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Validation of Fatigue Crack Growth Modeling Solutions using Measurements Collected on API X65 Piping Specimens

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DA-08-02 FFS Involving Piping and Pipelines
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Thursday, 10:15 AM - 12:00 PM

Session Chairs: Clay Rodery, Yasumasa Shoji, Shunji Kataoka, Kannan Subramanian, Gys van Zyl, Bhaskar Shitolé

Motivation

- There is a continuous engineering need to assess damage tolerance capability of a component in service. A set of standards and practices (API 579-1/ASME FFS-1, BS 7910, DNV-RP-F108), 3D FEA capabilities as well as dedicated reduced order modeling tools are available for the PVP community to assist these needs.

- Verification & Validation (V&V) is a very important task that needs to be accomplished because it provides a higher confidence level in the component-level fatigue crack growth modeling solutions

- 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 solution.

Overview: Numerical solutions used in the V&V benchmarking

Model type:

- Multi-degree of freedom: no crack front shape constraint
  - ✓ 3D FE modeling capabilities available in SimModeler Crack

- Two degrees of freedom: elliptical crack front increments
  - ✓ AFGROW's API 529 built-in model
  - ✓ AFGROW's Beta table input
  - ✓ Modified 3D FE procedure to accommodate elliptical crack front increments

Verification

Reference for validation benchmarking: fractograpy based measurements from four mechanical test procedures reported in:

- 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.

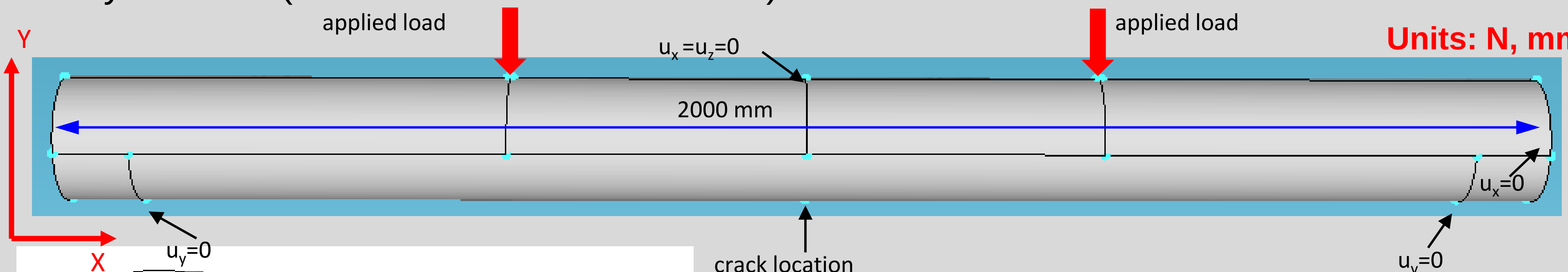
FCGR scatter:

- ✓ Using BS 7910 average FCGR data
- ✓ Off-nominal FCGR data within the nominal bounds provided by BS 7910

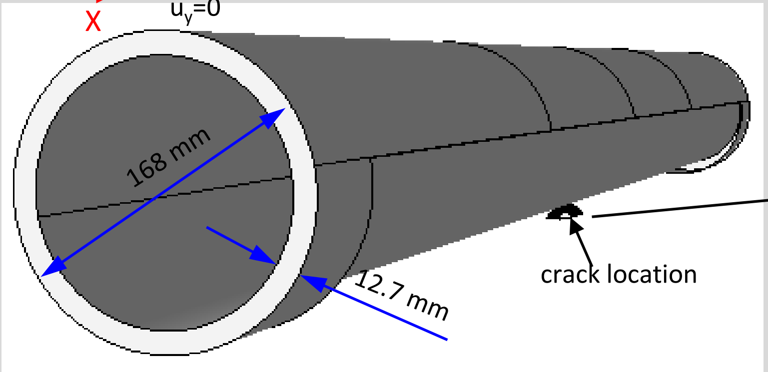
Validation

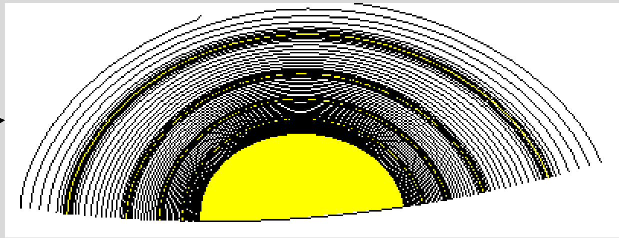
Overall model definition and mechanical testing procedure (Li et al.*)

- 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 CAD 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

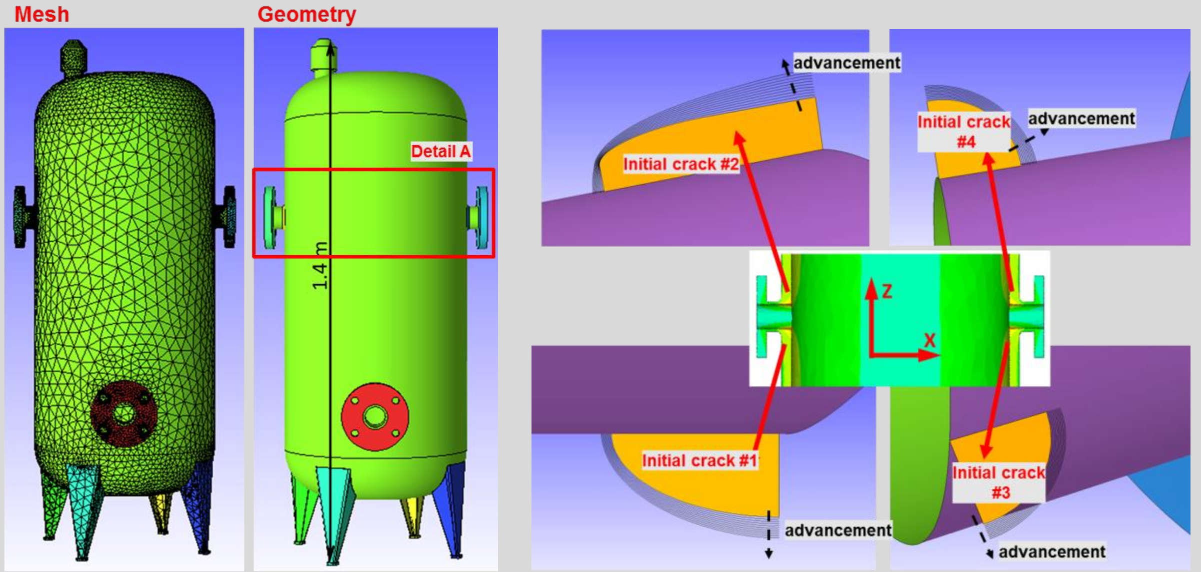




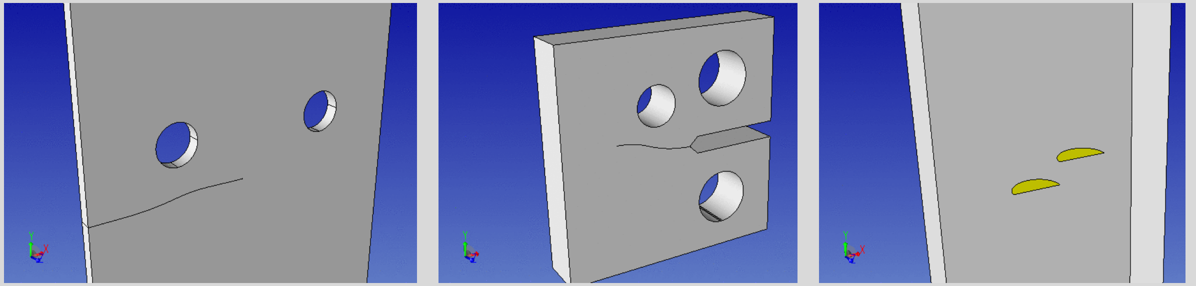
Experimental procedure captured in the model based on available data.

SimModeler Crack: component level fatigue crack growth life assessment

- Capabilities
  - CAD-Mesh continuous associativity
  - Automatic simulation process for 3D fatigue crack growth solutions
  - CAD or volumetric meshes can be used to perform the simulation
  - Robust remeshing capabilities
  - Solver Plugin capability
  - Interface planar and non-planar crack definition, multi-material through-crack modeling

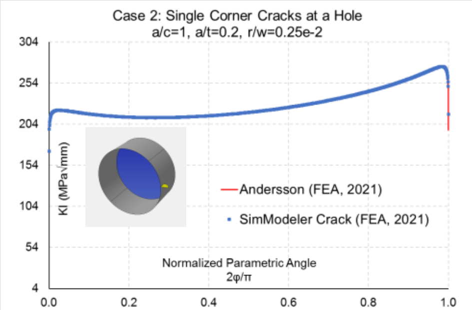


- Validation benchmarking
  - Using experimental data published in open literature
  - For out-of-plane crack growth
  - For single and two-cracks
  - For constant amplitude loading missions (different R ratios, loading blocks)



- Verification benchmark
  - Pilarczyk R., 2021. “Cross-Comparisons of Stress Intensity Factors from Various Sources. The Pathway to Improved SIF Solutions”. AFGROW Workshop.

No. element edges along crack front	Average of relative differences (absolute values) using Andersson' semi-analytic solution as reference	
	0.01 < 2*phi/pi < 0.99	0.001 < 2*phi/pi < 0.999
100	0.42%	
200	0.15%	
300	0.23%	
1000	0.13%	0.13%
2000	0.14%	0.14%
3070	0.19%	0.19%
8200	0.18%	0.18%

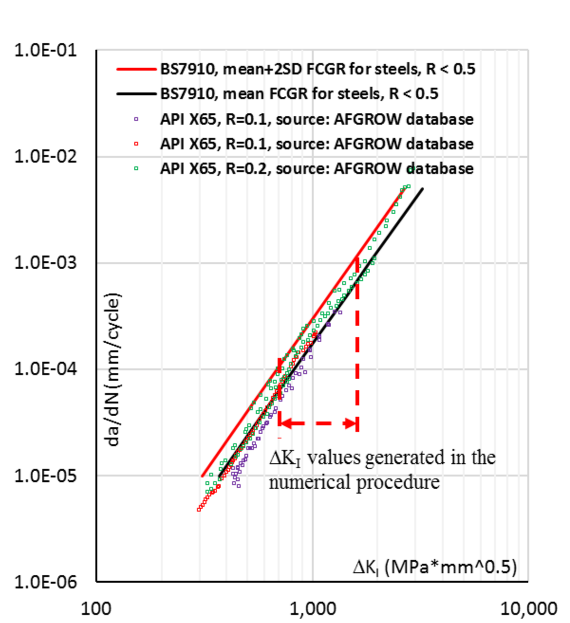


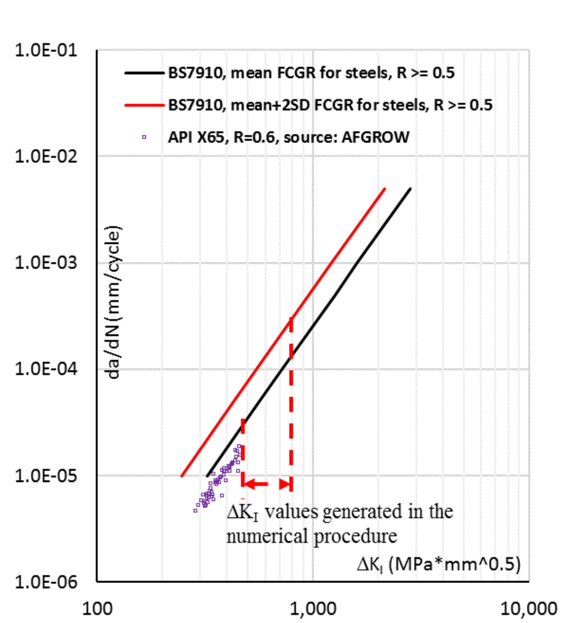
BS 7910: Fatigue crack growth rate data

- BS 7910 recommended fatigue crack growth rate for steels (ferritic, austenitic or duplex ferritic-austenitic) exposed to air using the following Paris' parameters {C, n} (da/dN [mm/cycle], ΔK [N/mm$^{3/2}$]):

	Mean curve	Mean + 2SD curve
R < 0.5	{3.98e-13, 2.88}	{6.77e-13, 2.88}
R ≥ 0.5	{5.86e-13, 2.88}	{1.29e-12, 2.88}

- Data available in AFGROW's database for API X65 confirms the recommended BS 7910 curves

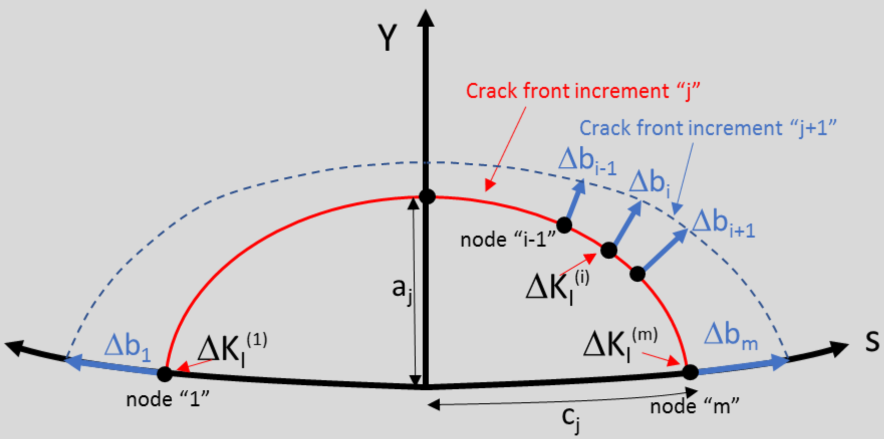




BS 7910 recommended curves (labeled "nominal") were used in the modeling procedure for generating solutions correspondent to four experimental fatigue crack growth measurements.

Multi-degree of freedom solution: formulation

- LEFM framework
- Displacement correlation technique for K_I, K_{II}, K_{III} computation at nodal level
- Verification benchmarking for K_I was reached on a different type of geometry
- Paris' relationship for relating crack driving force ΔK_I to fatigue crack growth rate

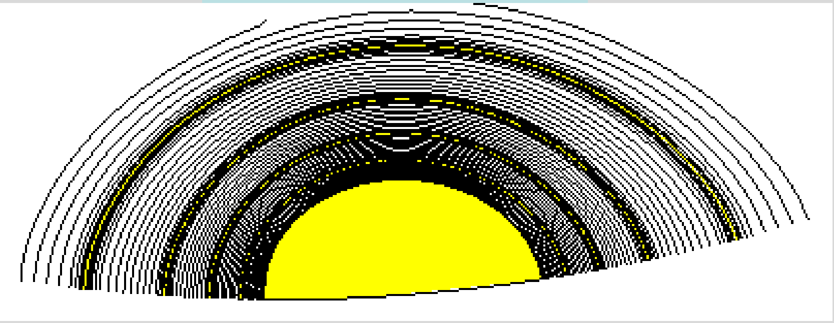


$$\Delta b_i = \left(\frac{\Delta K_I^{(i)}}{\Delta K_I^{max}} \right)^n \Delta b_{max}$$

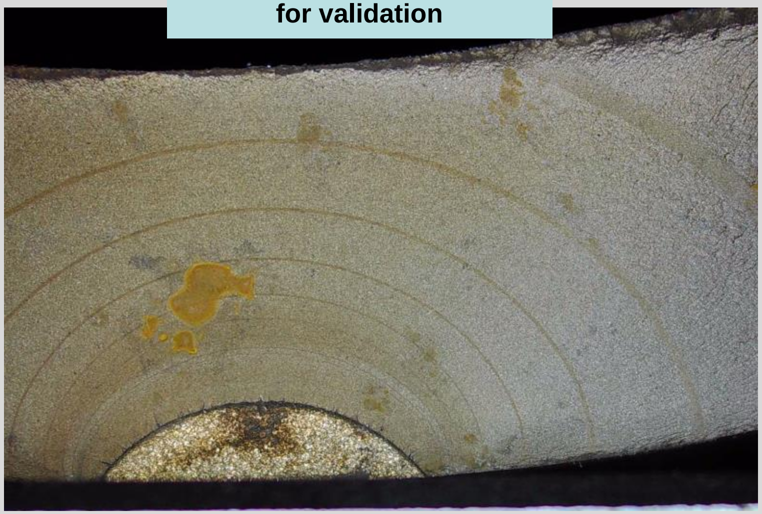
$$\Delta N = \frac{\Delta b_{max}}{C \left(\Delta K_I^{(max)} \right)^n}$$

The multi-degree of freedom does not constrain the crack front increments to an elliptical shape. In this benchmarking, crack front increment shape is defined by nodal ΔK_I values.

Typical numerical solution



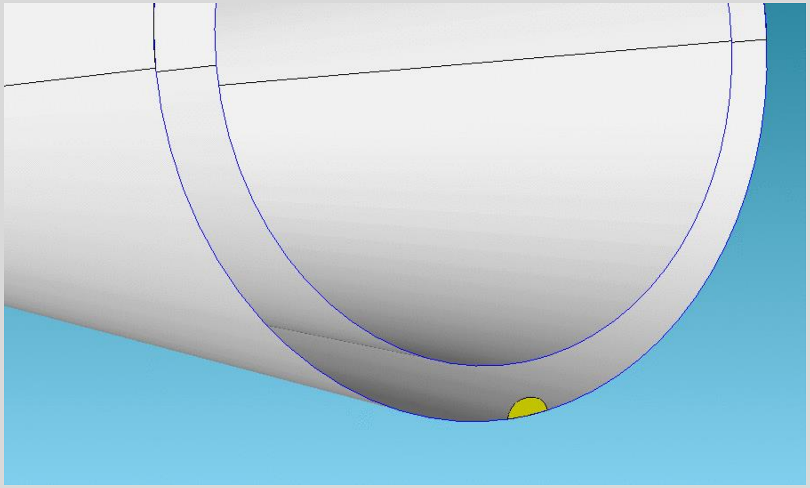
Typical beach mark data for validation



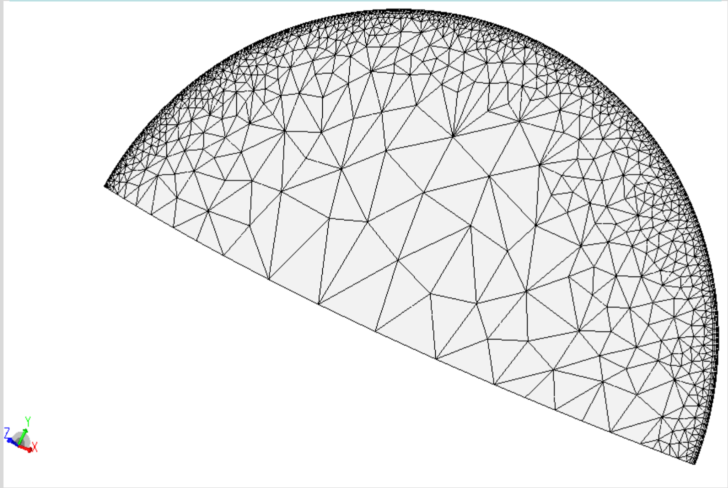
Multi-degree of freedom solution: modeling procedure

- Remeshing technique used for fatigue crack growth modeling
- The automatic modeling procedure uses from 100 to 150 crack front increments for a solution used in the validation benchmarking
- Permanent geometry (CAD model) mesh association for each model generated in the modeling process

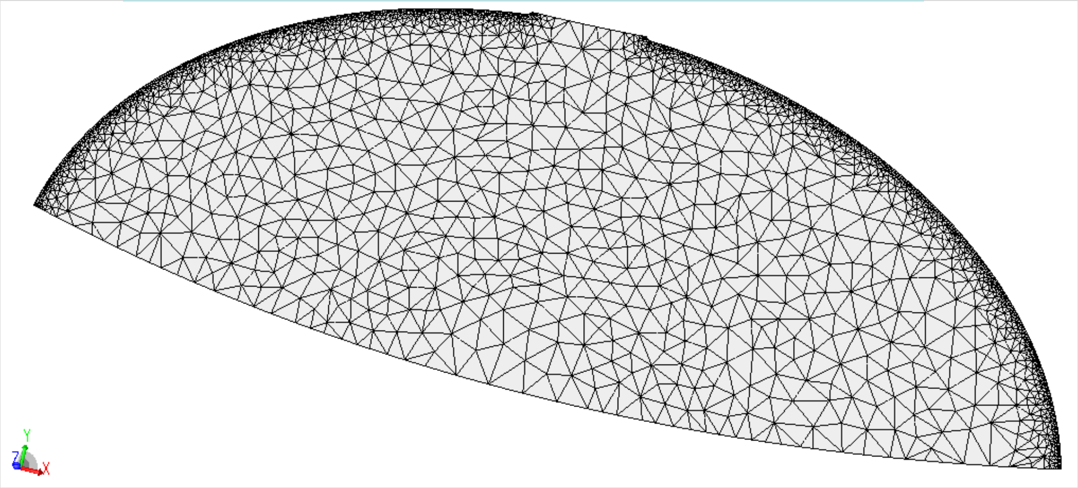
Deterministic LBB solution can also be performed



Mesh associated with initial crack surface definition



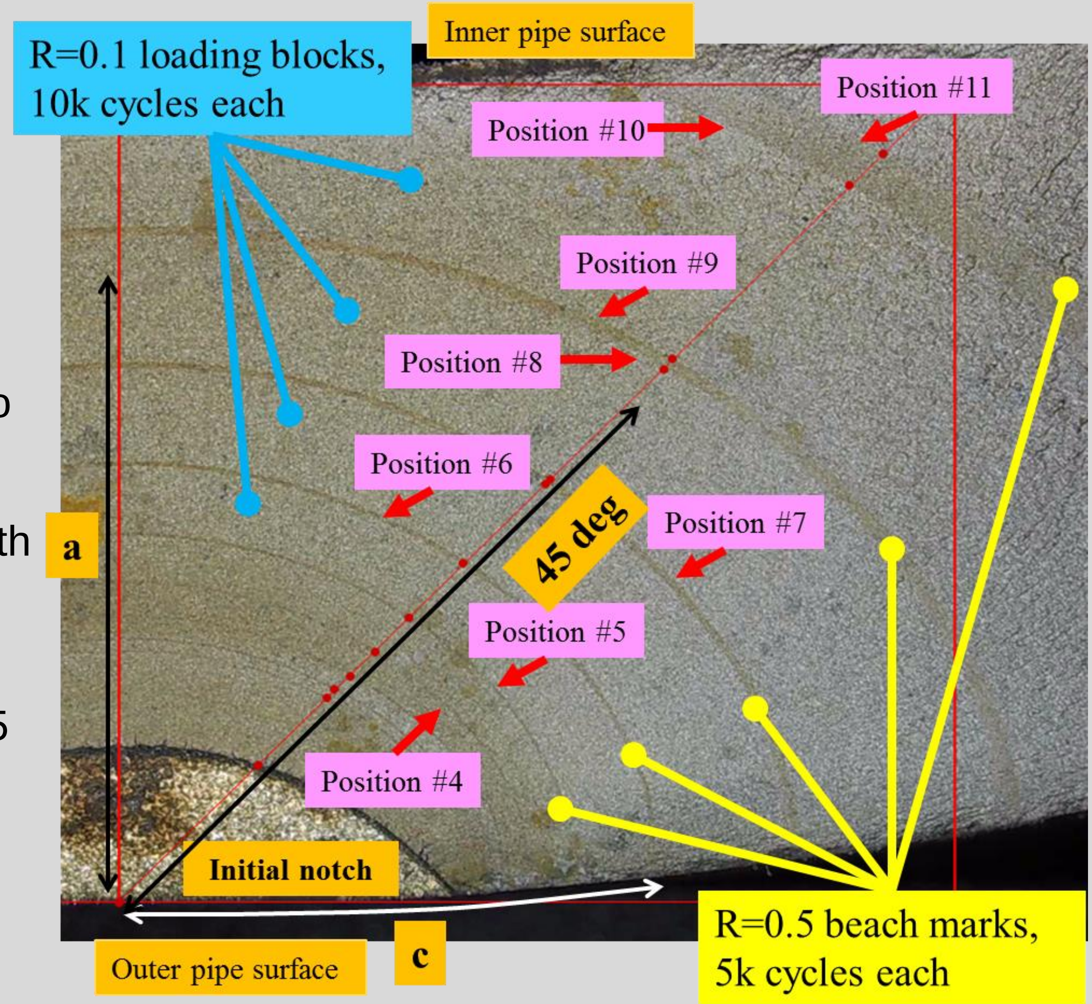
Mesh associated with crack surface post wall break-through



Robust remeshing meshing delivers automatic fatigue crack growth modeling procedure

Validation benchmarking: multi-degree of freedom solutions vs. PE-1-1 beach mark data

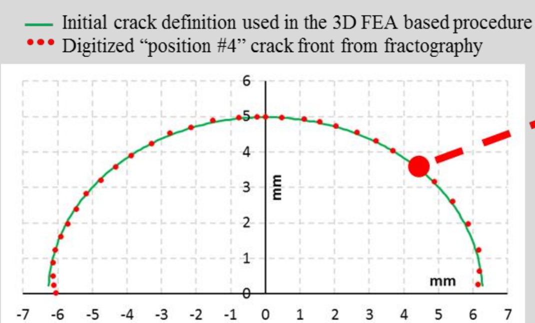
- Beach mark data was used to determine crack size during the testing procedure
- To avoid any uncertainty related to initial crack size and the end of the precracking, the modeling procedure considers position #4 as the initial crack size
- For the beach mark correspondent to position # 4, 5, 6, 7 it 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
- In the validation benchmarking, numerical solutions are compared with beach mark pattern along exterior surface ("c"), along the thickness ("a") and at 45 degrees as well as the entire digitized beach mark against the crack front edge from the 3D FE model

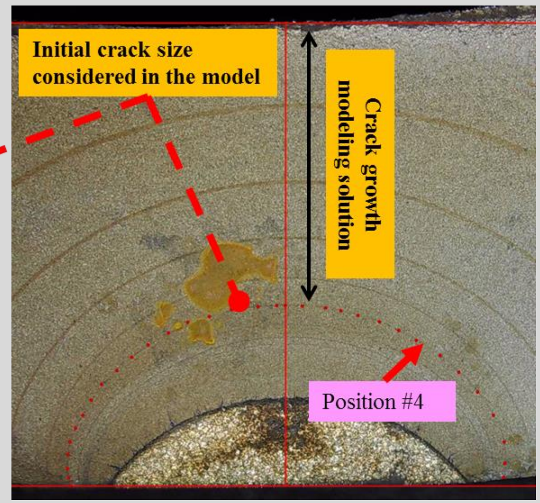


The modeling challenge is to match the beach mark pattern using the same loading mission as in the experimental procedure

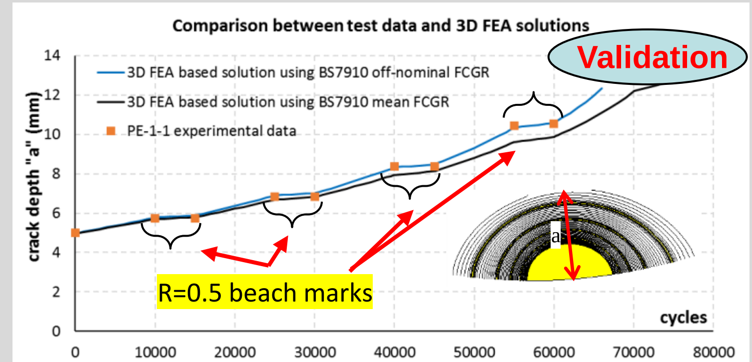
Validation benchmarking: multi-degree of freedom solutions vs. beach mark data collected from PE-1-1 specimen fractography

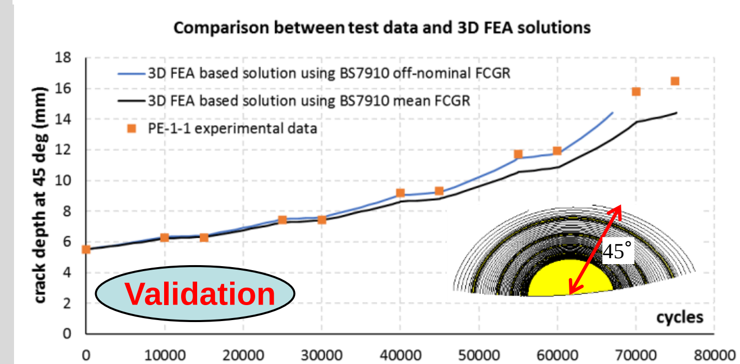
- A clear indication of the crack front was used to define an initial crack surface in the modeling procedure. An elliptical crack front shape captures the digitized beach mark quite accurately.
- Numerical solution is performed for more than 50% of the coupon thickness



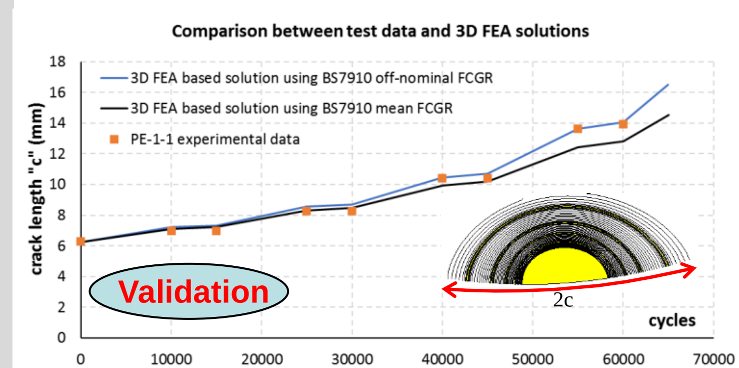


PE-1-1: Numerical solutions vs. beach mark data





- Two numerical solutions are carried out: using mean BS 7910 FCGR curves (for R < 0.5 and R ≥ 0.5) and, slightly off-mean but within the scatter bounds recognized by BS 7910

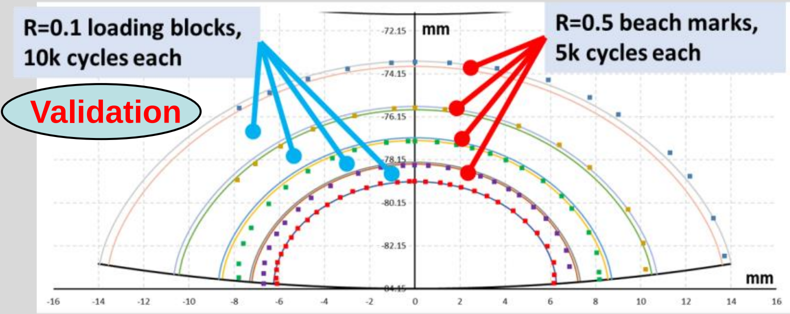


The off-nominal FCGR data (slightly off-mean FCGR) matches accurately the beach marks recorded on PE-1-1 coupon.

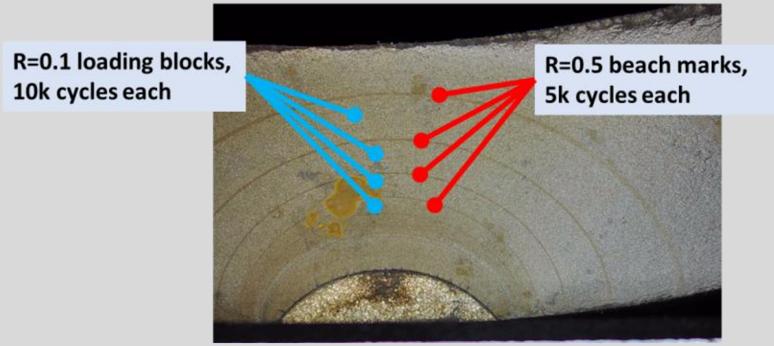
Validation benchmarking: multi-degree of freedom solutions vs. beach mark data collected from PE-1-1 specimen fractography

- Each crack front edge collected in the comparison indicates a switch in the loading's R ratio
- The off-nominal FCGR is within the scatter recognized by BS 7910
- The off-nominal FCGR data (slightly off-mean FCGR) matches accurately the beach marks recorded on PE-1-1 coupon.

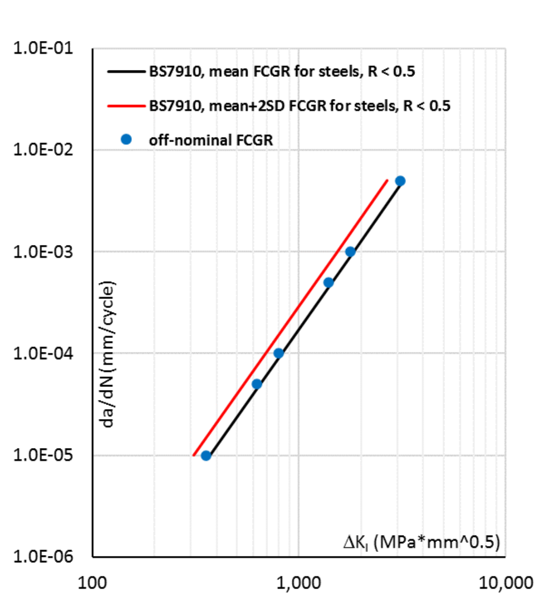
Digitized beach mark vs. crack front edges from numerical solution correspondent to each R ratio loading switch

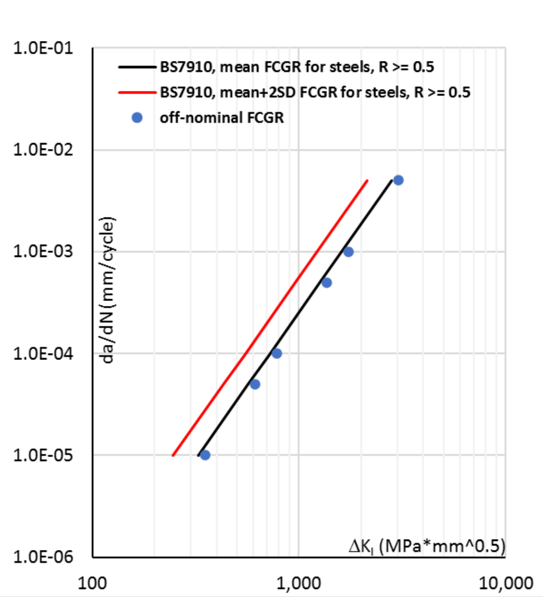


Discrete crack front representations: digitized beach marks
Continuous crack front representations: numerical solutions



Nominal BS 7910 FCGR curves (average and +2SD) vs. off-nominal used in the validation benchmarking



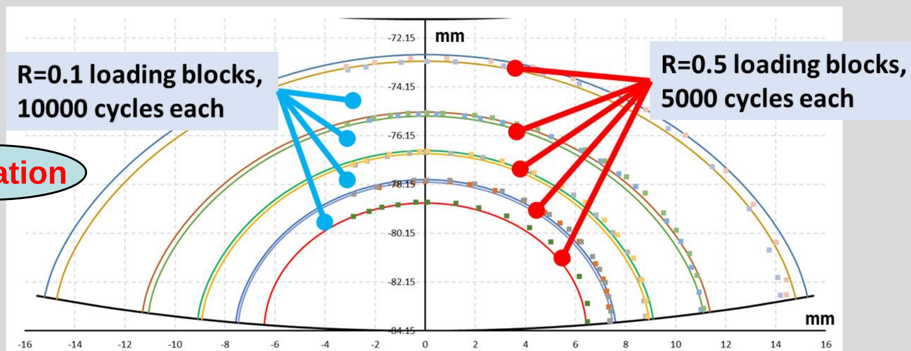


Modeling validation is reached

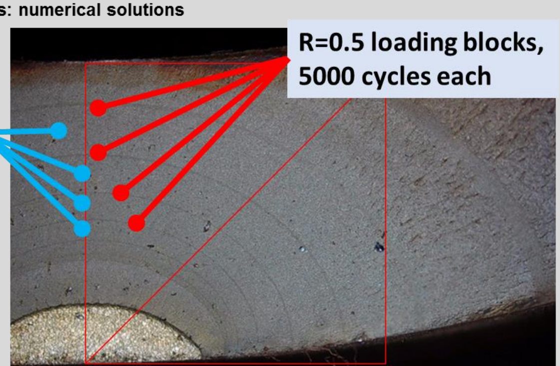
Validation benchmarking: multi-degree of freedom solutions vs. beach mark data collected from PE-1-2 specimen fractography

- Same modeling procedure is applied to a different beach mark data: PE-1-2.
- The same off-nominal {C, n} input used for PE-1-1 produces a solution that matches the beach mark data for PE-1-2 within 2% while the numerical solution using mean FCGR curve is within 5% from the experimental data (using "a" and 45 deg" measurements at 60k cycles).

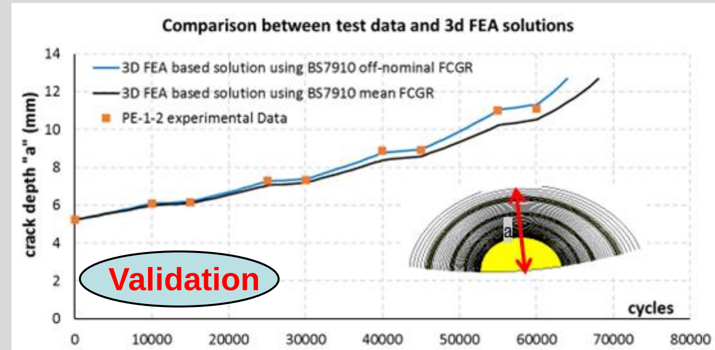
Validation

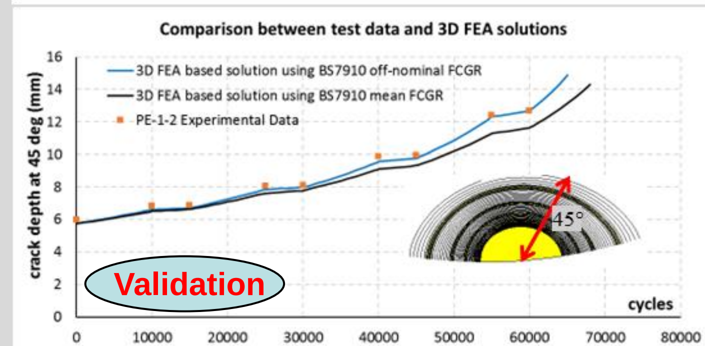


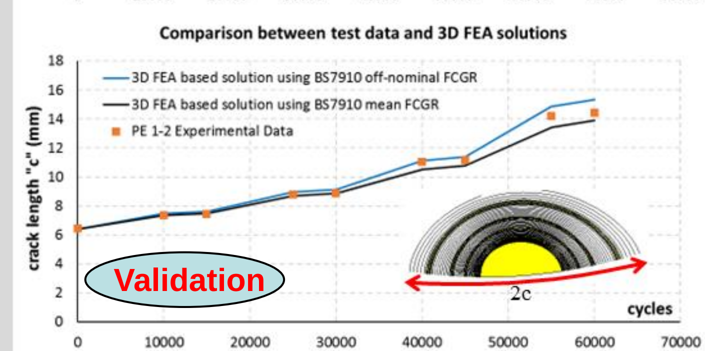
Discrete crack front representations: digitized beach marks
Continuous crack front representations: numerical solutions



PE-1-2: Numerical solutions vs. beach mark data



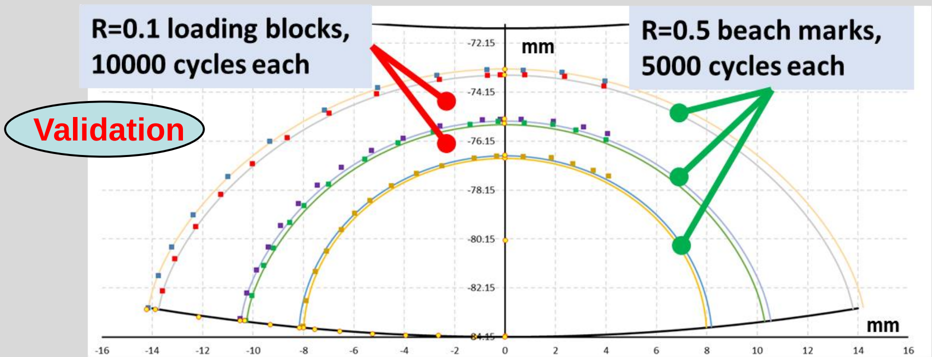




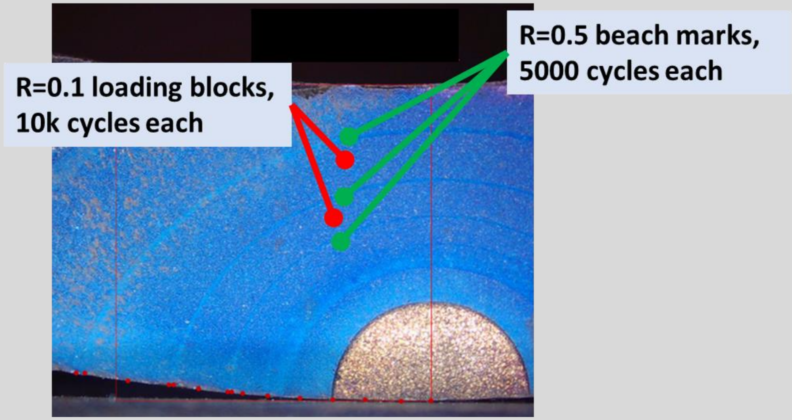
Modeling validation is reached

Validation benchmarking: multi-degree of freedom solutions vs. beach mark data collected from PE-3-1 specimen fractography

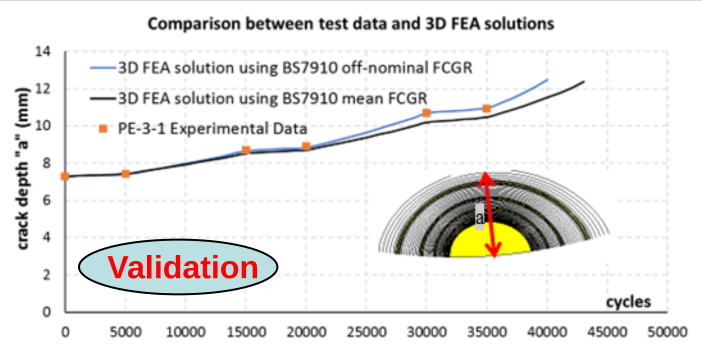
- Same modeling procedure is applied to a different beach mark data: PE-3-1.
- Similar off-nominal {C} input used for PE-1-1and PE-1-2 produces a solution that matches the beach mark data recorded on PE-1-3 coupon within 1% while the numerical solution using mean FCGR curve is within 10% from the experimental data (using “a” and 45 deg” measurements at 35k cycles).

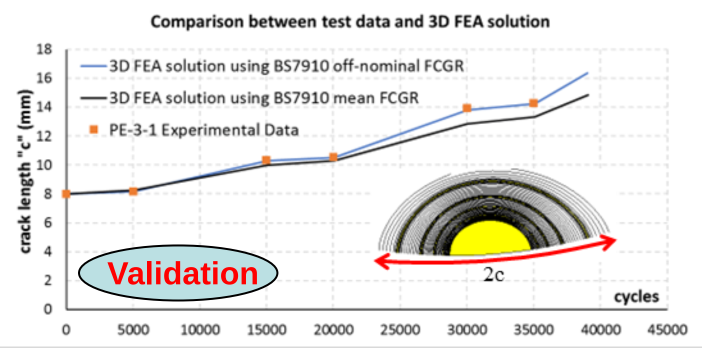


Discrete crack front representations: digitized beach marks
Continuous crack front representations: numerical solutions



PE-3-1: Numerical solutions vs. beach mark data

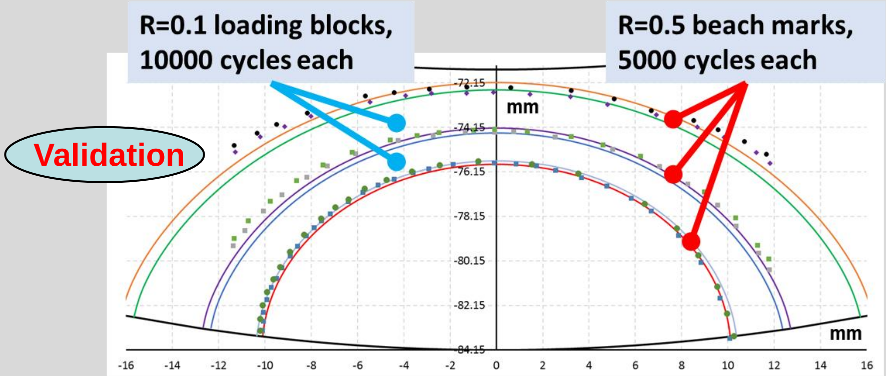




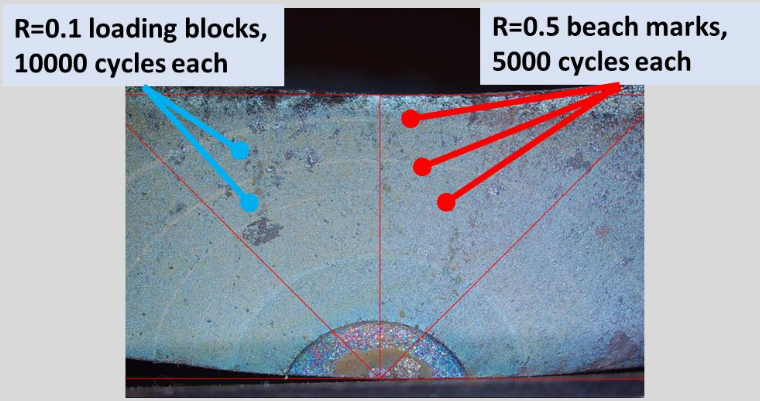
Modeling validation is reached

Validation benchmarking: multi-degree of freedom solutions vs. beach mark data collected from PE-2-2 specimen fractography

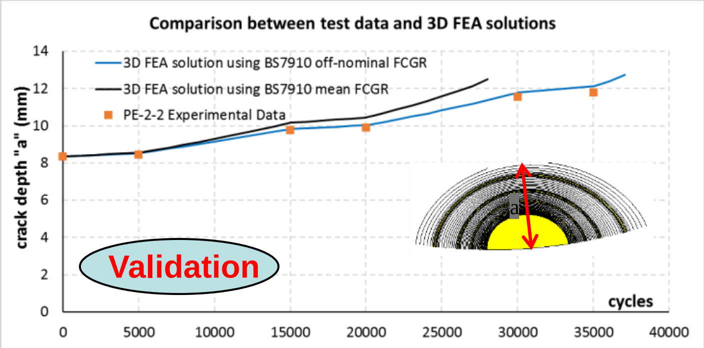
- Fourth validation performed against PE-2-2 measurement. Numerical solution using mean FCGR curve is within 25% from the experimental data (error estimated at 35k cycles).
- Slightly off-mean {C} input (within the BS 7910 bounds) produces a solution that reduces the error to 6%.

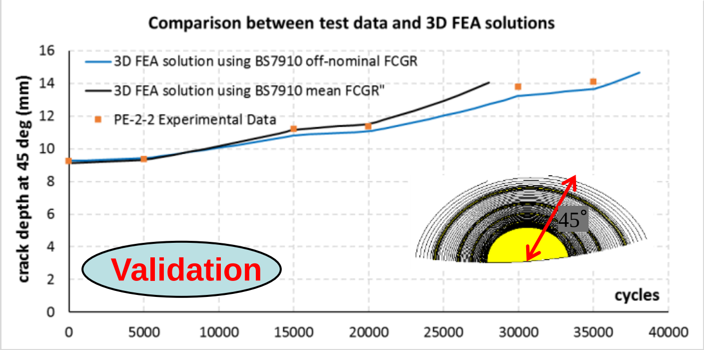


Discrete crack front representations: digitized beach marks
Continuous crack front representations: numerical solutions



PE-2-2: Numerical solutions vs. beach mark data



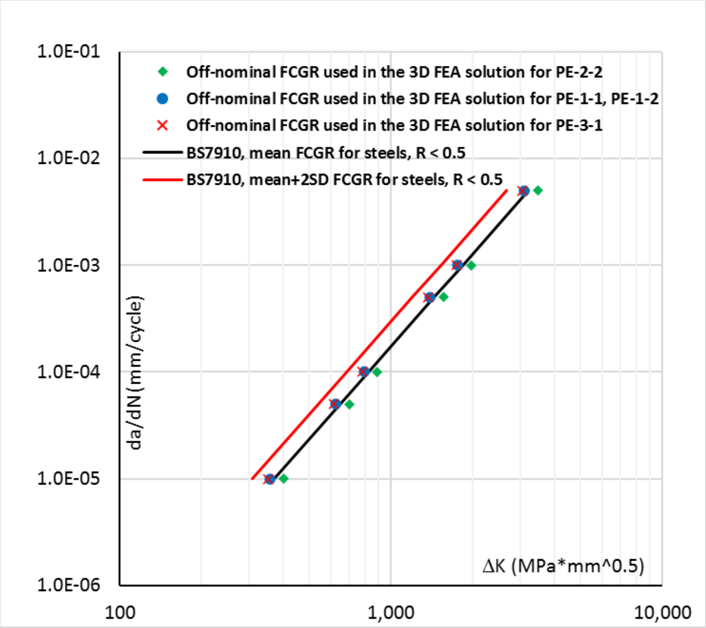


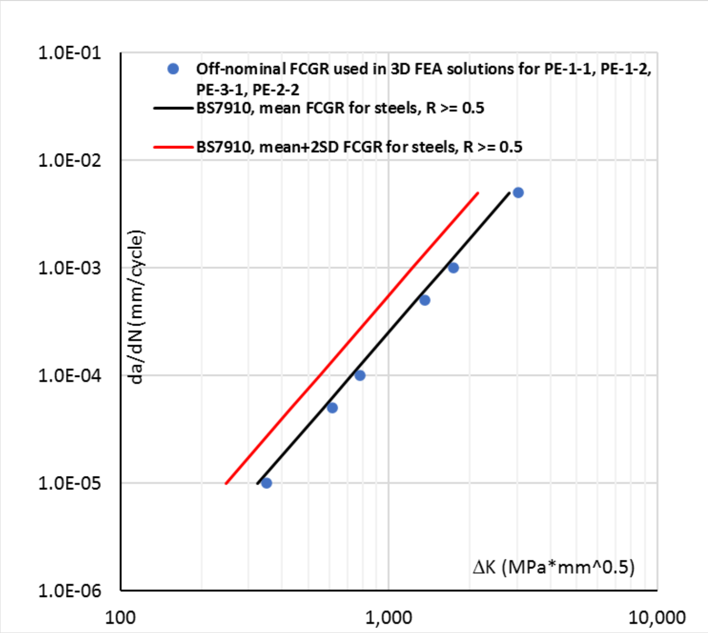
Modeling validation is reached

Off-nominal {C, n} used in validation benchmarking

- The {C} values used to match the experimental data recorded on 4 piping coupons with great accuracy, are slightly off-mean curve provided by BS 7910 and well within the expected intrinsic fatigue crack growth scatter associated with the material
- The {n} exponent provided in the BS 7910 was maintained in all numerical solutions

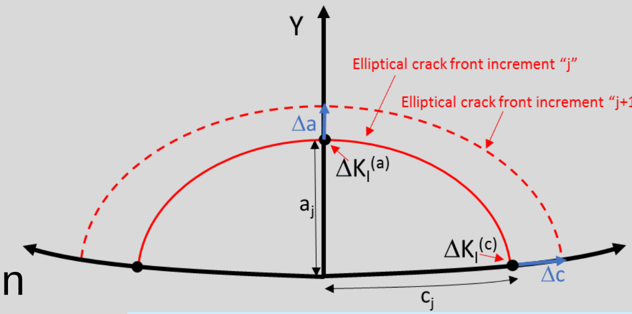
	R<0.5 off-nominal	R ≥ 0.5 off-nominal
PE-1-1	$1.12*(C)_{mean}$	$0.8*(C)_{mean}$
PE-1-2	$1.12*(C)_{mean}$	$0.8*(C)_{mean}$
PE-3-1	$1.17*(C)_{mean}$	$0.8*(C)_{mean}$
PE-2-2	$0.8*(C)_{mean}$	$0.8*(C)_{mean}$



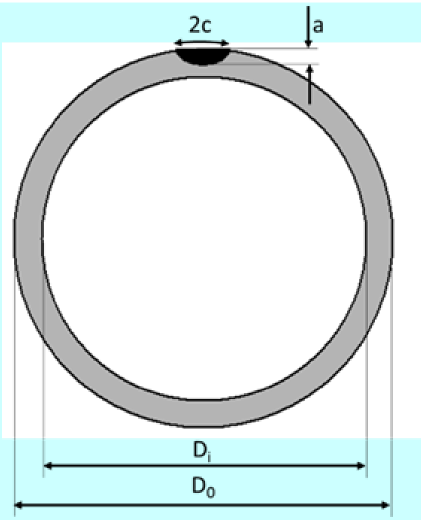


Two-degree of freedom solutions: three formulations

- The advantage of using a two-degree of freedom fatigue crack growth modeling is the efficient runtime.
- Only two locations are tracked (elliptical crack front is assumed) by the iterative solver and the model must be dedicated to the specific geometry and loading configuration



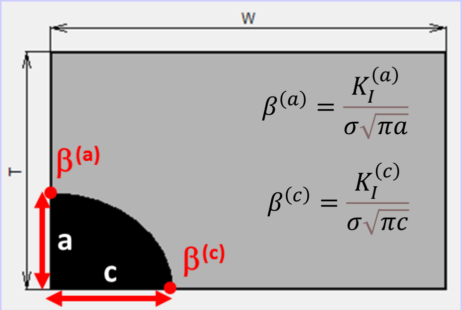
Option 1: API 579 AFGROW model

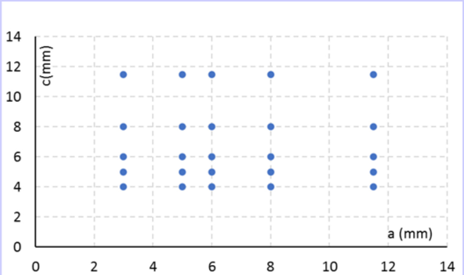


$$K_I = \left[G_0(S_0+p_c)+G_1S_1\left(\frac{y}{t}\right)+G_2S_2\left(\frac{y}{t}\right)^2+G_3S_3\left(\frac{y}{t}\right)^3+G_4S_4\left(\frac{y}{t}\right)^4\right]\sqrt{\frac{\pi a}{Q}}$$

- **Built-in model for external surface crack in a pipe under pure bending available in AFGROW**

Option 2: Beta table input in AFGROW

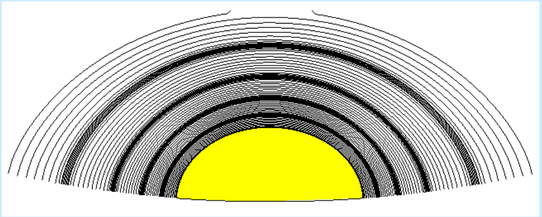




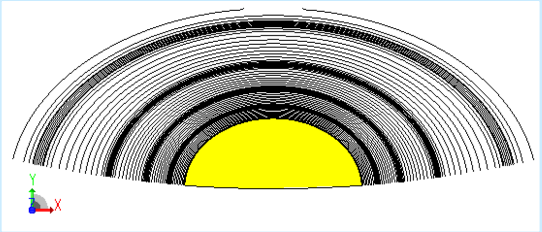
- **User based model definition available in AFGROW (β table)**
- **A set of 3D FEA based solutions (K_{Ia}, K_{Ic}) for predefined crack aspect ratios and sizes can be used to create the model**

Option 3: 3D FEA with constrained crack front shape

No crack front shape constraint



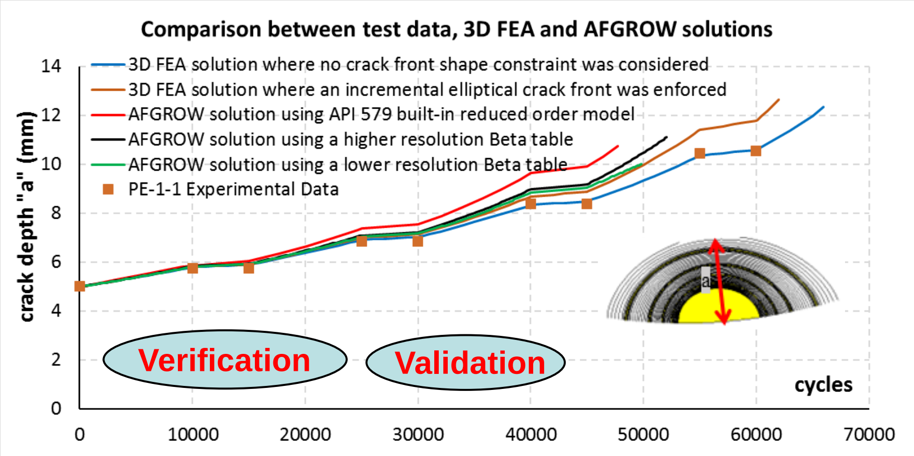
Elliptical crack front shape

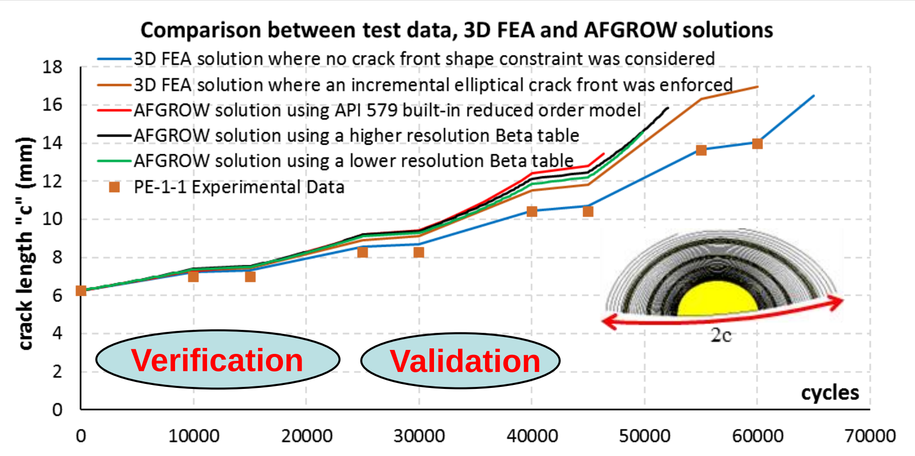


- **The multi-degree of freedom modeling procedure can be used to perform a solution where only the two locations (along depth "a" and along outer cylindrical surface "c") are used to define an elliptical crack front increment**

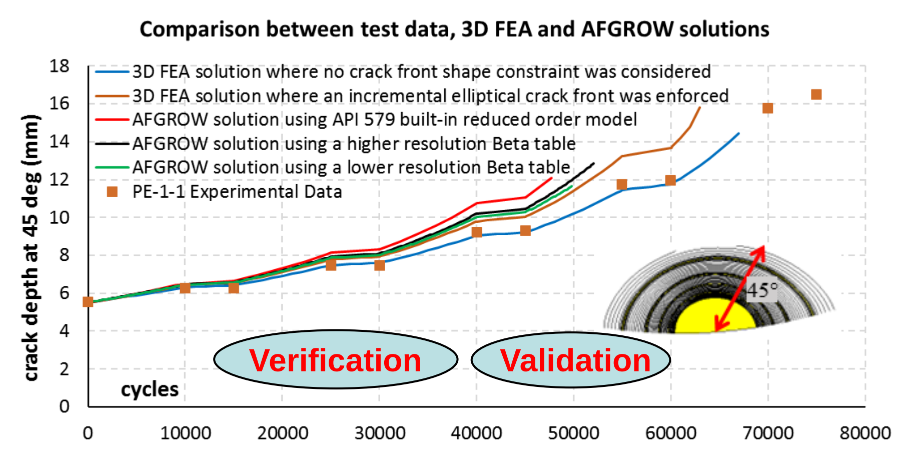
V&V benchmarking: two- and multi-degree of freedom solutions vs. beach mark data collected from PE-1-1 specimen fractography

PE-1-1: Numerical solutions vs. beach mark data





- The built-in AFGROW model provides a conservative solution
- The user defined model (β table) based on 3D FEA predefined crack sizes provides a solution between the built-in model solution and multi-degree of freedom as expected
- The 3D FEA two-degree of freedom solution matches the AFGROW user-based modeling solution within 3% which serves as a verification benchmark



AFGROW's user-based model definition (β table input) is a modeling technique that is geometry and loading agnostic and provides a trade-off between accuracy and runtime.

Solution runtime

- 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.

Conclusions

- Modeling validation was achieved by using fractography data from four different fatigue crack growth mechanical testing procedures as a reference. Recommended BS 7910 FCGR data (mean and within the scatter bounds) for API X65 was used in the numerical procedure to perform two- and multi-degree of freedom incremental crack growth solutions and benchmark against the beach marks from fractography.

- Numerical solutions are sensitive to the FCGR intrinsic scatter. Validation benchmarking needs to take that into consideration.

- Two-degree of freedom solutions were also performed for verification benchmarking and a comparison with multi-degree of freedom solutions. The two-degree of freedom solutions were conservative when compared to the multi-degree of freedom solutions.

Questions?