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LCF INITIATED - HCF PROPAGATED CRACK LIFE ESTIMATION OF GAS TURBINE BOLTS

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ABSTRACT

This paper discusses the methodology to calculate high cycle fatigue (HCF) crack propagation life of gas turbine bolts and compares two dimensional (2D) HCF crack propagation life to three dimensional (3D) HCF crack propagation life. Gas turbine bolts when exposed to fatigue loading are prone to crack initiation and propagation (structural failure) during operation. In such cases cracks mostly are initiated by low cycle fatigue (LCF) and propagated by HCF. Therefore in current illustration the authors have evaluated crack propagation primarily initiated by low cycle fatigue and propagated by high cycle fatigue. 2D and 3D fracture methodology approaches had been used for analytical evaluation. The authors conclude on the efficacy of both the methods based on the data from the field. The coupling joint bolts located in the engine mid-section, which are used to join compressor rotor with turbine rotor are being considered for crack evaluation studies. The coupling bolts located in mid-section are primarily loaded by high axial bolt pre-loads needed to keep the joint intact, as well as loaded in bending due to rotor gravity sag. The crack propagation life is evaluated and validated with field data using cracked bolt specimen from the field.

INTRODUCTION

Failure of gas turbine coupling bolts at the thread location was observed on few older Westinghouse gas turbines which were designed 25 years ago. Figure 1 is a typical cross-section of an older Westinghouse gas turbine. The compressor and turbine rotors of this engine are coupled together using coupling bolts. Coupling bolts are intended to transmit torque while keeping the coupling joint intact.

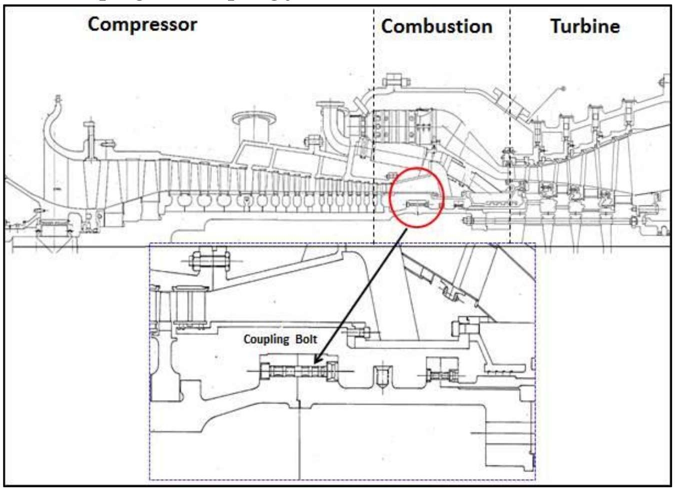

Figure 1: Engine cross section

Coupling bolt used in the current study for crack propagation evaluation is also shown in Figure1. Figure 2 shows 3D model of an M24x350 coupling bolt with threads modeled in the current scope of work. Authors in this study first evaluated the impact of all sources of loading which led to crack propagation and failure. Various loads, such as mean stress loads and alternating loads are calculated using analytical equations & further validated with finite element analysis using ANSYS 17.2 version. Crack propagation life is then evaluated by calculating the resultant Stress Intensity Factors (SIF) at the crack tips. SIF computation is considered as an important part of crack propagation evaluation. Crack tip SIF solutions are influenced by complex 3D geometries. Typically 2D SIF solutions are provided in most crack growth evaluation software's such as NASGRO and IWM-VERB. 2D SIF solution is obtained by idealizing complex 3D geometries to simple plate geometries. The authors in this study perform 3D crack propagation evaluation using FRANC3D. FRANC3D allows for a more representative SIF solution by considering complex 3D geometry, non-standard crack shape and non-planar crack growth. Finally a comparison of SIF solutions and life from both 2D and 3D approaches are compared. The benefit of 3D crack propagation over 2D approach is discussed in the conclusion.

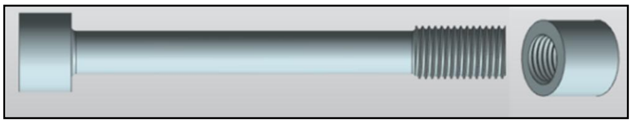

Figure 2: Typical coupling bolt with nut

MEAN STRESS ASSESSMENT OF BOLTS

To perform mean stress assessment, the following loads were being considered to simulate baseload engine operation.

1. Bolt preload: 0.2% initial strain
2. Thermal load: 350 °C
3. Rotational speed: 376 Rad/s

Bolt preload was applied to bolt in order to keep the coupling joint intact. A Finite Element Analysis (FEA) was setup to simulate the thermal & mechanical loads acting on the coupling bolts. Figure 3 shows cyclic sector set-up of a coupling flange along with the bolt. Figure 4 shows the meshed analysis model set up of bolt and coupling flange. Solid185 elements were used to model the compressor and turbine disk coupling flanges. Solid187 elements were used to model the bolts. Cut boundary conditions were applied to flange ends to simulate whole engine model deflections.

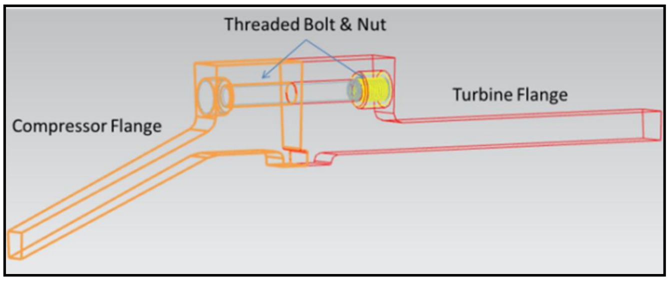

Figure 3: Analytical set up

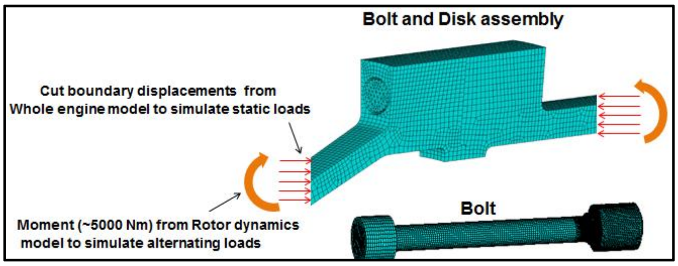

Figure 4: Meshed model with boundary conditions

Figure 5 shows the analysis predicted bolt stresses at the threads during baseload operation. Bolt stresses were normalized to yield strength for IN718 material. Analysis predicted normalized average bolt shank stress is about 0.49 MPa and maximum stress at thread region is about 1.7 MPa. Average stress predicted by finite element model closely matches the stress corresponding to applied initial strain. Normalized stress value equivalent to 0.2% strain is about 0.46 MPa.

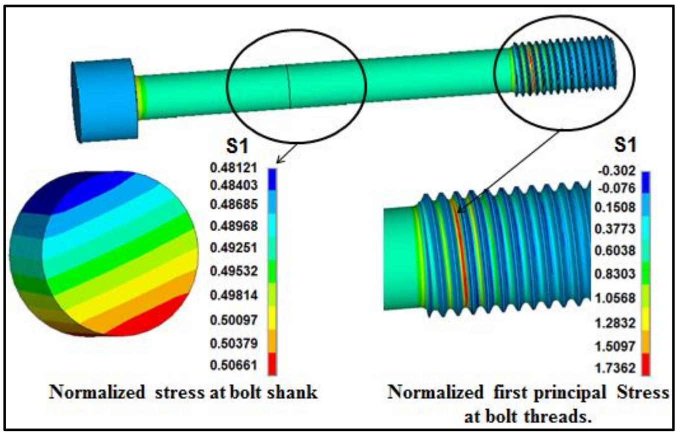

Figure 5: Bolt thread mean stress at baseload operation

A ratio of thread peak stress (1.73 MPa) to bolt shank average stress (0.49 MPa) predicts a stress concentration factor (K_t) of 3.5 at threads. The K_t predicted by analysis has been compared to theoretical k_t of 4.8 obtained from Shigley and Misckhe's data [6]. It should be noted that, the modeling of bolted joint does not fully simulate the geometry as well as nonlinear response that occur in bolted joint. However the analytically predicted K_t provides an insight of K_t which will be used for crack propagation calculations in NASGRO.

ALTERNATING STRESS ASSESSMENT OF BOLTS

Rotor dynamic unbalanced response occurring at the center of the gas turbine rotor produces alternating high cycle fatigue loading on coupling bolts. The first rotor dynamic mode from rotor gravity is located close to the center of rotor as shown in Figure 6. The first bending mode from rotor sag is the primary source of alternating load acting on the bolts. Authors in this study have used theoretical equations to estimate the alternating stress acting on the bolts from bending mode. Table 1 shows the alternating stress calculation. Alternating stress has been normalized to the endurance limit for IN718 material.

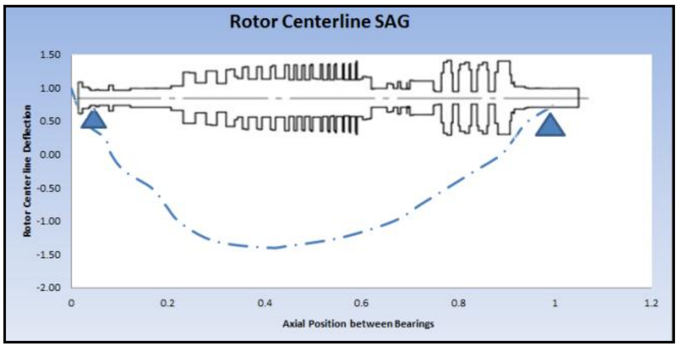

Figure 6: Rotor center line sag (bending mode)

Bolt Pitch circle Radius	600	mm
Change in Length (X)	1.28E-02	mm
Bolt Stiffness (K_b) =($A_b E_b / L_b$)	519132.86	N/mm
Bolt Load from sag (Kb*X)	6622.06	N
Bolt Shank Area	500	mm^2
Normalized bolt alternating Stress	0.04	MPa

Table1: Bolt alternating stress calculation

Further FEA was performed on the bolts to evaluate the stresses from alternating loads. Alternating load such as bending moment acting on the flanges is obtained from rotor dynamics model. This moment load was applied to the rotor flange as shown in Figure 4.

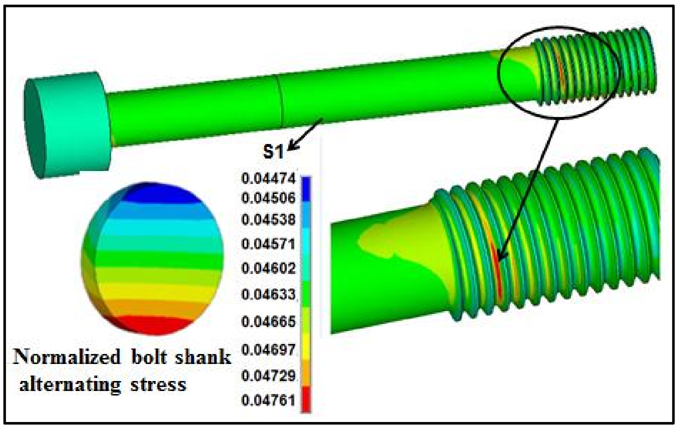

Figure 7: Bolt alternating stress at baseload operation

Figure 7 shows the normalized alternating stresses on the bolt as predicted by analytical simulation in ANSYS 17.2. Alternating stress was normalized to endurance limit of IN718. Analytical predictions closely match alternating stresses calculated in table 1. Having set up the loads acting on the bolts along with the associated stresses, further crack propagation study on the bolts associated with the above loading and stresses is established in the next sections.

TWO DIMENSIONAL CRACK PROPAGATION STUDY USING NASGRO

Two dimensional fracture mechanics assessment was performed using standard bolt model provided in NASGRO standards library. Based on analytical predications from previous sections, crack initiation location is considered to be at the first thread root. Figure 8 shows the fracture mechanics set up for a rolled thread bolt model. A rolled thread typically cracks near first contact thread as shown in Figure 8. The maximum stress location predicted by analysis closely matches with the thread crack initiation location considered in NASGRO crack modeling set-up.

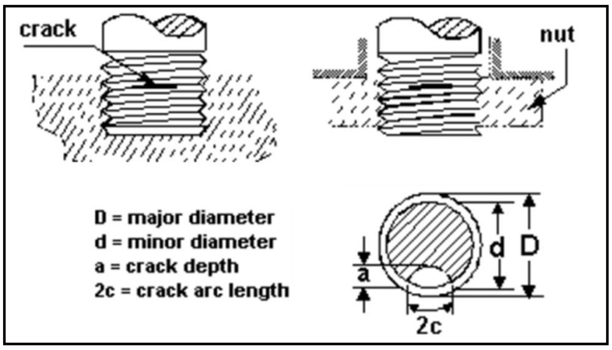

Figure 8: Thread crack set-up using NASGRO

Mean stress (~0.495 MPa) and alternating stress (~0.044 MPa) was used in NASGRO to propagate an initial flaw of 0.5mm. Bolt thread K_t effect of 3.5 has been applied to alternating stress used for crack propagation. Loading spectrum used for crack propagation is shown in Figure 9. IN718 fracture properties were used for crack propagation studies. Paris Law equation shown below [7] is used internally by NASGRO to integrate the crack propagation life. Figure 10 shows the crack tip stress intensity factor (SIF) computed in NASGRO for the above provided boundary conditions. Figure 11 shows the number of hours consumed for crack to get unstable under HCF loading. The bolt would accumulate ~25 hours before crack propagation becomes unstable, with critical size of ~13.5 mm.

$$\frac{da}{dn} = C(\Delta K)^m$$

$\frac{da}{dn}$ = Crack growth rate per loading cycle due to fatigue.

C, m = constants that depend on materials, environment & stress ratio.
ΔK = range of stress intensity factor during fatigue cycle i.e. $(K_{max}-K_{min})$.

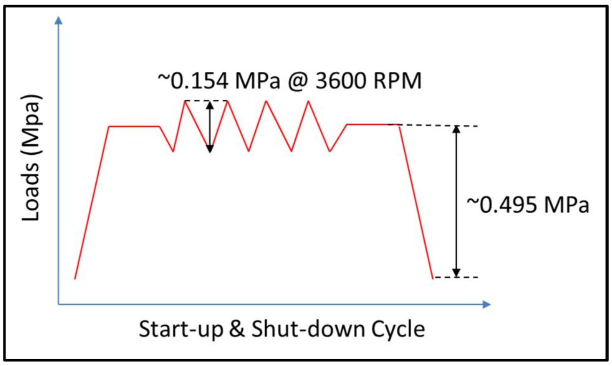

Figure 9: Mission definition and stress ratio

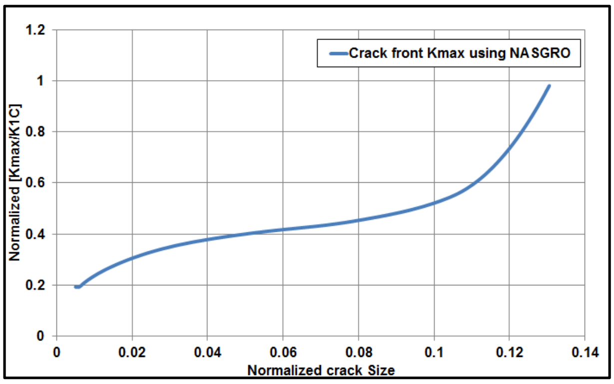

Figure 10: Normalized K_{max} (vs) crack Size

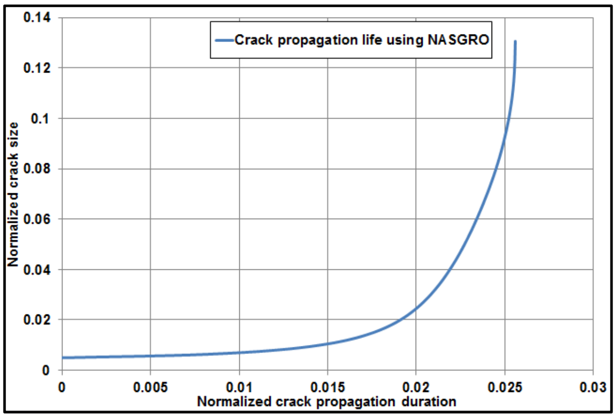

Figure 11: Crack propagation life using NASGRO

THREE DIMENSIONAL CRACK PROPAGATION STUDY

Three dimensional fracture mechanics assessment was performed using FRANC3D and ANSYS 17.2 software. FRANC3D model is full scale representation of actual cracked geometry with crack front being modeled. A global model approach provided in FRANC3D was used to perform crack propagation studies. Cracked bolt along with disks are modeled for 3D fracture assessment as shown in Figure 4. Cracks were inserted into the bolt threads using FRANC3D meshing capabilities. Figure 12 shows the cracked bolt created using solid187 and solid186 higher order elements. A crack tip in the cracked bolt was modeled using quarter-point elements to capture crack tip singularity. Figure 13 shows the solid 186 crack tip elements modeled in FRANC3D. Solid185 higher order elements were used to model the rotor disks. ANSYS 17.2 solver was used for analytical simulation. Multiple load cases were created to superimpose the effects of alternating stress loads over the mean stress loads.

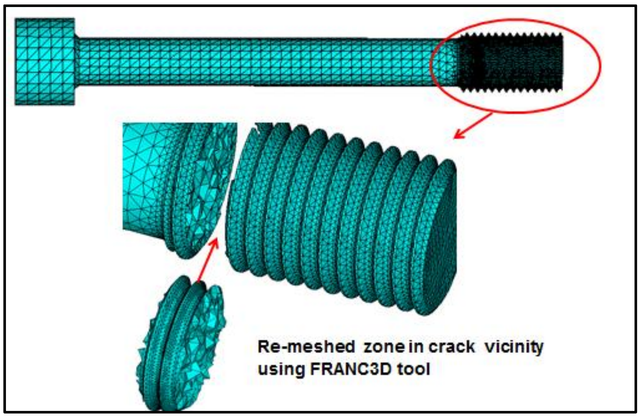

Figure 12: Cracked bolt mesh using FRANC3D

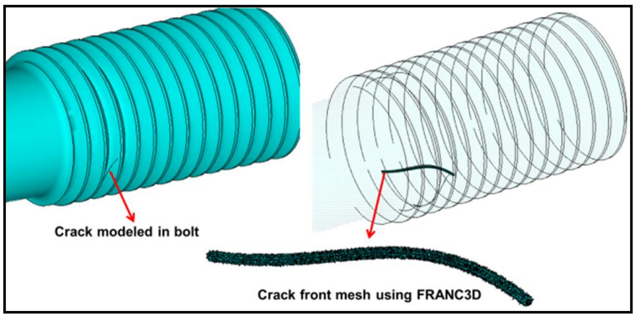

Figure 13: Crack front elements from FRANC3D

The growth of crack at different step sizes in FRANC3D can be visualized using ANSYS preprocessor as shown in Figure 14 below.

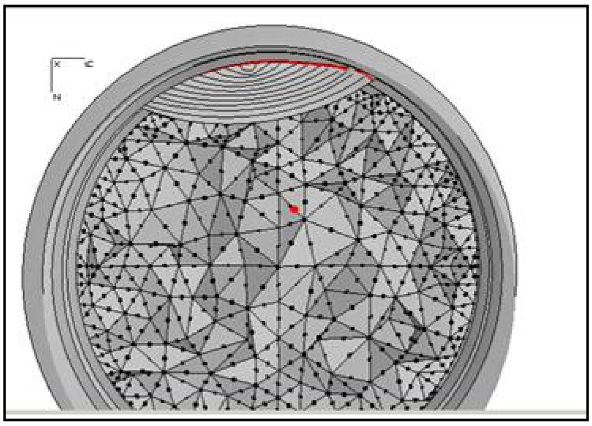

Figure 14: Crack propagation in FRANC3D

CRACK PROPAGATION ASSUMPTIONS USING FRANC3D

Authors in current study used the M-Integral approximation to calculate crack tip stress intensity factor (SIF). M-Integral formulation also termed as interaction integral in literature has relatively good accuracy with <1% error for reasonable mesh density. Authors decided not to include crack closure terms for computing SIF due to high stress ratio (>0.5) and because no oxide debris formation was observed in the field. Stress ratio (R) computation [6] is shown below.

$R = \sigma_{min} / \sigma_{max}$
$\sigma_{min} = \sigma_{mean} - \sigma_{alt} = (0.498-0.154) = 0.35$ MPa
$\sigma_{max} = \sigma_{mean} + \sigma_{alt} = (0.498+0.154) = 0.65$ MPa
$R = 0.35/0.65 = 0.53$

Mean stress and alternating loads were applied to the analysis model in multiple load cases. ANSYS 17.2 solver was used to solve the cracked bolt model obtained from FRANC3D. NASGRO properties for IN718 bolt were imported onto FRANC3D with median front crack extension technique used for solving. Semi-circular crack with a 0.5mm radius was inserted into the bolt as an initial flaw using FRANC3D. Figure 15 shows the Mode I fracture SIF distribution along the crack front as well as the variation in Mode I fracture SIF, starting from an initial flaw to critical crack.

The change in maximum SIF along crack depth is shown in Figure 16. Crack propagation life predicted using FRANC3D is shown in Figure 17.

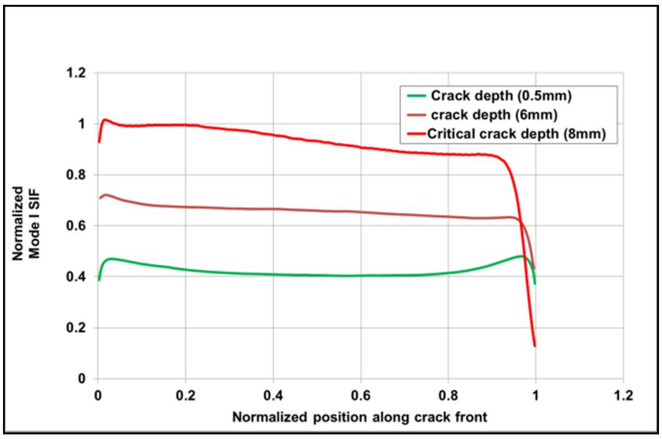

Figure 15: Variation of Mode I SIF along crack front

It was concluded that FRANC3D predicts results with better accuracy due to realistic loading and instantaneous change in crack front K_{max} due to crack arrest. 3D crack propagation rate predicted by FRANC3D is slower when compared to the 2D crack propagation rate predicted by NASGRO. The critical crack size is about 8 mm with estimated propagation life of 98.3 hours

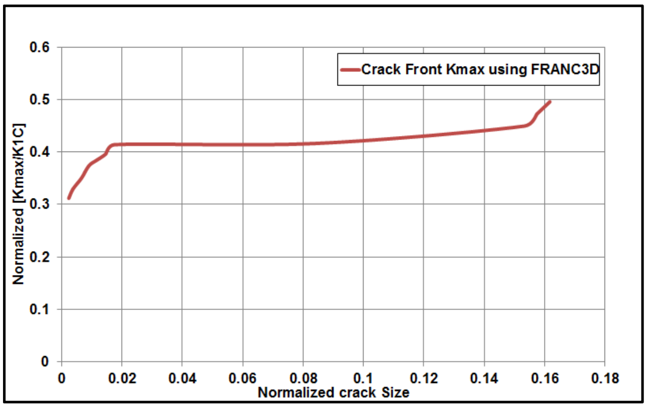

Figure 16: Normalized K_{max} (vs) crack Size

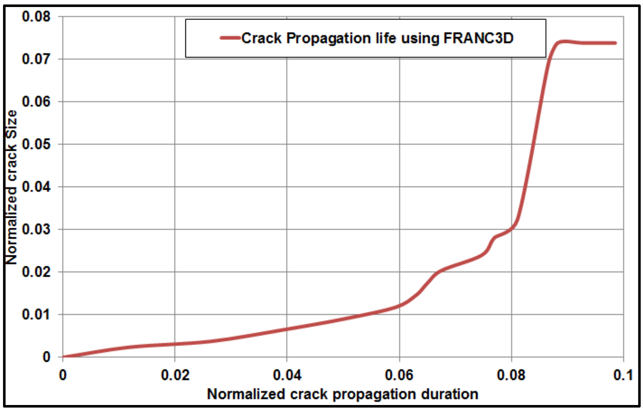

Figure 17: FRANC3D crack propagation life

VALIDATION

Figure 18 shows the surface of a cracked bolt specimen obtained from field. Metallurgical evaluation of the fractured bolt indicates mode of failure was primarily driven by HCF. Figure 18 also shows multiplane crack propagation from HCF followed by tensile overload. FRACNC3D predicts multiplane crack propagation and closely matches field observation as shown in Figure 19.

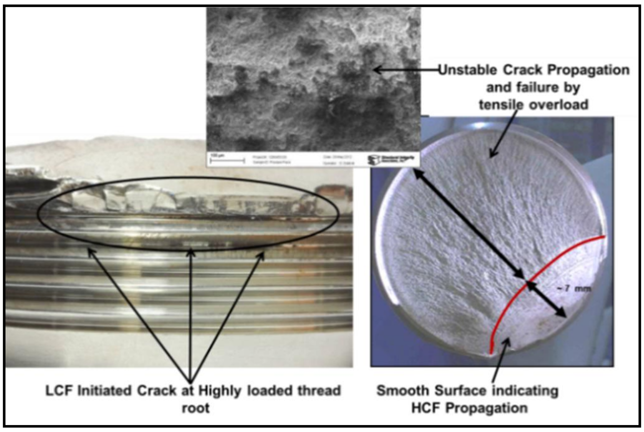

Figure 18: Crack initiation and propagation surface

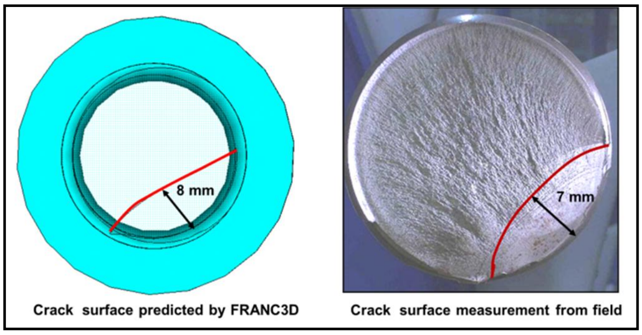

Figure 19: Analytical prediction comparison to field measurement

CONCLUDING REMARKS

The 3D Crack propagation study provides a good prediction of HCF crack growth at the single initiation point as shown in the Figure 19. The 2D crack propagation analysis is more conservative. FRANC3D captures 3D effects, loading on bolt and stress gradients for improved accuracy of the results. However, FRANC3D would require high computational resource and time for accurate prediction. The accuracy of 3D crack propagation analysis can be further improved by increasing loads in incremental steps to accurately predict unsteady crack growth cycles.

Figure 20 shows SIF comparison between FRANC3D and NASGRO. Some of the conclusions from this comparative study are shown below.

1. Crack propagation is predicted by both approaches when K_{max} exceeds ΔK threshold indicating HCF.
2. SIF obtained from 3D simulation is significantly different from SIF obtained from 2D approach.
3. There is a 50% variation in SIF predicted by FRANC3D compared to NASGRO when the crack reaches critical size.
4. A lower value of SIF predicted by FRANC3D indicates crack arrest.
5. A higher value of SIF predicted by NASGRO indicates no crack arrest while using NASGO crack propagation approach.

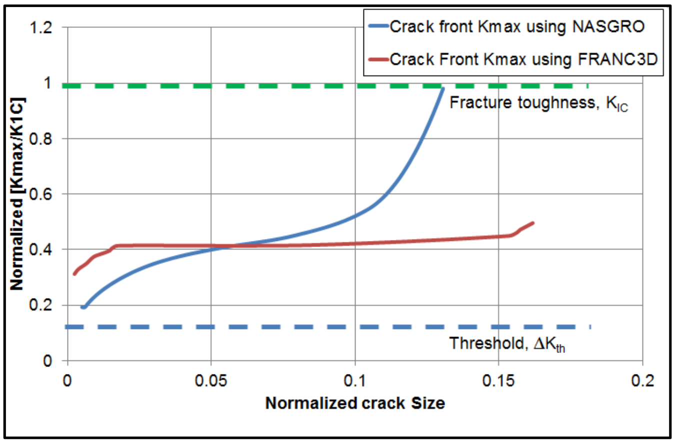

Figure 20: SIF comparison between FRANC3D and NASGRO

Figure 21 below shows the life predicted by NASGRO is conservative. FRANC3D predicts higher crack propagation life due to 3D effects and crack arrest.

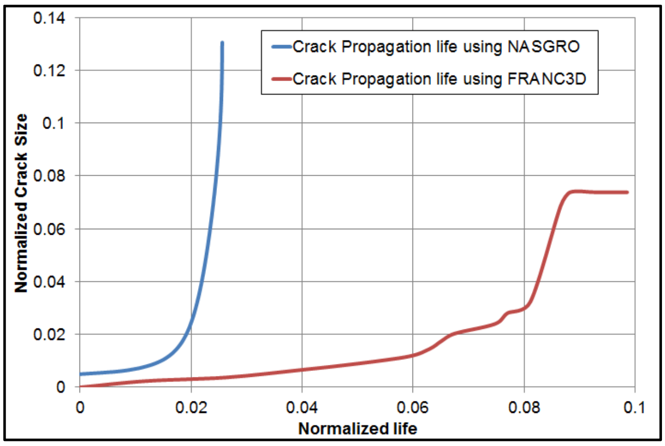

Figure 21: Crack propagation life comparison

Based on the above results, benefits of performing 3D crack propagation over 2D are summarized below.

1. Accurate prediction of component life during initial design phase.
2. Extension of component service intervals for existing designs that allows for longer usage.
3. Demonstrate serviceability of existing designs through life extension programs.
4. Reduction in maintenance cost by accurately defining inspection intervals.

NOMENCLATURE

HCF	High Cycle Fatigue
LCF	Low Cycle Fatigue
a	Crack length
2D	Two dimensional
3D	Three dimensional
FEA	Finite Element Analysis
K_b	Bolt stiffness
A_b	Bolt cross-sectional area
SIF	Stress Intensity Factor
K_t	Stress concentration factor
MPa	Mega Pascal's
°C	Degree Celsius
K_{max}	Crack front maximum SIF
K_{min}	Crack front maximum SIF
ΔK	Threshold delta K
Rad/s	Radians per second
Mode I	Opening mode of fracture

PERMISSIONS FOR USE.

ACKNOWLEDGMENTS

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