a given crack front increment, the next set of positions of the crack front points are predicted using a crack growth law, e.g., Paris law. Then, a five-parameter best ellipse fitting procedure is executed that places a best ellipse to the independently incremented set of crack front points used for the definition of the following crack front definition. In the next step, the updated fracture model and the corresponding finite element mesh is generated that represent the incremented crack configuration and the procedure is repeated until when fracture toughness or a specific crack length is reached. The results obtained from the simulations showed excellent agreement with the experimental data from the literature.





Material and Method

The main and most important method used within FCPAS is the three-dimensional enriched finite element technique incorporated within the solver part of FCPAS, FRAC3D. The second important part of the procedure is the crack growth process implemented within FCPAS.

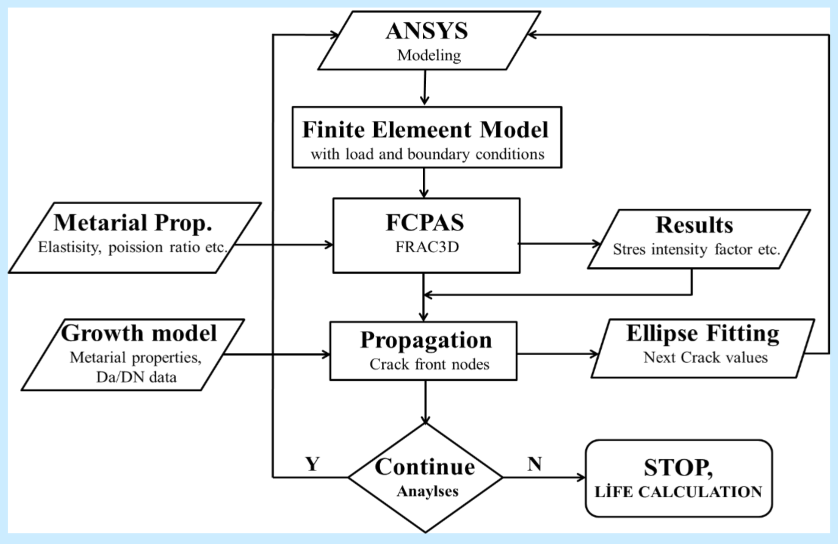
Formulations for Three-Dimensional Enriched Finite Elements and Crack Propagation

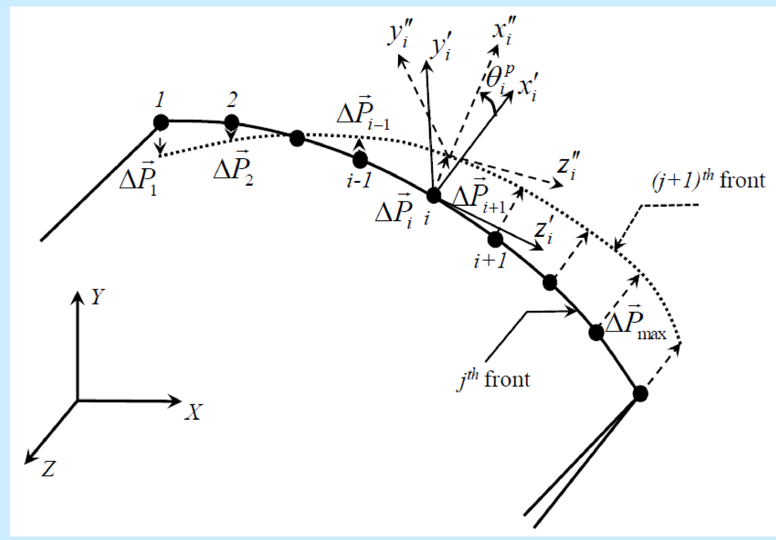
In the above figure, 20-noded hexahedral I enriched crack tip elements having an edge on the crack front of a practical fracture model are shown. It should be noted that the crack front is fully surrounded by these types of elements that touch the crack front. The stress intensity factors along a given crack front are included in the element formulation as unknowns in addition to nodal displacements and solved for directly in the solution phase. The finite element displacement formulation for enriched elements is given below [7].

$$u^k(\xi,\eta,\rho)=\sum_{j=1}^{m}N_j(\xi,\eta,\rho)u_j^k+Z_0(\xi,\eta,\rho)\left(f^k(\xi,\eta,\rho)-\sum_{j=1}^{m}N_j(\xi,\eta,\rho)f_j^k\right)\left(\sum_{i=1}^{ntip}N_i(\Gamma)K_I^i\right)$$
$$+Z_0(\xi,\eta,\rho)\left(g^k(\xi,\eta,\rho)-\sum_{j=1}^{m}N_j(\xi,\eta,\rho)g_j^k\right)\left(\sum_{i=1}^{ntip}N_i(\Gamma)K_{II}^i\right)$$
$$+Z_0(\xi,\eta,\rho)\left(h^k(\xi,\eta,\rho)-\sum_{j=1}^{m}N_j(\xi,\eta,\rho)h_j^k\right)\left(\sum_{i=1}^{ntip}N_i(\Gamma)K_{III}^i\right)$$

Once the stress intensity factors along the crack front are calculated, using a crack propagation law, e.g., Paris-Erdogan law, the incremental new positions of the crack front nodes, which define the outline of the new crack front, are predicted. Then, generally, a five-parameter ellipse is fitted to the discrete points of the new crack front profile. The procedure is summarized below [8]:

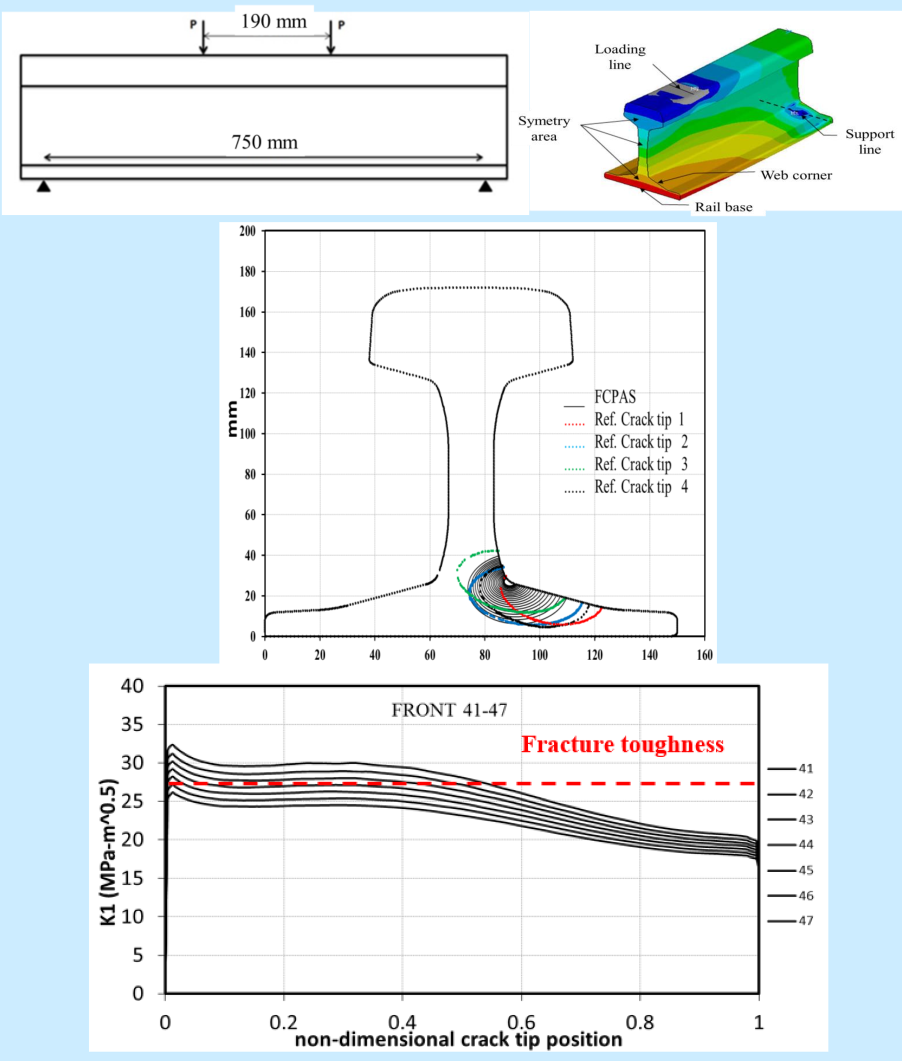
$$\frac{da}{dN}=C(\Delta K)^n \qquad \Delta a_i=\Delta a_{max}\left(\frac{\Delta K_i}{\Delta K_{max}}\right)^n$$



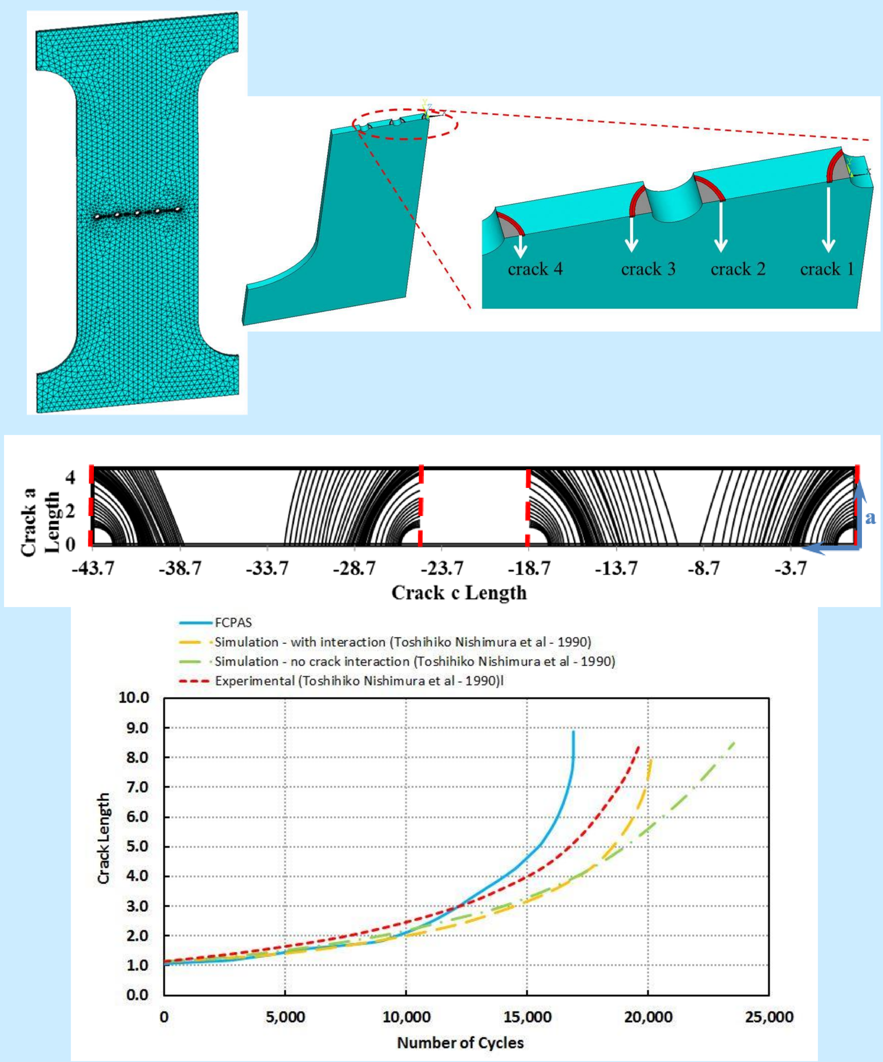


Numerical Examples

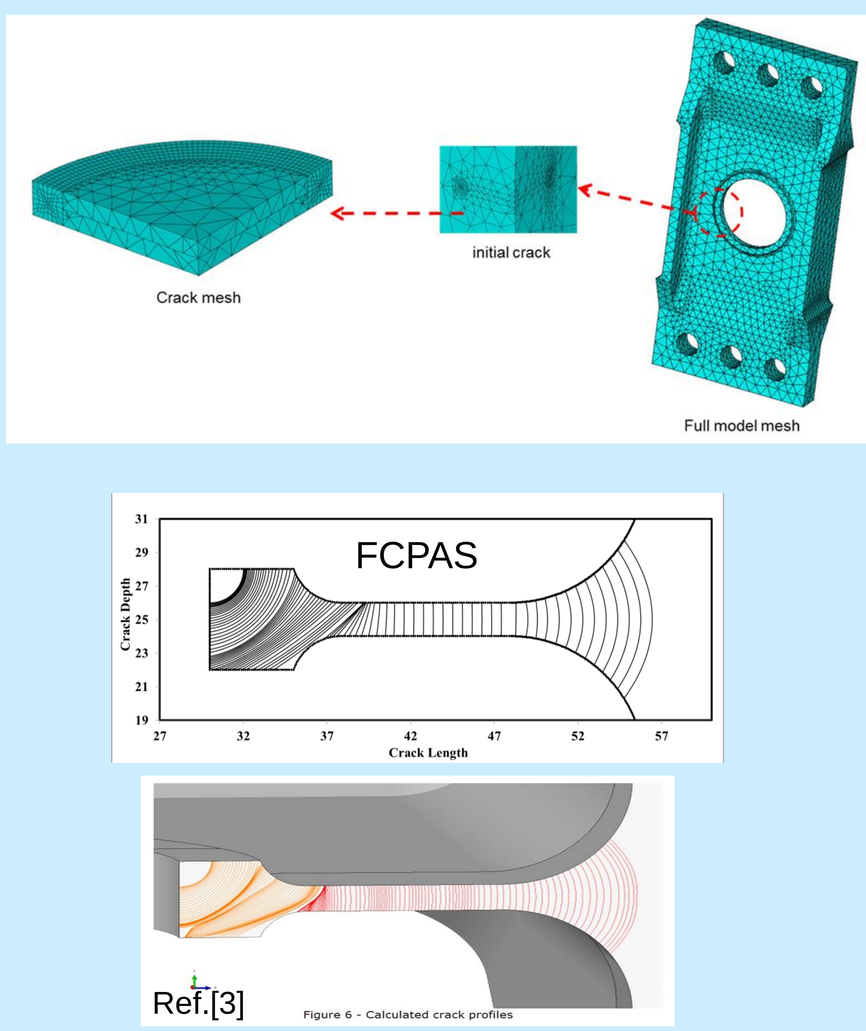
Web Corner Crack on UIC60 Rail



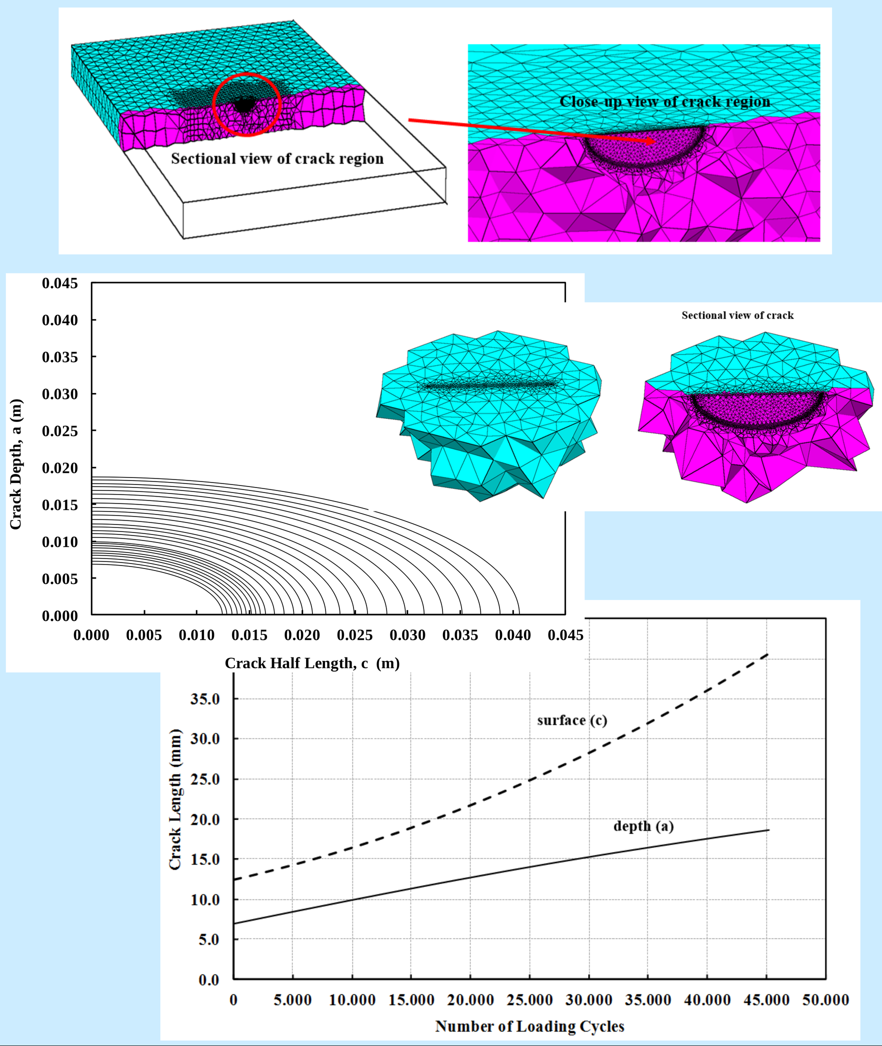
Multiple Cracks Initiated from Bolt Holes



Corner Crack in A Helicopter Lift Frame



Fatigue Crack Propagation Using Crack Insertion



Conclusion, Outlook & Acknowledgement

Applications are presented that demonstrate the usage of Fracture and Crack Propagation Analysis System (FCPAS) on a number of practical engineering applications for simulation of mode-I fatigue crack propagation. These applications are; web corner crack in a UIC60 rail, multiple cracks propagating from holes on a plate, corner crack on a helicopter lift frame and fatigue crack propagation simulation on a plate under bending using the crack insertion technique. For all applications presented, very good agreements were obtained with experimental/simulation literature data in terms of crack propagation patterns and lives. Therefore, it was concluded that the capabilities of FCPAS for performing mode-I crack propagation analyses on practical geometries were validated on a number of applications. Future studies will include developing capabilities for simulation of three-dimensional mixed-mode crack propagation. This will include numerical developments as well as experimental studies for mixed-mode crack growth.

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