Society of Automotive Engineers Fatigue, Design, and Evaluation Committee
Fall 2020 Meeting

Fatigue Crack Growth Life Assessment using 3D Finite Element and Machine Learning Models

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Presenter: Adrian Loghin

Motivation

- Runtime efficient and accurate procedures for uncertainty quantification and probabilistic fatigue crack propagation life assessment are always desired.
- Different tools are available to the engineering community to accommodate current computational needs: 3D FEA for deterministic fatigue crack growth assessment, machine learning algorithms, well established lifing tools (i.e. NASGRO, AFGROW).
- Verification&Validation (V&V) requirements need to be satisfied to the greatest extend possible to provide confidence in the methodology application at component level.
- Structural Health Monitoring, Damage Tolerant Design procedures can benefit from accuracy of 3D FEA and runtime efficient Machine Learning algorithms.

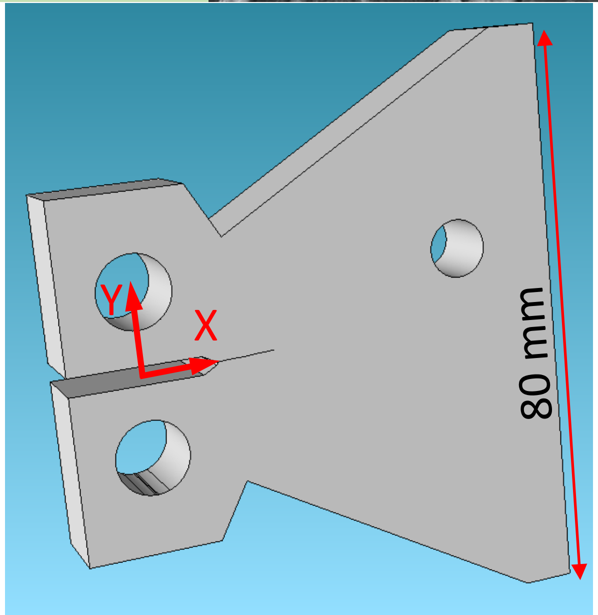
Modeling Process

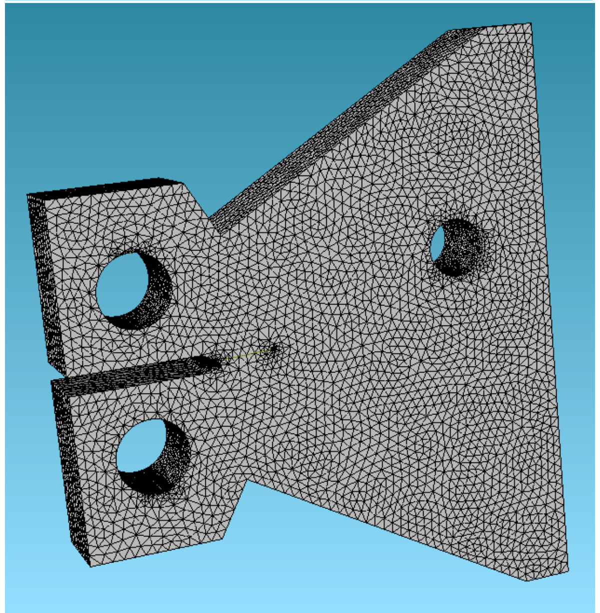
- SimModeler Crack was used for all 3D FEA crack growth simulations*
- Two ML methods are employed:
  - Radial Basis Function (RBF) based interpolation Response Surface modeling calibrated on 3D FEA simulations can provide an efficient methodology for crack path (out-of-plane crack propagation) and RUL (remaining useful life) UQ assessment (first example)
  - Gaussian Process Regression is evaluated as an alternative route to establishing a relationship between crack size, shape, loading conditions and, the corresponding Mode I stress intensity factors (second example)
- Public algorithms available in Python** are used in this development

Reference:
*A. Loghin, Life Prediction Modeling Capabilities for FE Applications, CAASE 2018, Cleveland OH.
** Scikit-learn: Machine Learning in Python, Pedregosa et al., JMLR 12, pp. 2825-2830, 2011

Example: 3D FEA & Response Surface Modeling

- Experimental data for this example is available* for validation purposes





Common questions

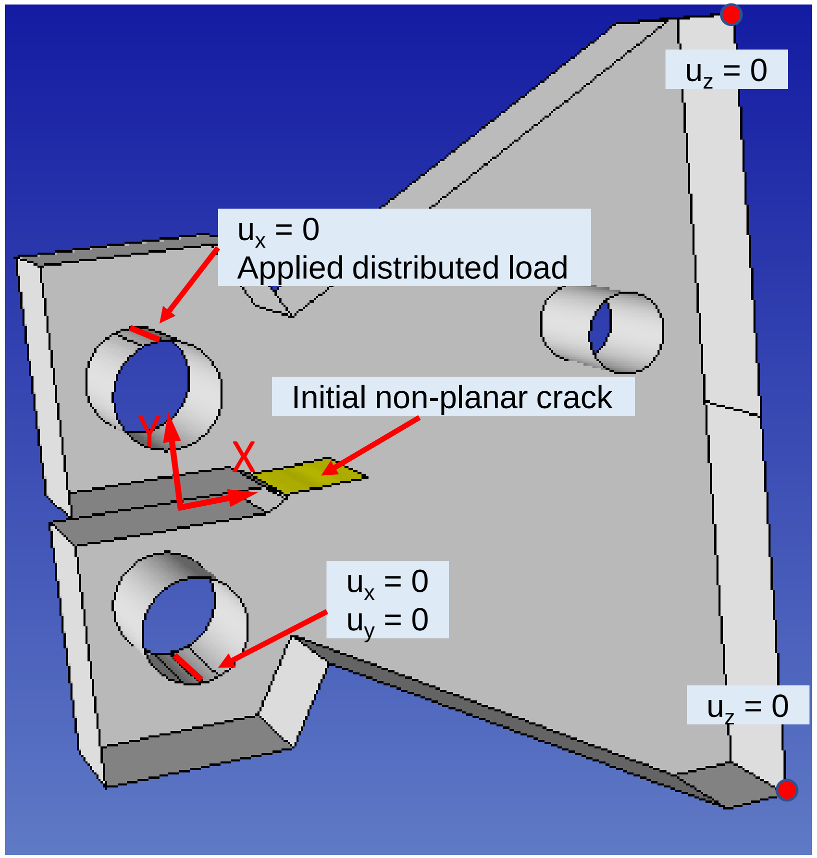
- How well the 3D simulation of the nominal test setup (specimen geometry, specimen alignment in the rig, loading conditions, initial precracking) predict test results?
- What is the sensitivity of the prediction to crack front mesh pattern, mesh refinement, type of boundary conditions to reproduce experimental setup?
- How can we identify a relationship between uncertainties related to the test conditions and crack path?
- How can we maintain model accuracy and not consider simplifications (reducing the 3D model to a 2D representation) for the sake of runtime speed?
- How can we make use of Response Surface modeling capabilities available in sciPy library to produce a runtime efficient fatigue crack growth prediction (path, remaining useful life) based on accurate 3D models?

References:
*Berrios, D.R., Franco, R., 2018. Análisis Experimental y Numérico de la Trayectoria de Propagación de Fisuras por Fatiga Utilizando XFEM. Información Tecnológica 29, no. 5, 19–34.

Example: 3D FEA & Response Surface Modeling

3D FE setup

- Parasolid model representing nominal dimensions was used to simulate crack propagation
- Initial crack was defined using measurement data from Berrios and Franco*. Initial pre-crack is not planar. A surface representation (Parasolid) of the measurement was used to define starting crack in this simulation.
- Automatic crack propagation is carried in SimModeler Crack using remeshing capabilities and Ansys Plugin feature
- Solution of each crack front increment was performed in Ansys
- Only the crack path validation and uncertainty was considered in this study**
- Each model correspondent to a new crack increment is post processed and stress intensity factors for all three modes are computed for each node along the crack front
- Displacement correlation technique is employed to compute $\{K_I, K_{II}, K_{III}\}$. Maximum tangential stress criteria is used to determine crack growth direction

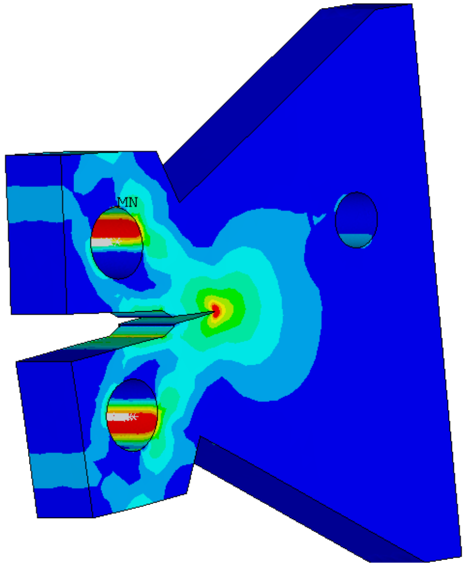


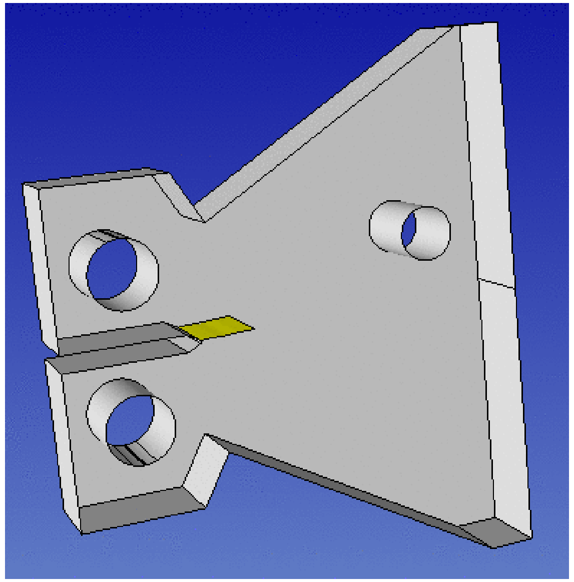
E = 20.6E4 MPa, $\nu = 0.3$
Simulation loading cycle: Max Load = 9 kN, Min Load = 0 kN

References:
*Berrios, D.R., Franco, R., 2018. Análisis Experimental y Numérico de la Trayectoria de Propagación de Fisuras por Fatiga Utilizando XFEM. Información Tecnológica 29, no. 5, 19–34.
**A. Loghin and S. Ismonov, Application of Response Surface Method in Probabilistic Fatigue Crack Propagation Life Assessment using 3D FEA, 1st Virtual European Conference on Fracture, www.vecf1.eu, 2020.

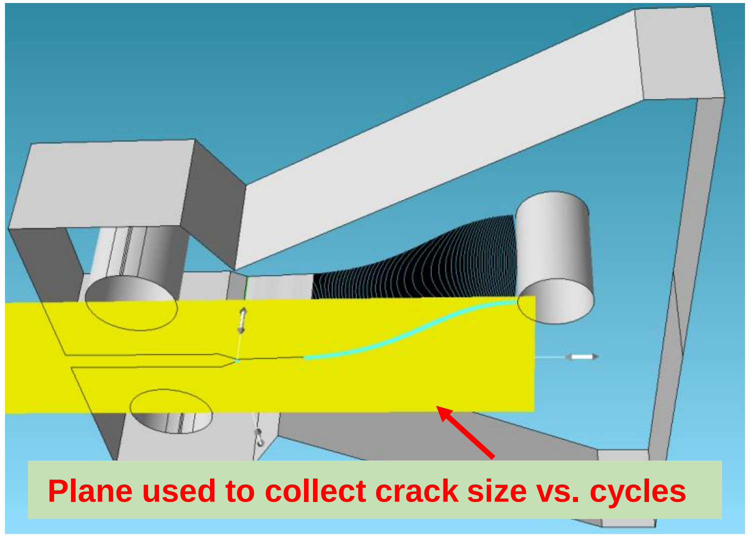
Example: 3D FEA & Response Surface Modeling

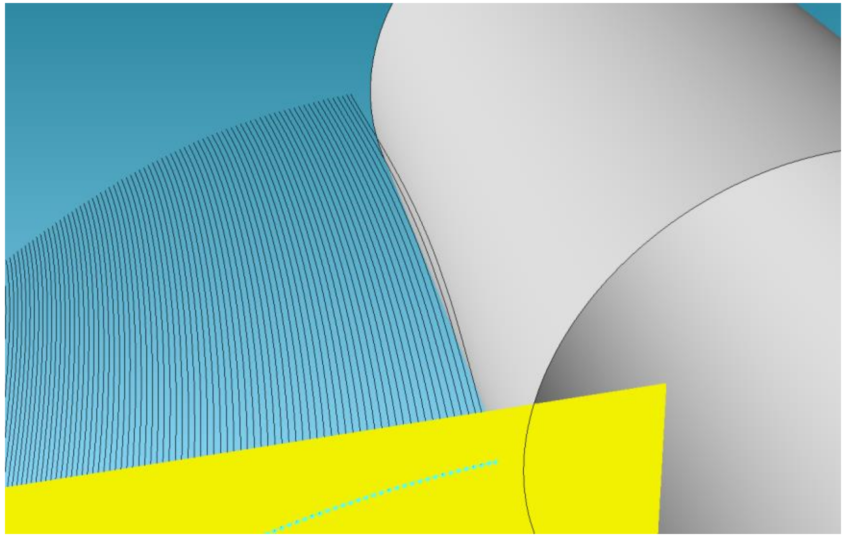
- Crack propagation simulation is performed in automatic mode
- Crack path is extracted at the free surface. No significant variation across specimen thickness is noticed.
- Predicted crack path is compared to experimental measurement
- Model modifications (i.e. position of the hole that controls crack path) can be easily made to perform crack path uncertainty studies

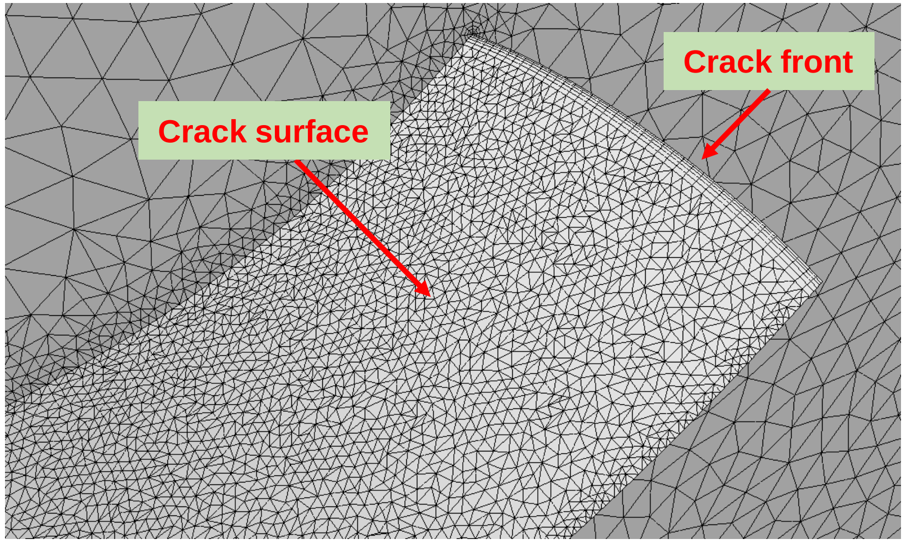




Nominal geometry and test conditions: 3D prediction and crack path post-processing

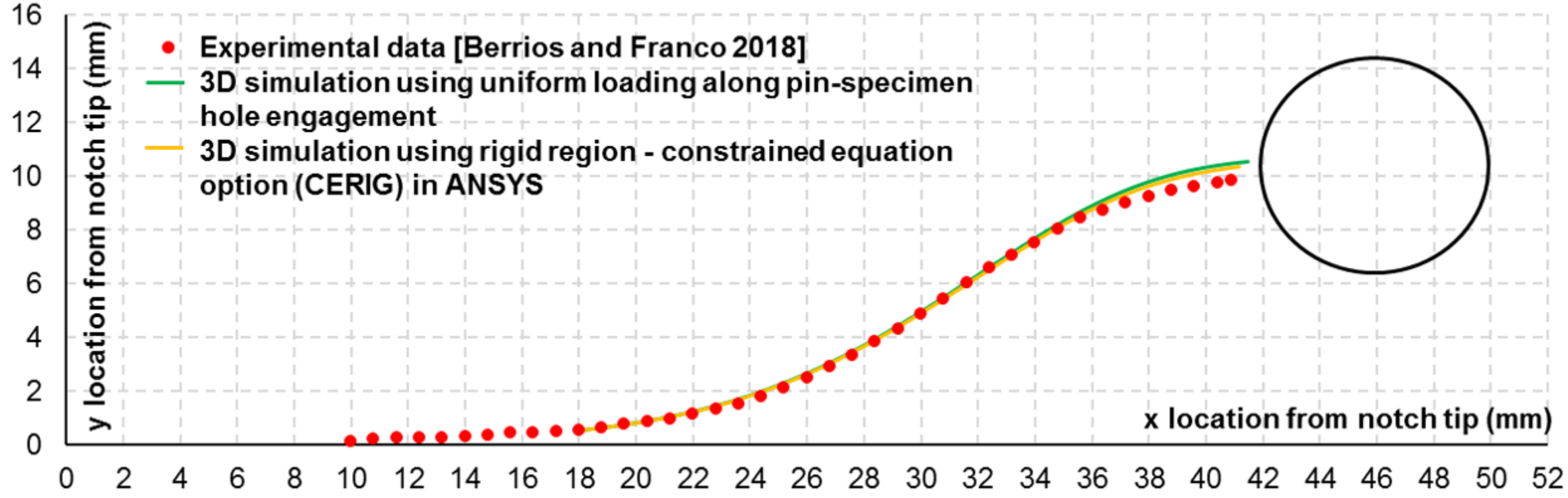




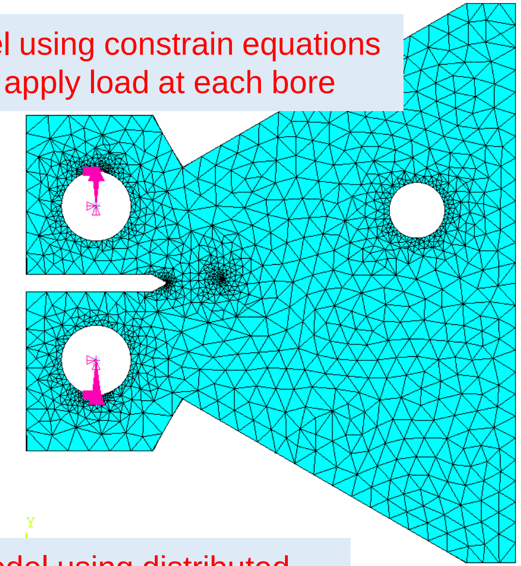


Example: 3D FEA & Response Surface Modeling

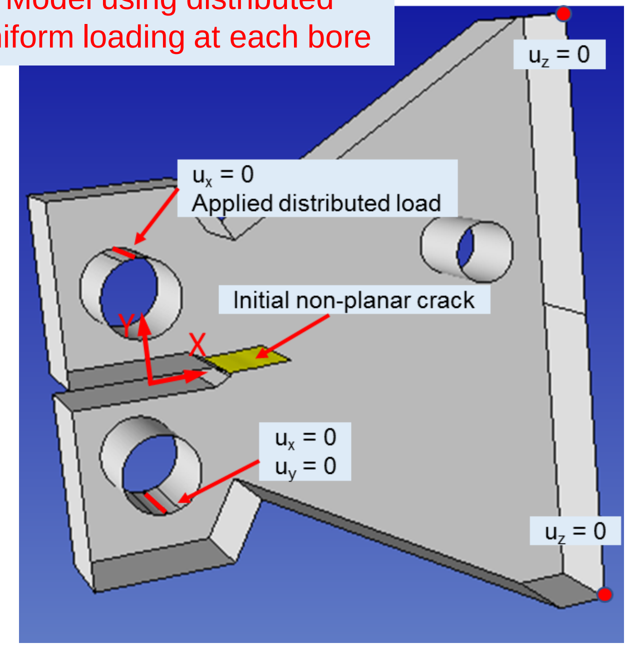
- First assessment is performed using nominal dimensions
- Two different procedures to assign load at the pin holes are employed to understand influence of boundary conditions modeling on crack path prediction
- 3D FEA is performed for two different loading assignment (the rest of the FE setup is maintained):
  1. using constrained equations similar to the 2D model in the reference
  2. load applied directly to the bore
- The two deterministic simulations produce similar crack path. Distributed uniform loading is adopted as standard.
- Both crack path predictions compare quite well with experimental measurement



Model using constrain equations to apply load at each bore

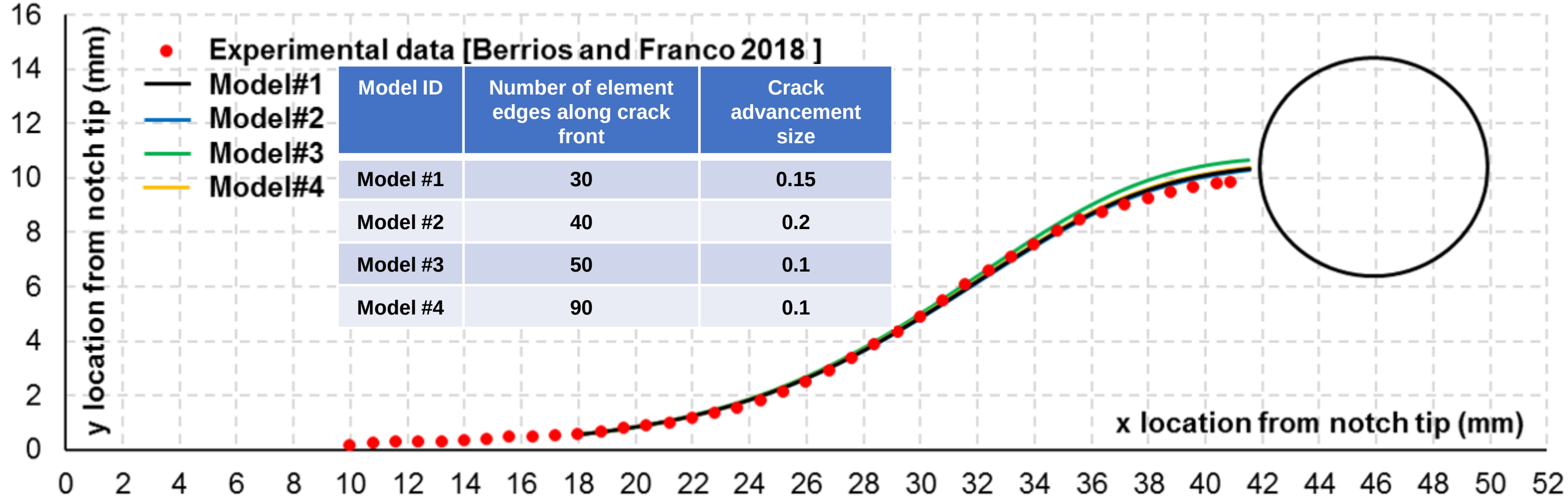


Model using distributed uniform loading at each bore

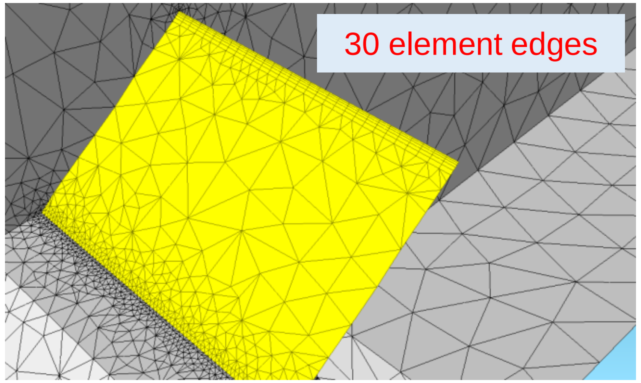


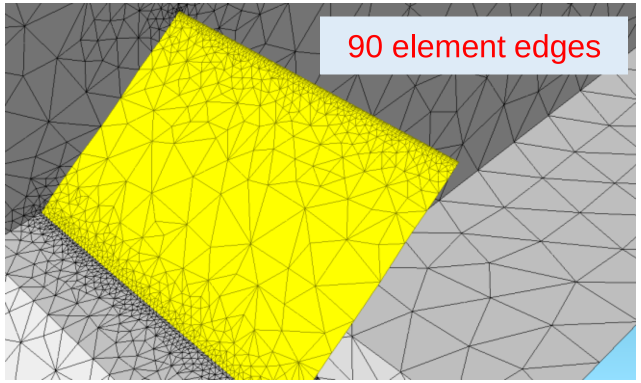
Example: 3D FEA & Response Surface Modeling

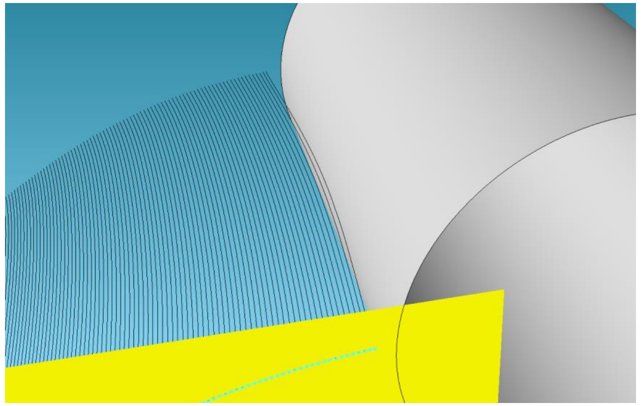
- A simple deterministic assessment is performed for identifying crack path sensitivity related to mesh and advancement increment
- Four different simulations are performed using different mesh refinement along crack front and advancement increments
- Three models predict same path. Model #1 (30 element edges along crack front, 0.15 mm advancement size) is adopted for a following study, crack path uncertainty due to hole location.
- Mostly depending on advancement size, the runtime for producing a deterministic crack path prediction is measured in hours.



Model ID	Number of element edges along crack front	Crack advancement size
Model #1	30	0.15
Model #2	40	0.2
Model #3	50	0.1
Model #4	90	0.1







Example: 3D FEA & Response Surface Modeling

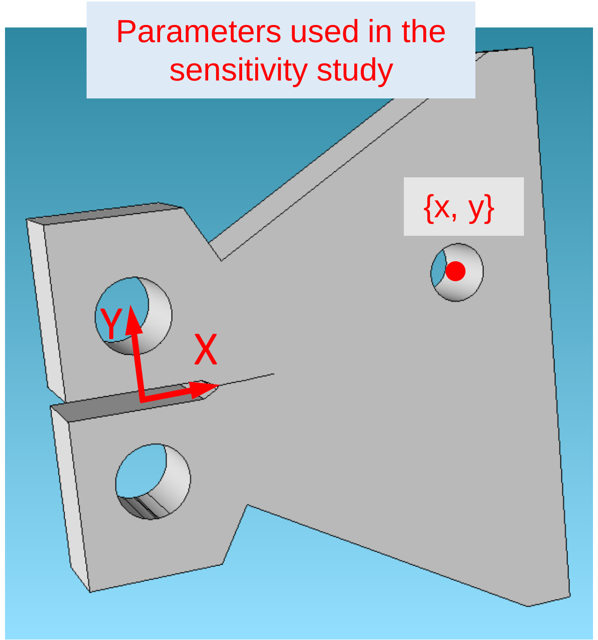
- The accuracy of the deterministic simulation is needed but the runtime makes any uncertainty study or probabilistic life assessment difficult to achieve

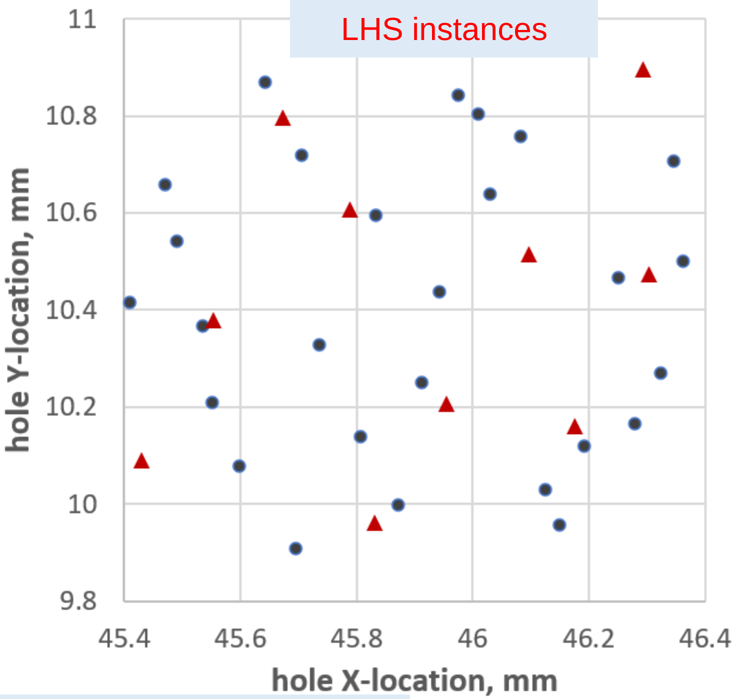
- A Radial Basis Function (RBF) based interpolation techniques (sciPy library) is adopted to set a response surface model (surrogate) for crack path and K_I solutions

- Parameters that would influence crack path are identified and Latin Hypercube sampling (LHS) is employed to assign different instances of these parameters. In this example the two parameters are the {x, y} position of the center of the hole

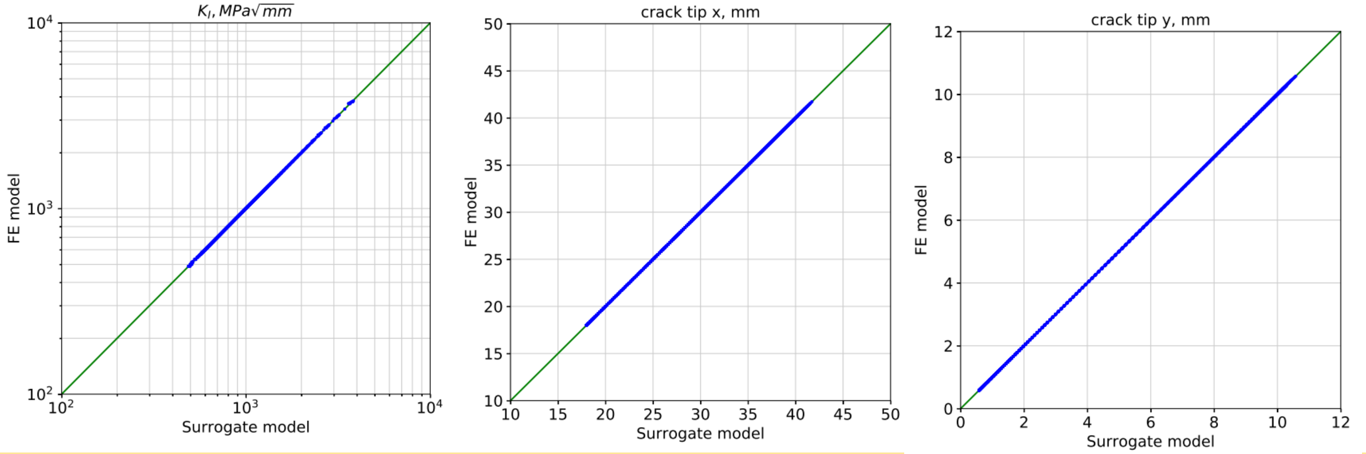
- 27 deterministic simulations are performed to train the response surface model and an additional 10 are used for verification purposes. All 37 simulations are performed in batch mode.

- The Response Surface model must pass verification requirements using the 10 deterministic simulations set aside for this purpose





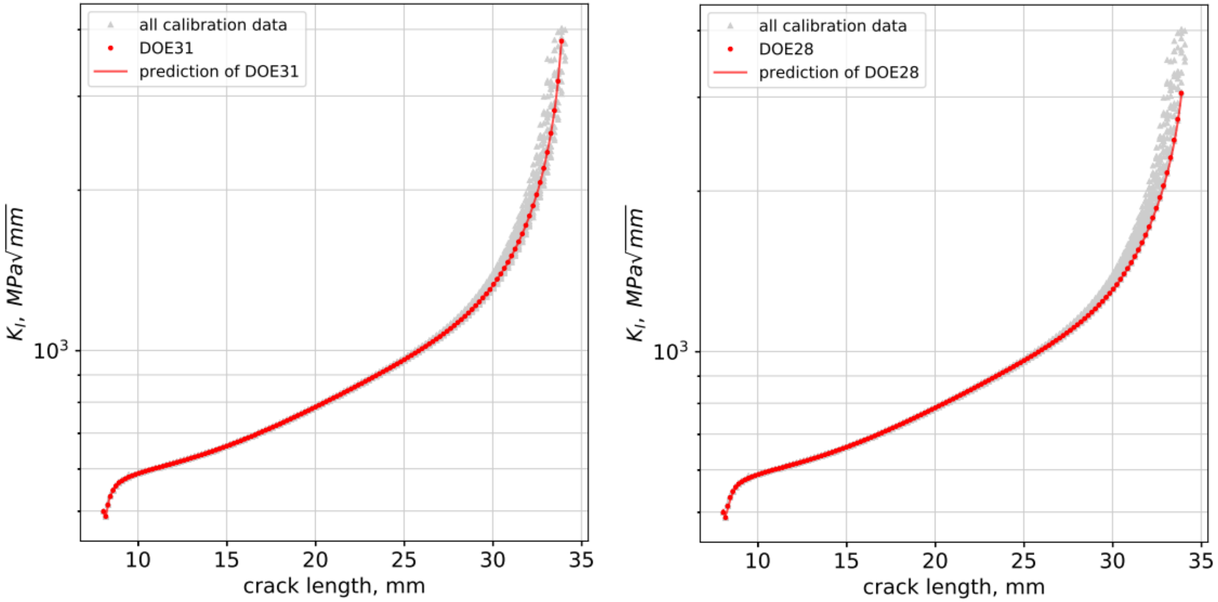
Surrogate model verification against 3D FEA



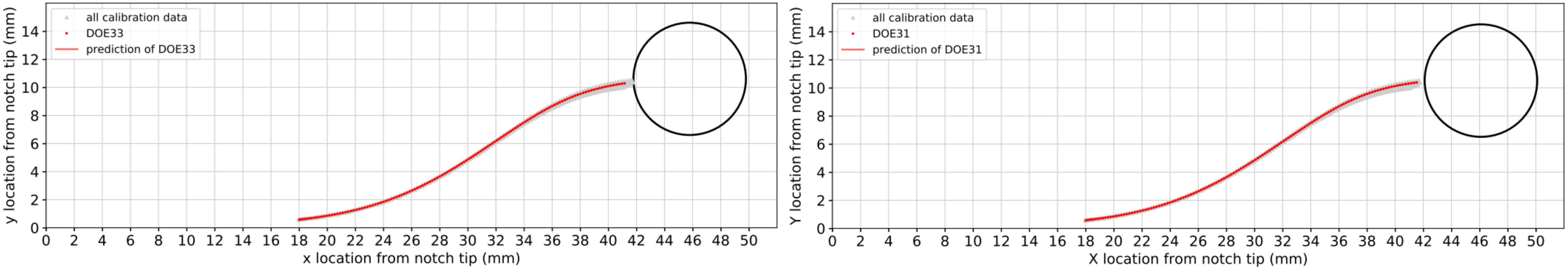
Example: 3D FEA & Response Surface Modeling

- Crack path and KI surrogate models are verified successfully against the deterministic models which were not used for calibration purposes
- The surrogate model runtime for predicting crack path for a deviation from nominal dimension or test condition is less than a second
- All the deterministic simulations can be performed in parallel since they are independent of each other
- The Response Surface model can be used in Monte Carlo simulations to assess a crack path distribution for an uncertainty related to hole location

Surrogate model verification against 3D FEA



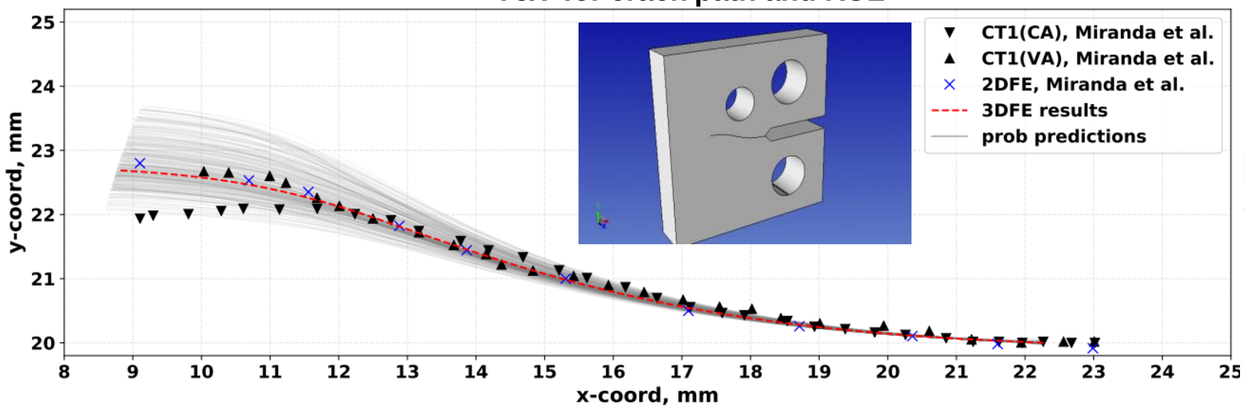
Surrogate model verification against 3D FEA

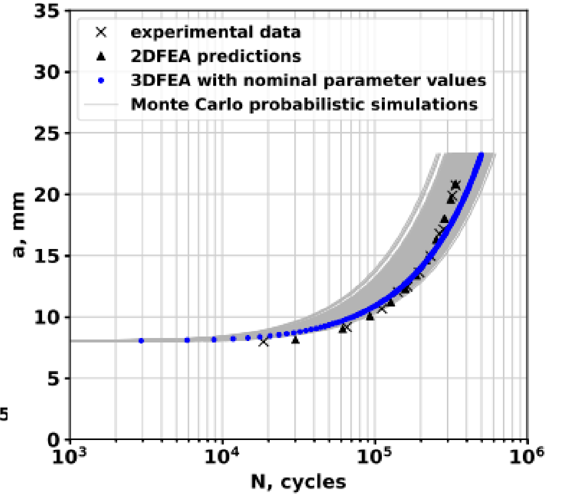


More Examples: 3D FEA & Response Surface Modeling

- Using the response surface model, Monte Carlo simulations are performed to assess crack path and RUL scatter. Crack path is very sensitive to small deviations from nominal dimensions
- 3D FEA based - Response Surface model can be used in out-of-plane crack path and RUL probabilistic assessment and Uncertainty Quantification assessments

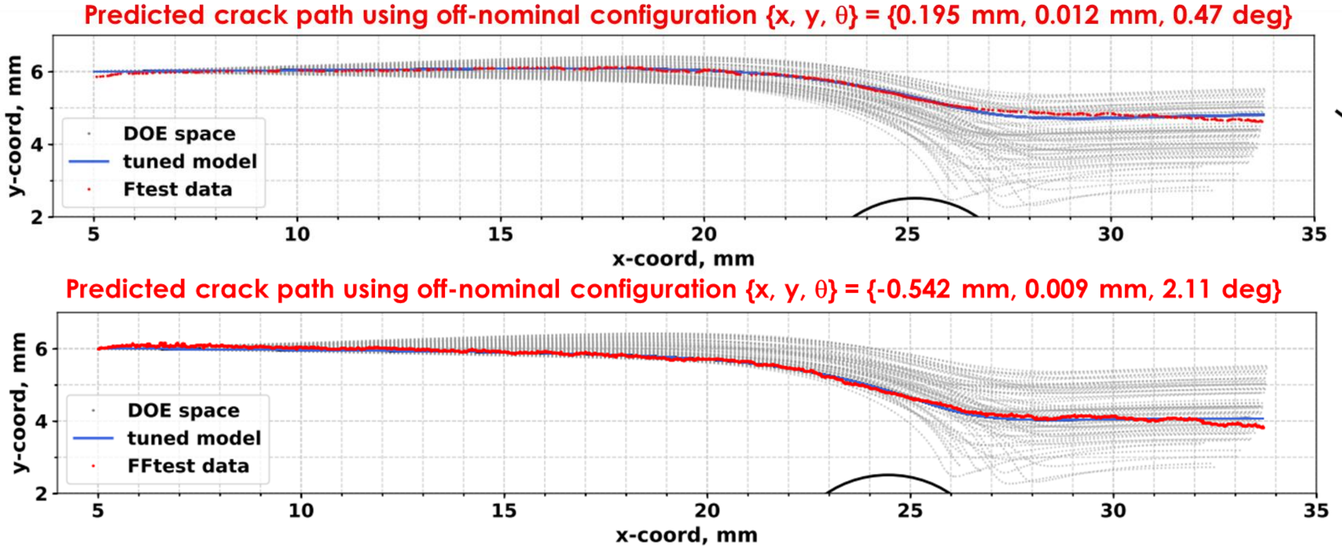
Monte Carlo simulations using Response Surface model
V&V for crack path and RUL

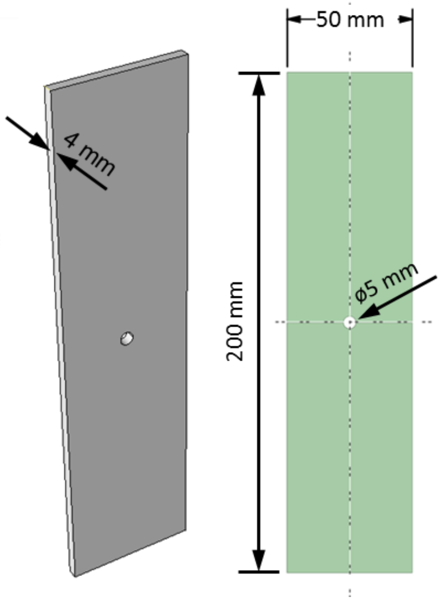




Reference: A. Loghin and S. Ismonov, Assessment of crack path uncertainly using 3D FEA and Response Surface Modeling, AIAA SciTech 2020.

- Three parameters were considered in the response surface modeling: hole location {x, y} and specimen misalignment
- Surrogate model used as an inverse function to identify potential off-nominal test configuration that would produce the recorded crack path





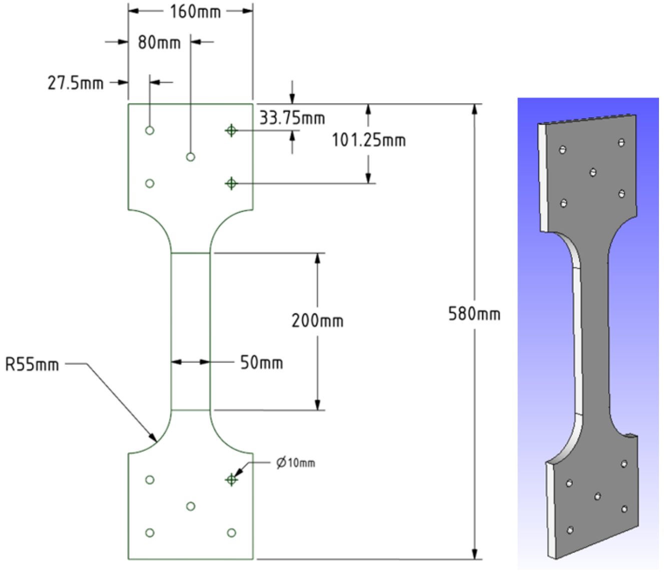
Reference: A. Loghin and S. Ismonov, Assessment of crack path uncertainly using 3D FEA and Response Surface Modeling, AIAA SciTech 2020.

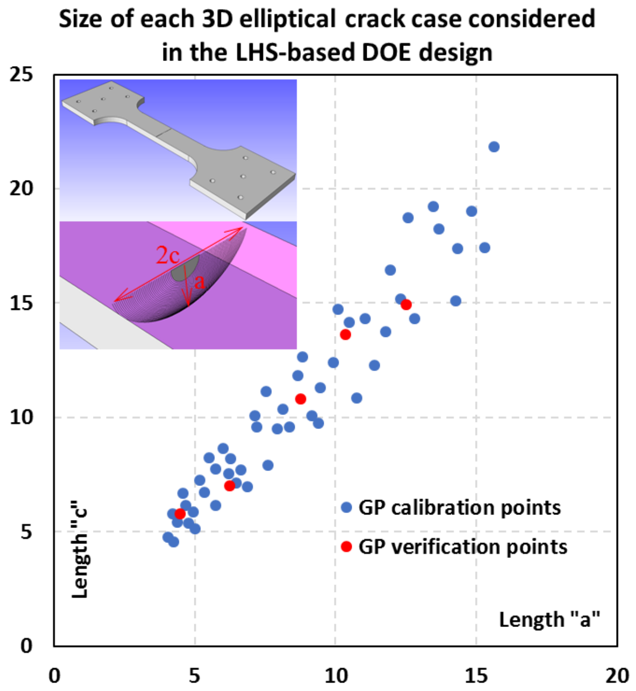
Example: 3D FEA & Gaussian Process Regression

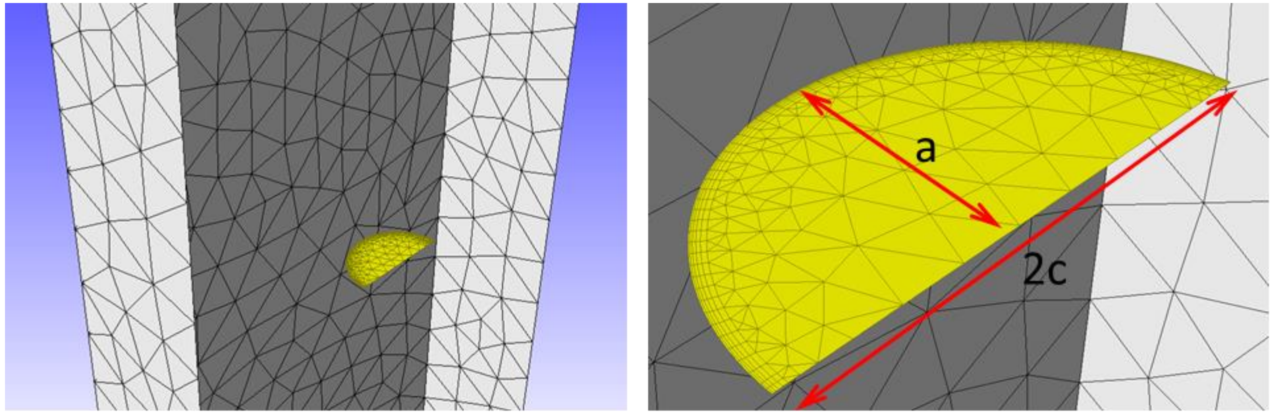
- Can 3D FEA and Gaussian Process Regression provide a more accurate reduced order fracture model (Mode I) that can be used efficiently in probabilistic life assessments?

- 3D FEA provides a more accurate representation of the geometry and loading gradients acting on the crack and, eliminates user dependent assumptions regarding fracture model choice (i.e. surface crack in a plate under uniform loading), its size and loading configuration.

- The procedure use Latin Hypercube Sampling for defining different crack of different size and shape, batch mode 3D FEA for performing all simulations automatic post-processing





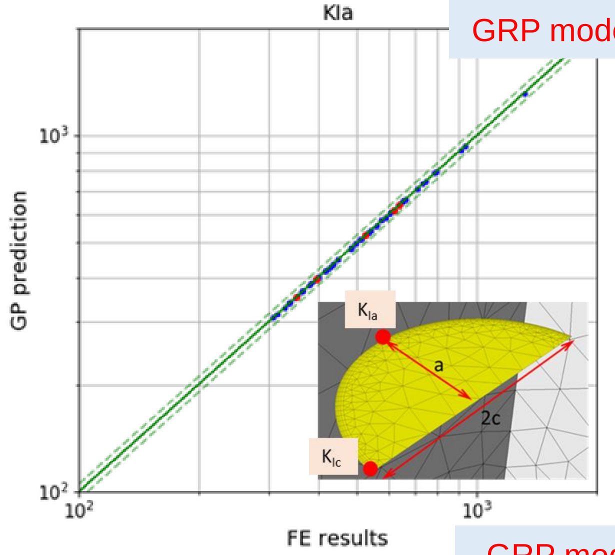


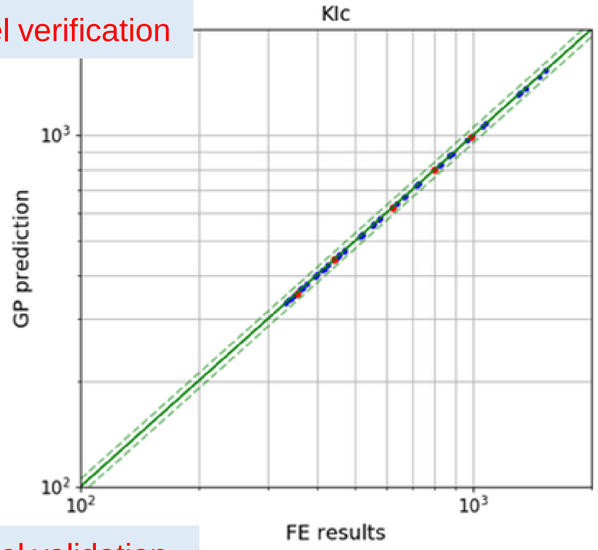
Reference:
Loghin, A., and Ismonov, S., “Application of Gaussian Process and Three-Dimensional FEA in Component Level Crack Propagation Life Assessment”, NAFEMS Congress 2019.

Example: 3D FEA & Gaussian Process Regression

- Once calibrated, successful verification of Gaussian Process Regression model is a requirement
- Verification and validation of the GPR model includes mode I stress intensity factors at the two locations, K_{Ia} and K_{Ic}, as well as fatigue crack growth prediction (length vs. cycles)

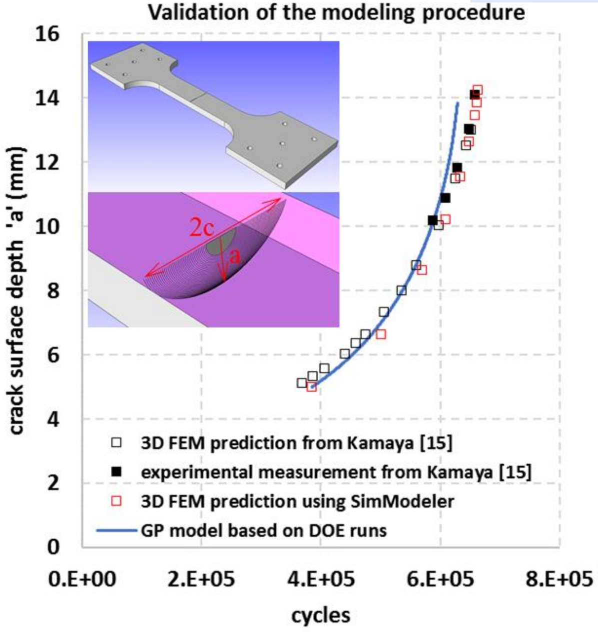
GRP model verification

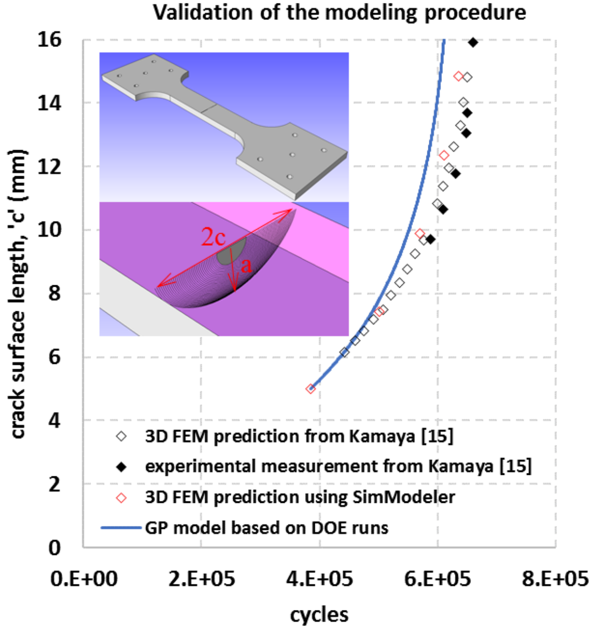




GRP model validation

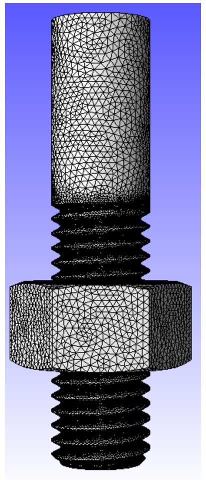
- Runtime stats:
  - 3D FE explicit crack propagation simulation runtime: 80 min (2 min/increment, 40 increments)
  - 3D FE solutions for GP model calibration: 50 independent simulations at 2 minutes each.
  - Once GPR model is verified, GPR based life assessment runtime: seconds



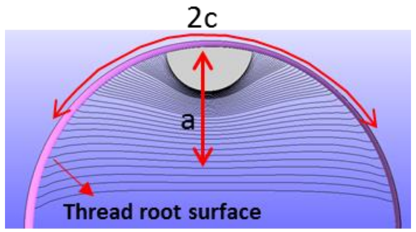


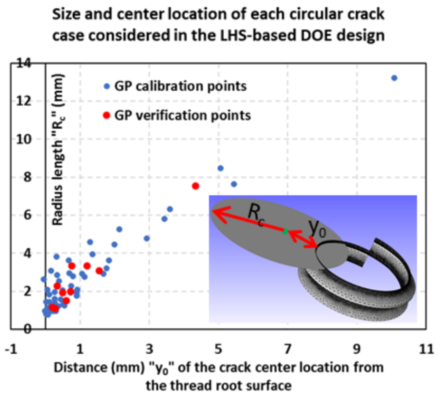
More Examples: 3D FEA & Gaussian Process Regression

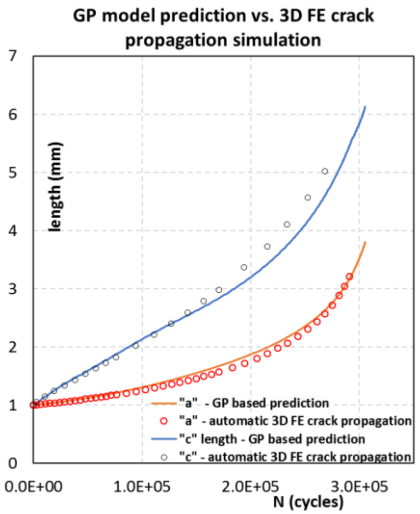
- Once calibrated, successful verification of Gaussian Process Regression model is a requirement
- Instead of typical {a, c} parameters for defining elliptical crack fronts, radius of a circular crack front and position of its center relative to the thread bottom surface are used to define crack front evolution



Different parameter type used to train GPR model

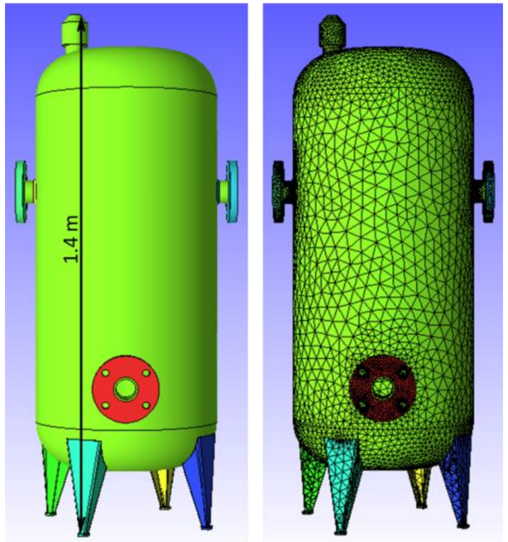


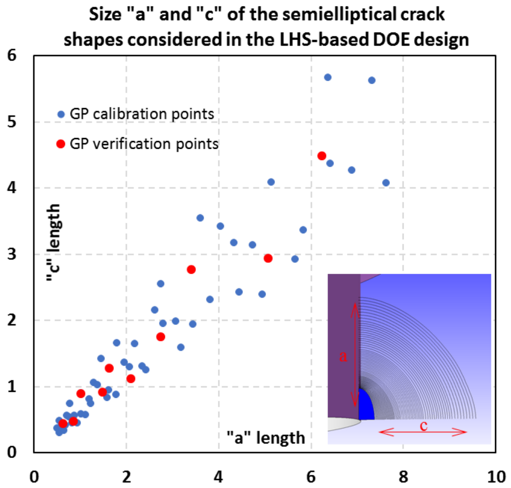


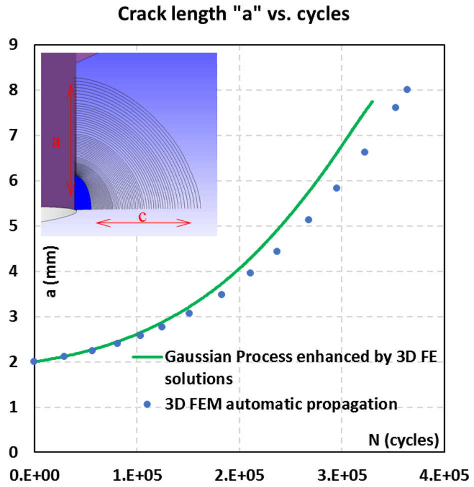


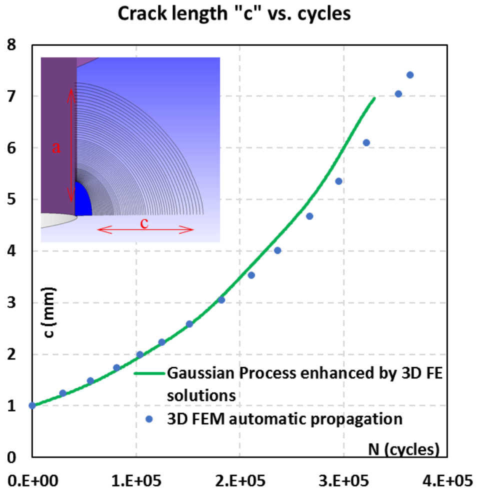
Component level GPR model

- The modeling process is applicable to component level geometries without adopting a simplified geometry in a reduced order model









References:
Loghin, A., and Ismonov, S., "Augmenting generic fatigue crack growth models using 3D finite element simulations and Gaussian process modeling", Proceedings of the ASME 2019 Pressure Vessels & Piping Conference, San Antonio, TX, 2019.
Loghin, A., and Ismonov, S., "Application of Gaussian Process and Three-Dimensional FEA in Component Level Crack Propagation Life Assessment", NAFEMS Congress 2019.

Conclusions

- The fatigue crack growth modeling validation process needs to account for uncertainties related to test conditions (off-nominal specimen geometry, crack initiation location, specimen misalignment) and inherent fatigue crack growth rate (FCGR) scatter. A model that uses nominal configuration or average FCGR data might not be sufficient to provide a good validation datapoint.

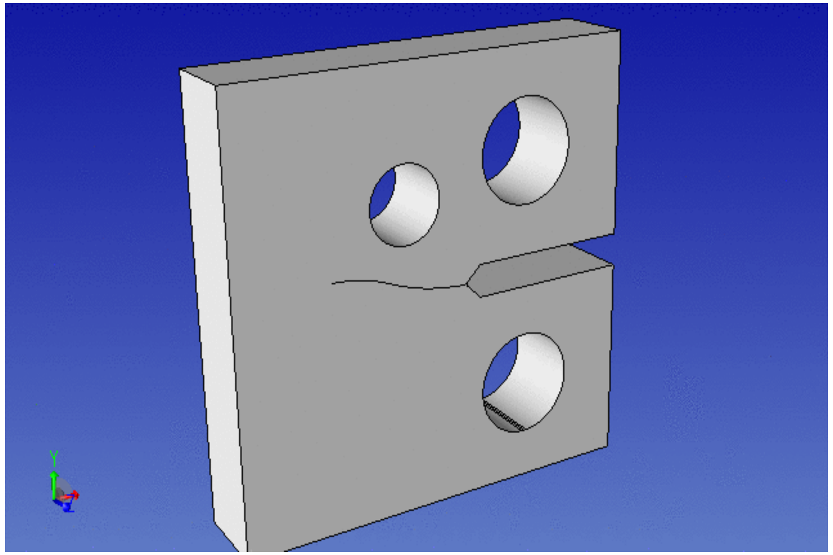
- Multiple experiments and accurate measurements (geometry, orientation) are also desired for providing a reliable reference for modeling validation effort.

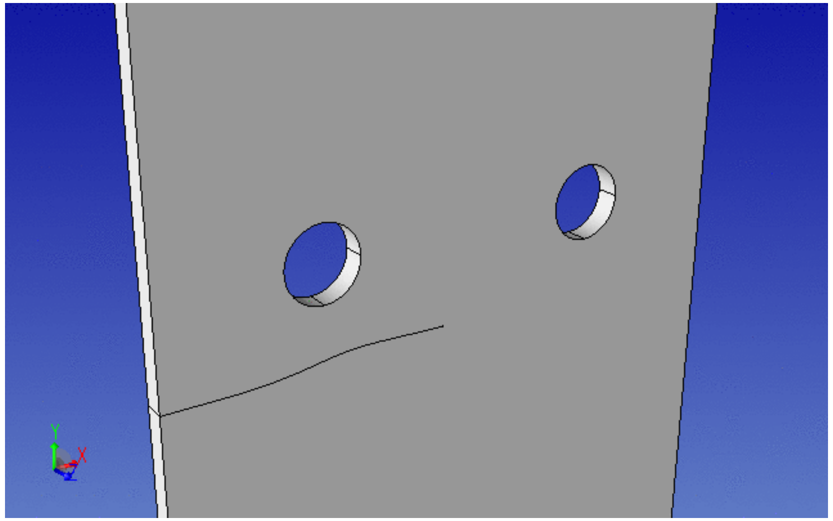
- 3D FEA using remeshing techniques can provide reliably the necessary meshes for computing accurately stress intensity factors, simulating crack propagation path and assess remaining useful life (RUL).

- Radial Basis Function - Response Surface and Gaussian Process Regression surrogate models can be trained on accurate 3D FE based crack propagation solutions for a more efficient process runtime required in uncertainty qualification (UQ) studies.

- SAE webinar: How to Perform Accurate, Automated 3D Fatigue Crack Growth Predictions:

  https://www.techbriefs.com/component/content/article/tb/webcasts/on-demand-webinars/37570





Questions?