Fatigue crack growth modeling validation using piping specimen experimental data

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Motivation

- Accomplishing fatigue crack growth modeling V&V is important for damage tolerance design community

- In the validation benchmarking, quite often the numerical solution does not match exactly the experimental measurements for various reasons.

- Sources of uncertainty (experimental or modeling process related) are many times neglected leaving unanswered questions related to accuracy of the numerical solutions presented in the Round Robin reports.

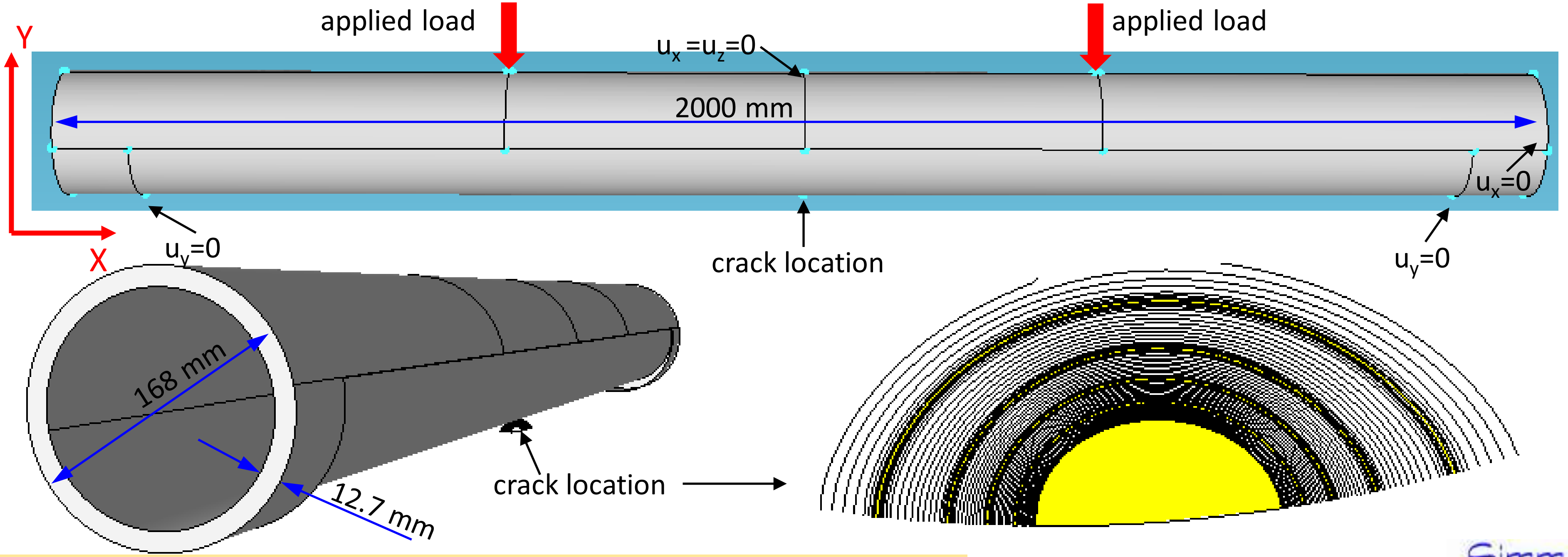
Overview

- Description of testing procedure (from Li et. al.*)
- 3D FEA based automatic crack growth solution verification
  - Reference numerical solution is provided by Li et. al.
  - Only considering R=0.1 cycles (R=0.5 cycles were neglected)
- Modeling validation using one experimental dataset: PE-1-1
  - 3D FEA model representative of the testing procedure. Both loading blocks (R=0.1, R=0.5) were considered.
  - Numerical solutions vs. beach marks at well defined cycle intervals in the physical testing procedure.
  - All automatic fatigue crack growth simulations were conducted with SimModeler Crack (Ansys solver)
  - Crack size vs. cycles based on mean and off-mean (within the ±2*SD scatter bands) FCGR (fatigue crack growth rate) characteristics of the material (X65 steel) using BS7910 standard
- Modeling V&V using AFGROW's User-Defined Beta table
  - All beta solutions collected via SimModeler Crack (Ansys solver)
- Conclusions

Experiment description (see Li et al.*)

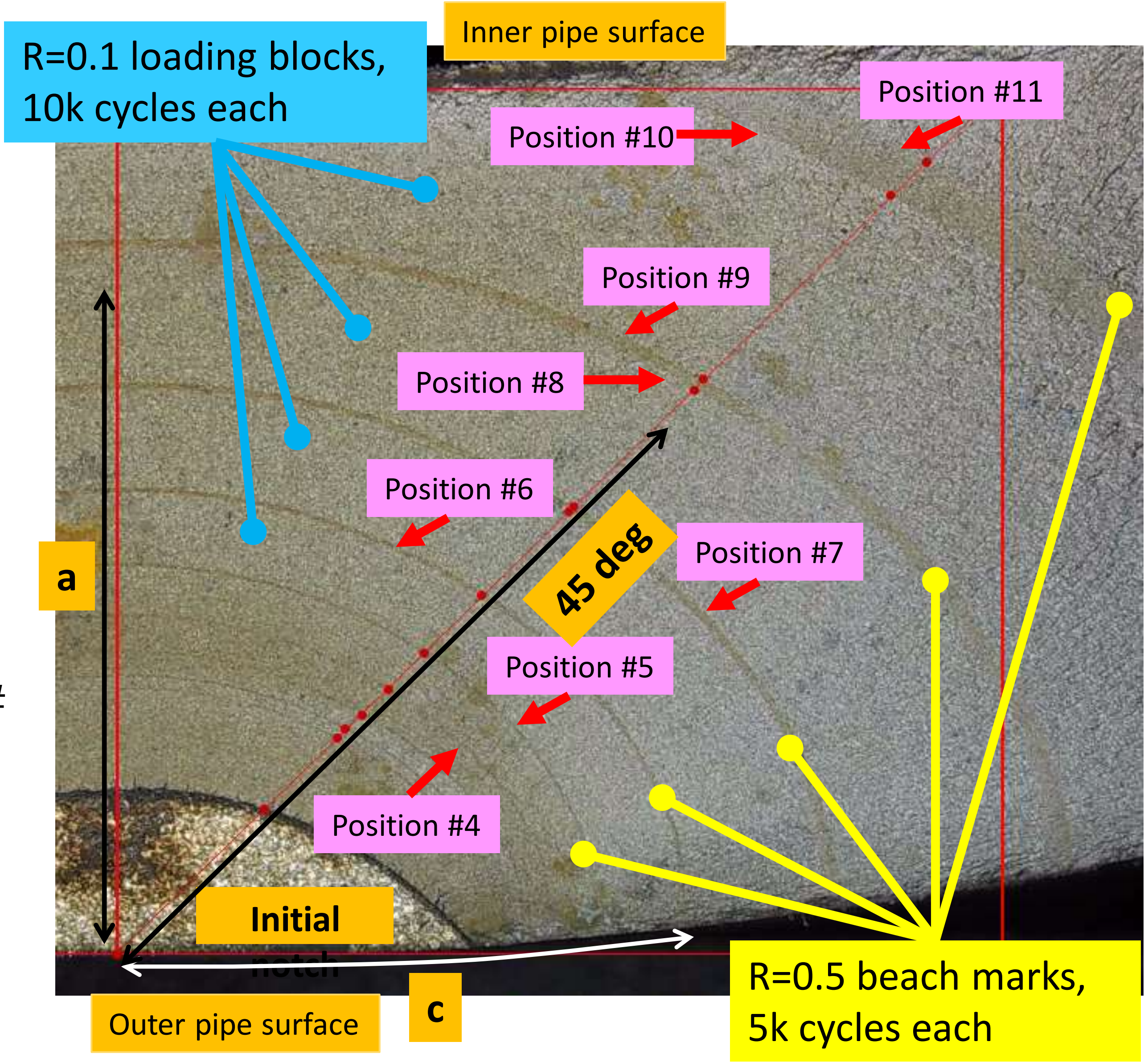
- Experimental measurements and analytical solution presented in Li. et. al.* are used for verification and validation purposes
  - *Reference: Li, Z, Jiang, X., Hopman, H, Liu, Z., An investigation on the circumferential surface crack growth in steel pipes subjected to fatigue bending, Theoretical and Applied Fracture Mechanics, pp. 205, 2020.
- Four out of a total nine experimental measurements were used in this study
  - A 3D Parasolid representation of a piping specimen (PE-1-1) is used in this demo. Mesh and FE Model completely defined in SimModeler.
  - API X65 steel used in piping industry, E = 20.7e4 MPa, ν = 0.3; Paris relationship used in the assessment, C = 3.98e-13, n = 2.88 (mean values, BS 7910, 2013+A1)
  - Post precracking loading mission: R=0.1 for 10,000 cycles followed by R=0.5 for R=5,000 cycle block (same Max load = 241.54 kN).

Units: N, mm



PE-1-1 beach mark data

- Beach mark data was used to determine crack size during the testing procedure
- Each beach mark corresponds to an R=0.5 5000 loading block
- Between the beach marks, an R=0.1, 10000 cycles loading block is performed
- To avoid any uncertainty related to initial crack size and the end of the precracking, the modeling procedure considers position #4 as the initial crack size
- For the beach mark correspondent to position # 4, 5, 6, 7 it is difficult to identify the beginning and the end of the R=0.5 5000 cycles. A single length definition is used for these beach marks.
- For beach marks correspondent to position #8, 9, 10, 11 the transition from R=0.1 to R=0.5 is clear

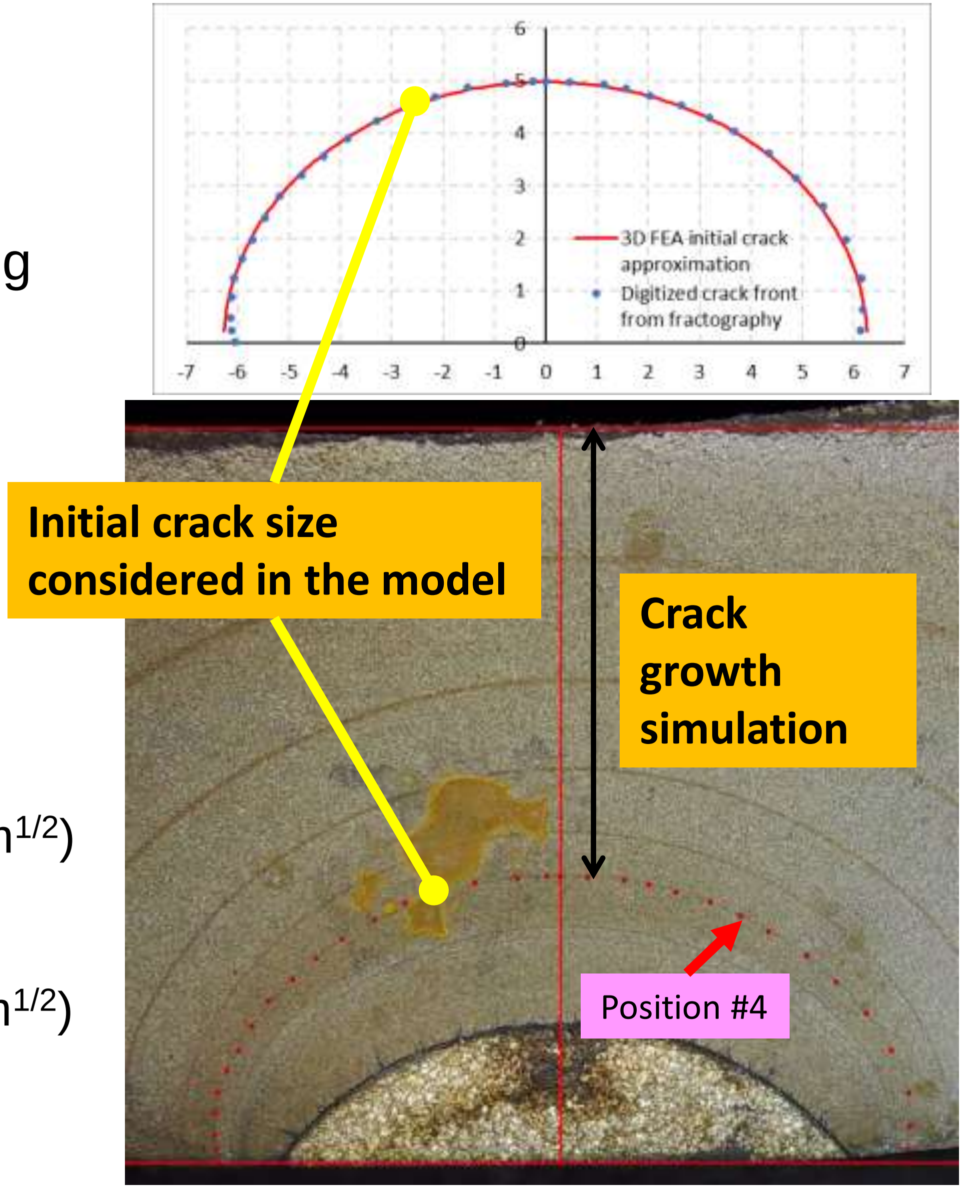


BS7910 FCGR data & modeling procedure

- Initial crack is modeled as semi-elliptical and captures the beach mark at position #4
- Crack growth is modeled from position #4 to crack penetrating through the interior surface of the pipe
- ΔN based 3D FEA simulation: repeating loading blocks of 10,000 cycles at R = 0.1 followed by 5,000 cycles at R = 0.5 (max load is maintained)
- BS7910 provides the following fatigue crack growth rate (FCGR) {C, n} Paris' values for steels exposed to air environment:
  - R < 0.5, mean {C, n} = {3.98e-13, 2.88} (ΔK > 363 MPa*mm$^{1/2}$)
  - R < 0.5, mean+2s {C, n} = {6.77e-13, 2.88} (ΔK > 315 MPa*mm$^{1/2}$)

  - R ≥ 0.5, mean {C, n} = {5.86e-13, 2.88} (ΔK > 196 MPa*mm$^{1/2}$)
  - R ≥ 0.5, mean+2s {C, n} = {1.29e-12, 2.88} (ΔK > 144 MPa*mm$^{1/2}$)

  - These values are considered "**nominal**"



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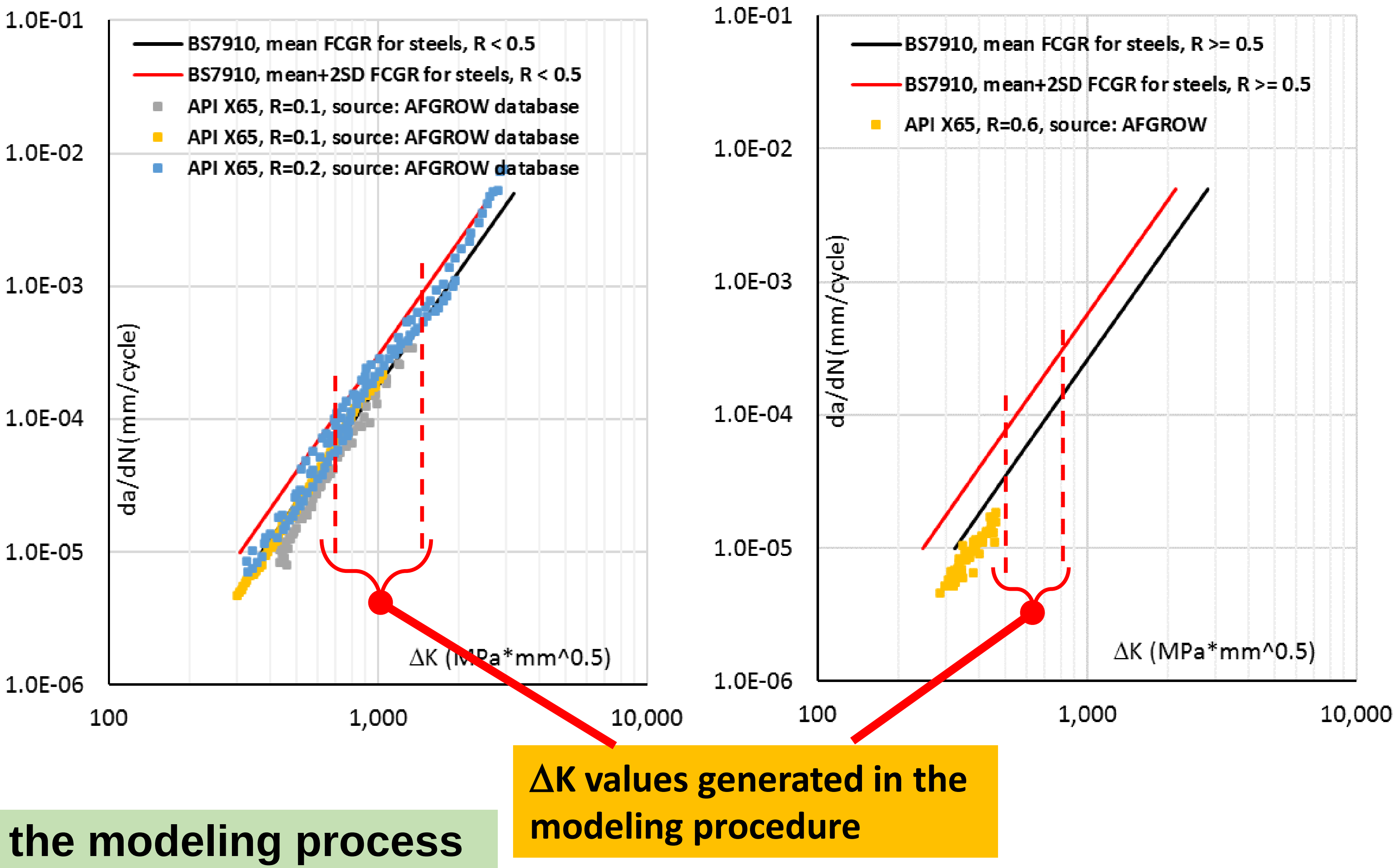
Available FCGR data

- BS7910 provides mean and mean+2SD air-exposed FCGR data for steels (ferritic, austenitic or duplex). These data sets will be called “nominal”.
- API X65 specific FCGR R=0.1 data (AFGROW database) seems to be consistent with the generic bounds provided by BS7910
- For R=0.6, the specific API X65 FCGR data is insufficient to determine if the data is consistent with BS7910 bounds

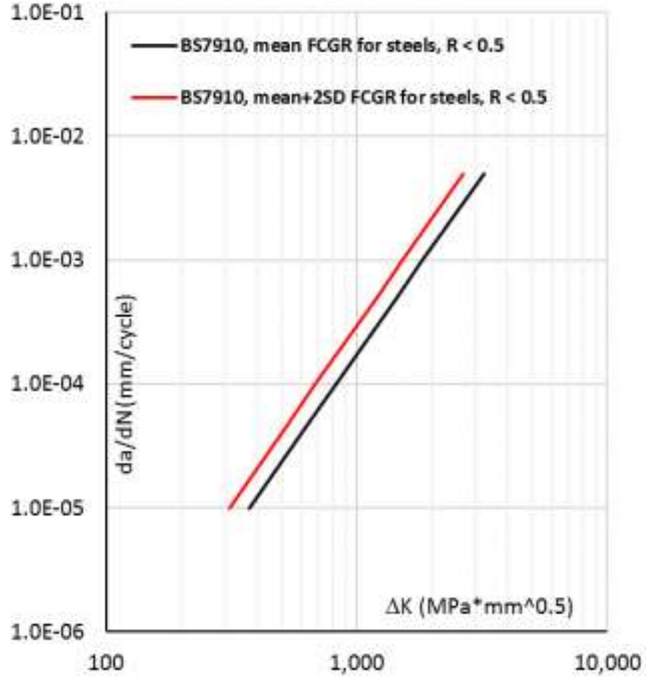


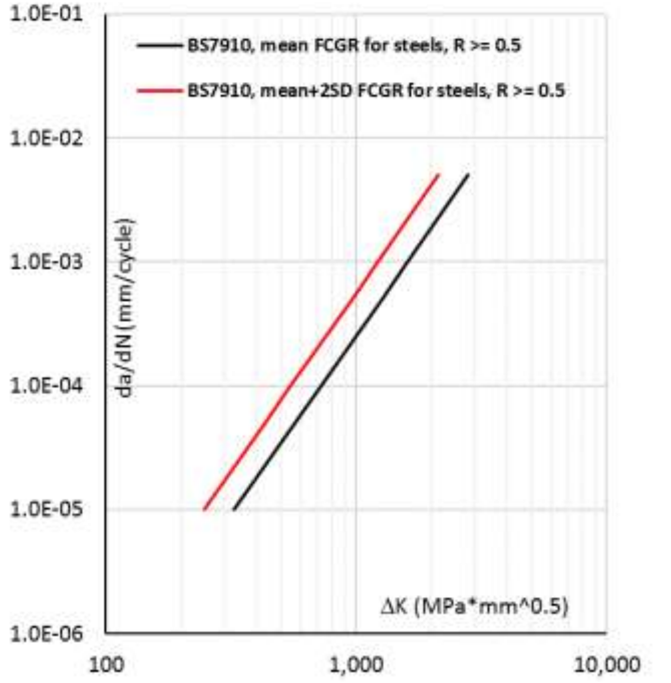
BS7910 FCGR will be used in the modeling process

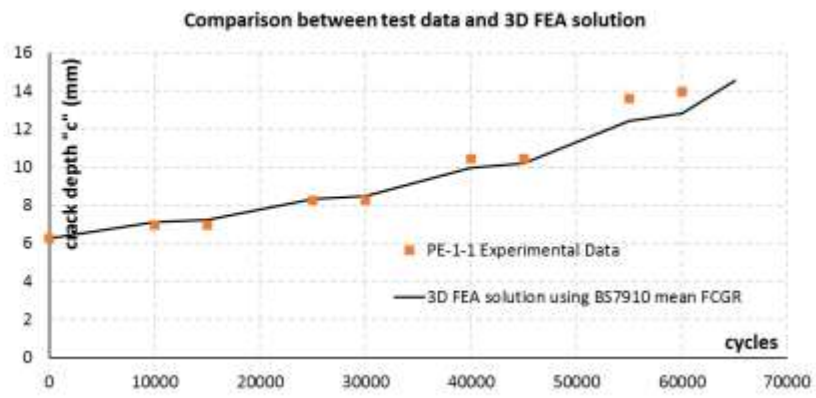
Modeling validation using PE-1-1 beach mark data

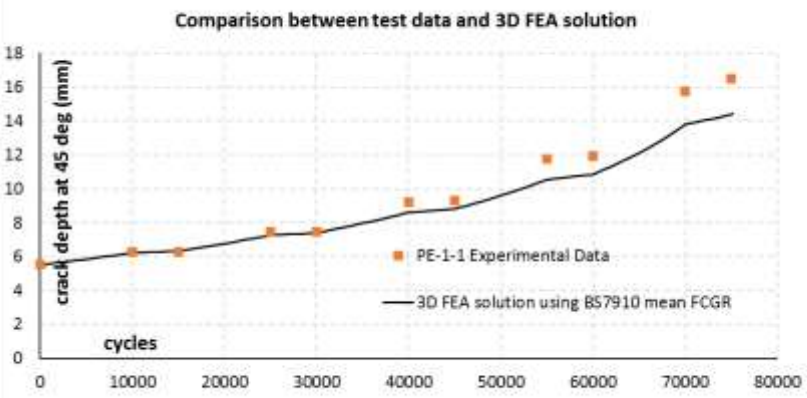
- BS7910, mean FCGR data is used in the numerical procedure
- Starting with an elliptical crack definition that resembles beach mark position #4, the automatic 3D FE modeling procedure follows testing mission, 10k cycles at R=0.1 followed by 5k cycles at R=0.5 (same max load of 241.5 kN)
- Numerical solution captures quite well crack size (“a”, “c”, and along 45 deg) identified post-failure

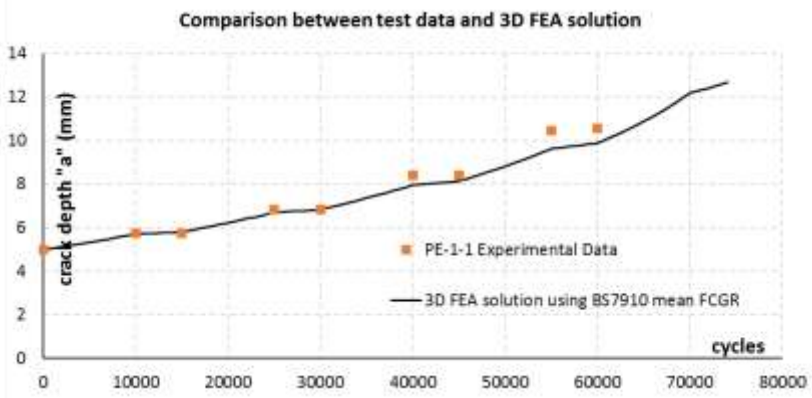
Nominal FCGR data (mean and mean+2SD for R < 0.5, R ≥ 0.5)







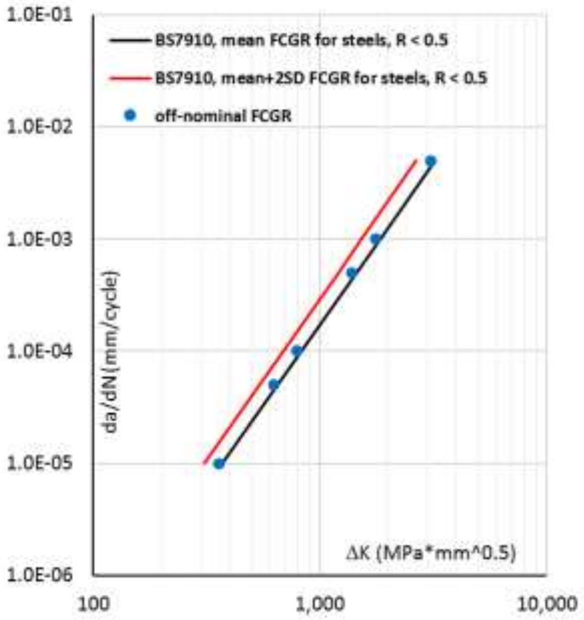


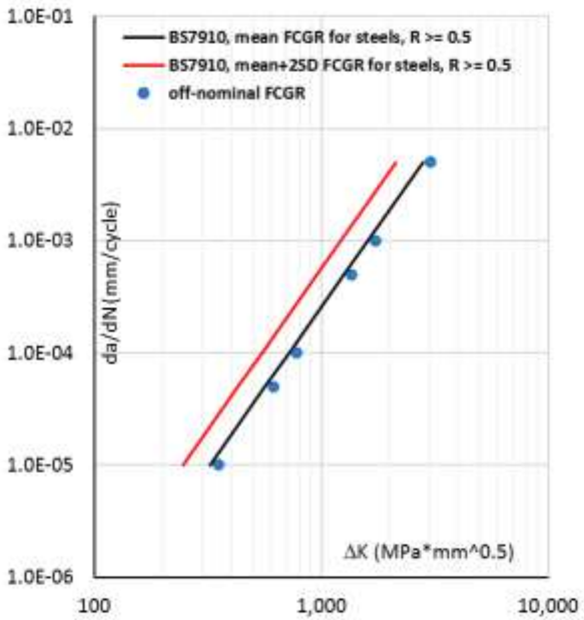


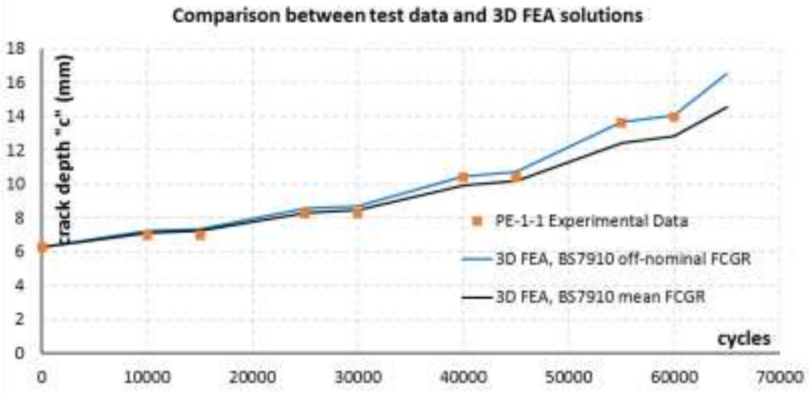
Modeling validation using PE-1-1 beach mark data

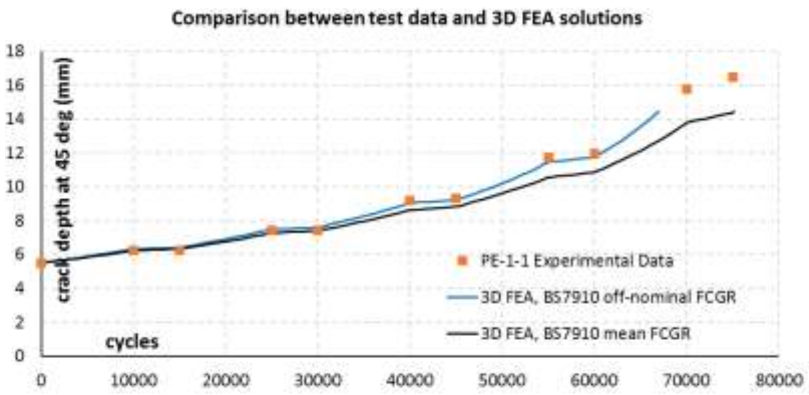
- Since there is some discrepancy between numerical solution and experimental measurements at large crack depths (“a” values) and, inherent FCGR scatter is a major factor that needs to be accounted for in the validation process, “off-nominal” FCGR data is considered for both R ratios used in the simulation
- The “off-nominal” data is within the FCGR BS7910 bounds
- Excellent agreement between numerical solution and beach mark data along the three directions (“a”, “c”, and at 45 deg)

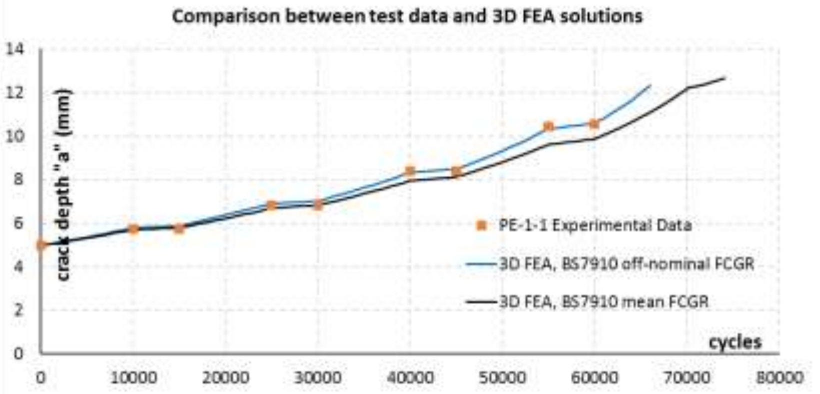
Comparison between nominal (mean and mean+2SD) and off-nominal FCGR data used for PE-1-1





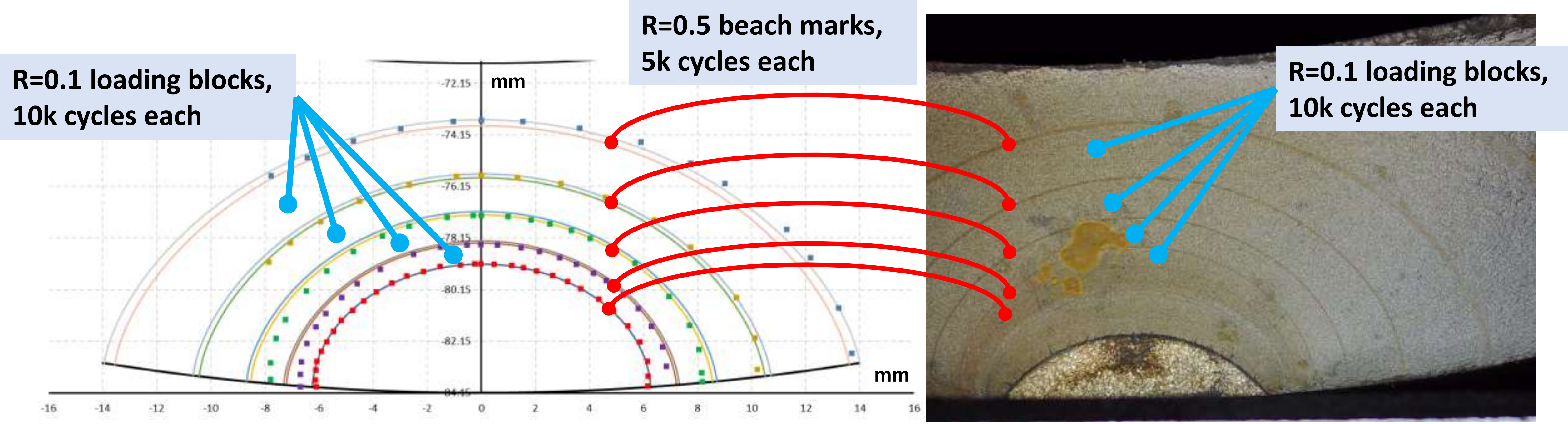






Modeling validation using PE-1-1 beach mark data

- For “off-nominal” FCGR data (within expected scatter), a complete comparison between beach marks and 3D FEA based solutions is provided
- When compared to the beach marks, position and shape of the crack front at the beginning and at the end of each R = 0.5 loading block is very well captured by the numerical solution

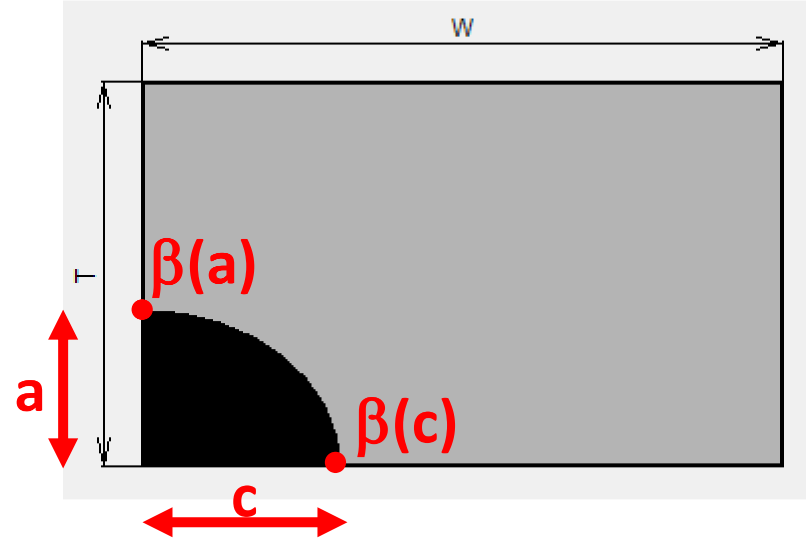


Dots: digitized beach marks
Continuous crack front representations: numerical solutions

Modeling V&V using AFGROW's User-Defined β table

- A "Part Through Crack" model available in AFGROW is selected. This model is agnostic to the 3D geometry. AFGROW' solution algorithm tracks two locations: "a" and "c"
- A predefined set of elliptical crack sizes is needed to generate β(a) and β(c) values correspondent to the two tracked locations
- SimModeler is used to perform the 3D FEA solutions, collect $K_{I(a)}$ and $K_{I(c)}$ values at the two tracked locations

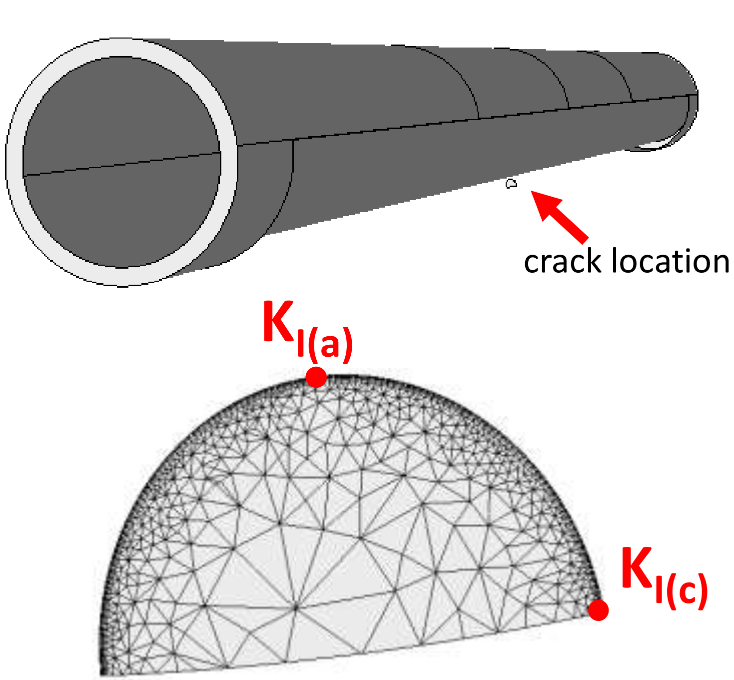
AFGROW model

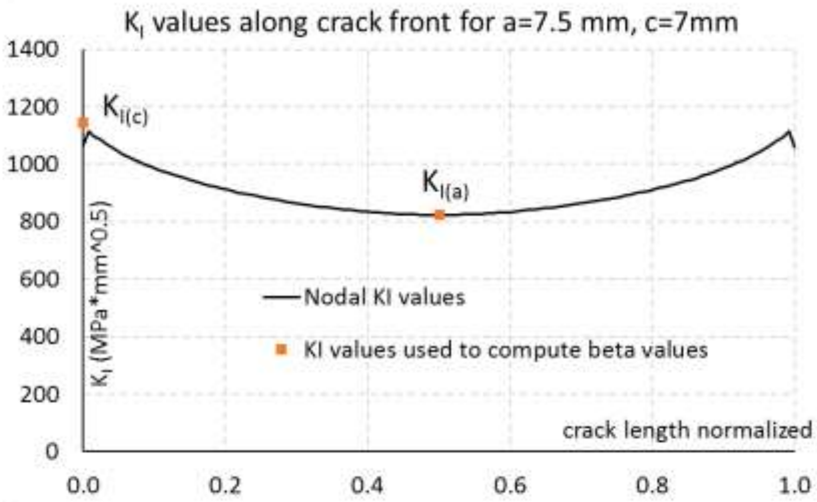


For the [a] crack length dimension: $K = \sigma_{ref}\sqrt{\pi a}\,\beta(a)$

For the [c] crack length dimension: $K = \sigma_{ref}\sqrt{\pi c}\,\beta(c)$

SimModeler Crack: $K_{I(a)}$ and $K_{I(c)}$ postprocessing example

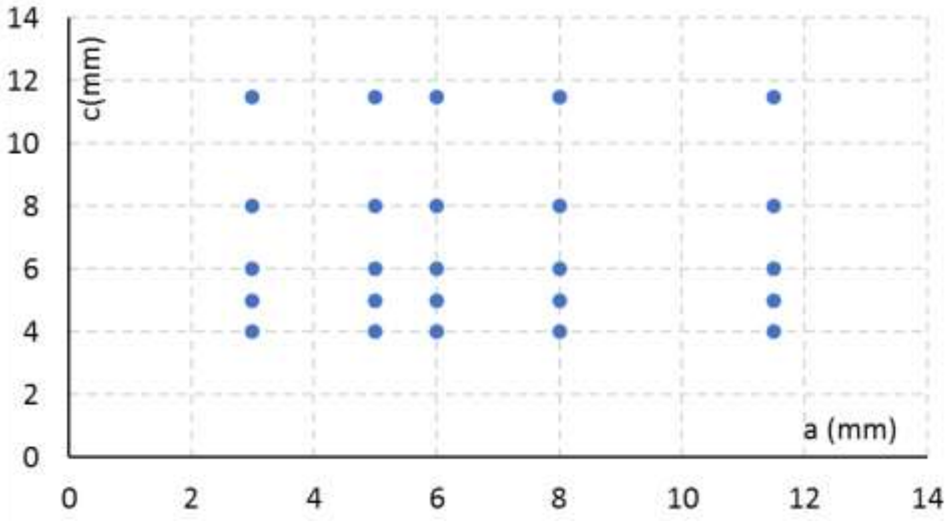




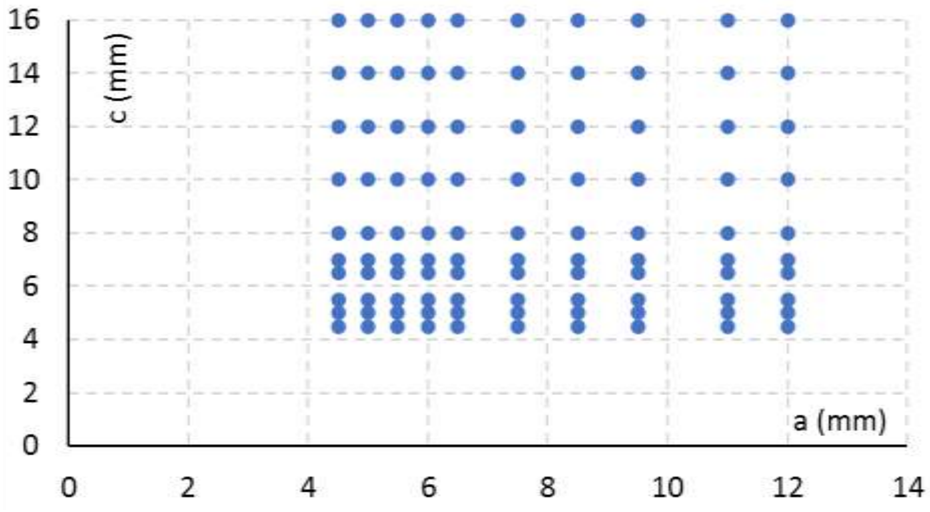
AFGROW's User-Defined β table

- Two square matrices (a, c) are defined: a lower resolution using a 5x5 matrix size and a higher resolution using a 10x10 size
- For each pair $(a, c)_i$, a 3D FEA solution is computed with SimModeler. All solutions are performed automatically including ($K_{I(a)}$ and $K_{I(c)})_i$ post-processing

Lower resolution β table definition



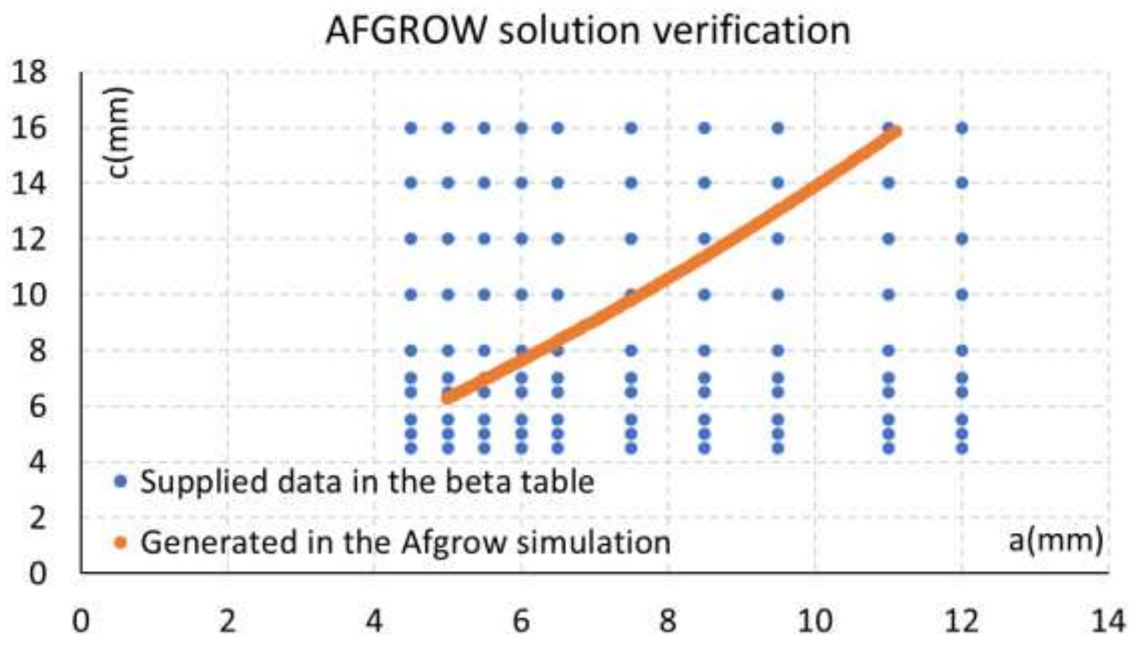
Higher resolution β table definition

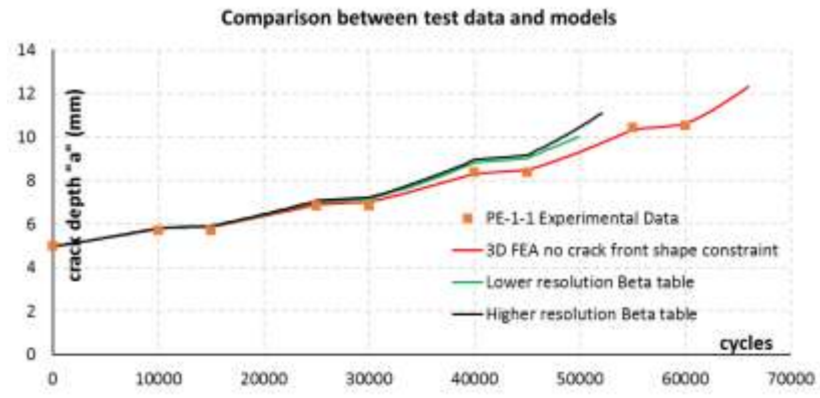


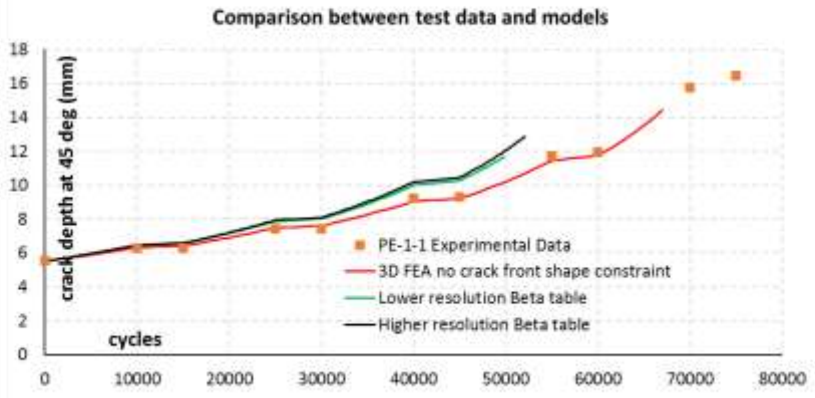
- To be consistent with the solution obtained via 3D FEA where no crack shape is assumed, the same "off-nominal" FCGR data (within expected scatter) was used, and no retardation effects were considered during the AFGROW solution

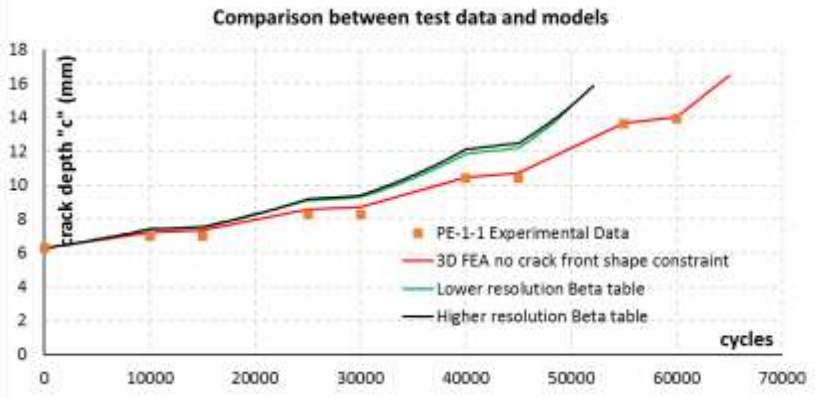
Fatigue crack growth solutions using AFGROW's User-Defined β table

- The 3D FEA based solutions for ($K_{I(a)}$ and $K_{I(c)}$) are normalized to provide the β tables as required by AFGROW
- The two solutions using lower resolution and higher resolution β table definitions, are consistent
- An (a, c) comparison between the elliptical crack definitions used in the higher resolution β tables and the solution can be used to make sure that the β table provides all necessary data points for interpolation



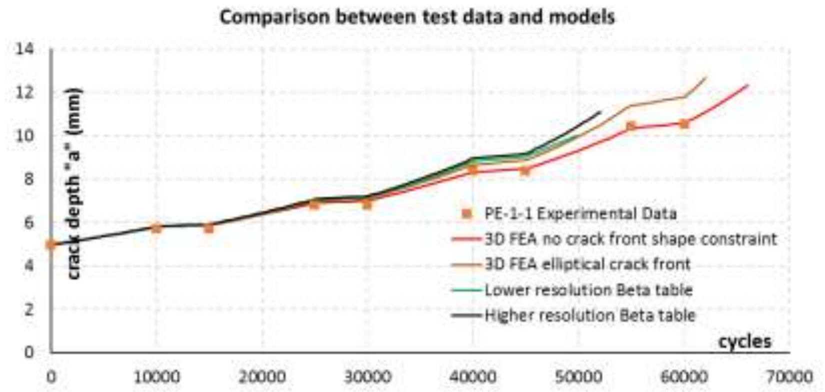


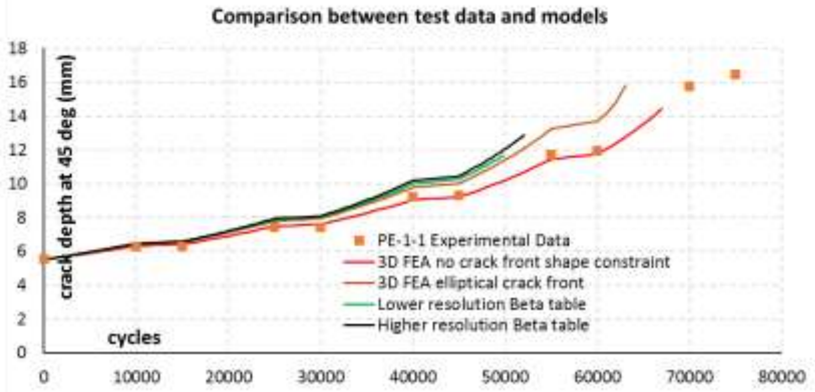


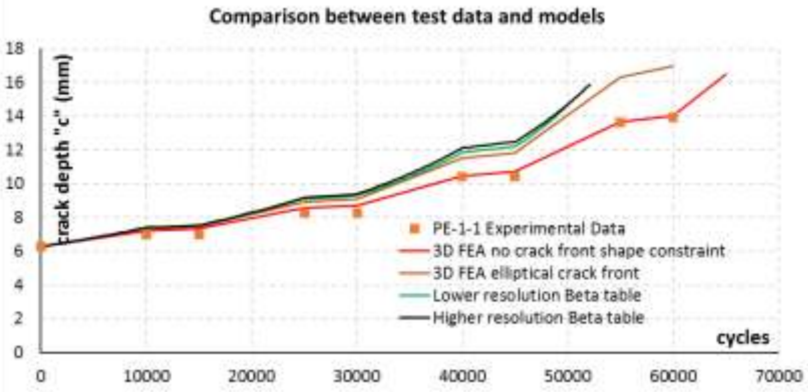


β table solutions vs. 3D FEA using incremental elliptical crack front definitions

- Another solution is added to the comparison to assess the observed difference between the 3D FEA solution where no crack front shape is assumed and the β table solutions (crack front ellipticity is assumed)
- The 3D automatic crack propagation simulation was modified to constrain each crack front increment to an elliptical shape. More info about the procedure was provided in:
  - ERSI meeting, April 2021
  - Fatigue Crack Growth Modeling Validation and Sensitivity Study: Corner Crack Round Robin Challenge, ASIP 2021
  - Quantification of the impact of the crack shape constraint assumption onto predicted remaining useful life, ASME Turbo Expo 2022.
- The AFGROW β table solutions and the 3D FEA using elliptical crack front increments verify against each other
- The assumed crack front shape is a contributor to the observed difference between the β table solutions and the 3D FEA based solution (no assumed crack front shape)







Conclusions

- Using a fatigue crack growth experimental measurement dataset, modeling validation is reached using FCGR data within the bounds provided in BS7910.
- In the fatigue crack growth modeling validation process, it is important to consider uncertainty related to FCGR scatter.
- Accurate 3D FEA solutions can be used to provide β values for a runtime efficient AFGROW's user defined table-based solution
  - Solution runtime for one 3D FE model that represents a crack of a given shape and size is: 2 minutes
  - Runtime for achieving a 3D FEA incremental fatigue crack growth solution is 130 steps * 2 minutes
  - Runtime for obtaining 25 solutions using 3D FEA to fill in the β table (low-resolution table) is 25 * 2 minutes if the simulations are performed in serial mode. In the case of performing all the cases simultaneously, the runtime becomes 2 minutes.
- For an elliptical crack front assumption, verification is also reached between an incremental 3D FEA based solution and the β table solution

Questions?

Acknowledgements

- Many thanks to Zongchen Li for providing fractography pictures and some info related to the test procedure.
- Many thanks to Jim Harter for guidance using the β tables

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