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Building a New EPRI J Handbook with Advanced Algorithms and Parallel Computing

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Original EPRI Handbook Concept: 1981-89

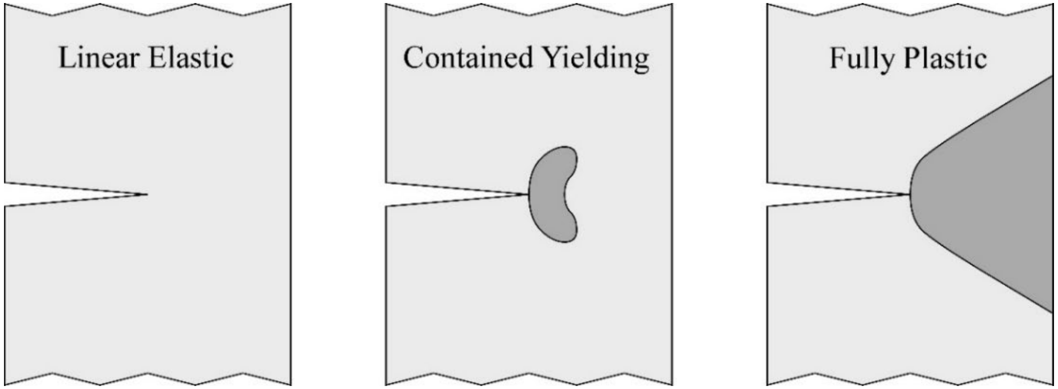
- The vision was for a series of handbooks of elastic-plastic J solutions as a companion to existing stress intensity factor (K_I) solutions.
- The elastic contribution to J, inferred from the corresponding elastic K_I solution, was added to the plastic contribution, inferred from finite element analysis. The latter was fit to a parametric equation.
- This vision was not practical at the time, however, due to limitations in computing capabilities.
  - The original 1981 handbook volume was restricted to simple 2D configurations.
  - A 3-volume set published in the late 1980s contained numerous errors and “solutions” with no documented technical basis.

New EPRI EPFM Handbook

- The original EPRI vision has now been realized in a large project that entails nearly 20,000 3D elastic-plastic finite element solutions to date.
- A new parametric equation was developed that overcomes limitations of the original formulation.
- Geometries in the First Edition:
  - Flat plates.
  - Cylindrical shells.
  - Elbow-to-straight pipe joints.
- Solutions:
  - J-integral
  - Load line displacement (laboratory specimens in the 2nd Edition).
  - Crack mouth opening displacement (CMOD).
  - Crack opening area.

Development of a Parametric Relationship for J

3 Zones of Deformation



- Linear elastic: $J_{el} = \Omega_1 P^2$
- Fully plastic: $J_{pl}{}^{FY} = \Omega_2 P^{n+1}$
  - Assuming a Ramberg-Osgood stress-strain curve: $\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n$
- Contained yielding: $J_{pl}{}^{CY} = \Omega_3 P^k$
  - The original EPRI Handbook used an Irwin plastic zone correction for contained yielding.

Parametric Equation for J

$$J = J_{el}\left[1 + \underbrace{\left(\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{n-1}}_{\text{Fully Plastic}} + \underbrace{\frac{\beta_1\left(\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{m_1}}{1+\left(\gamma_1\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{n-1}}}_{\text{Contained Yielding}}\right]$$

$$\sigma_{ref} = H_1\sigma\left(\frac{0.002E}{\sigma_{YS}}\right)^{\frac{1}{n-1}}$$

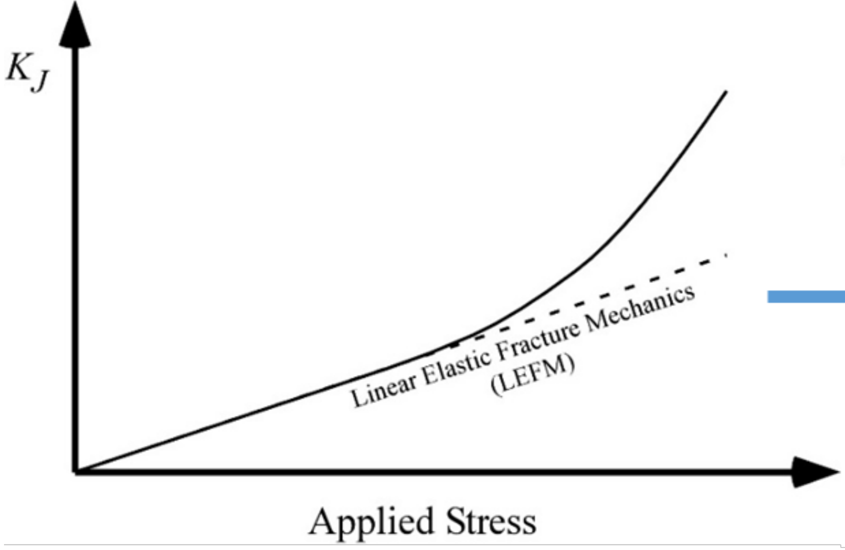
- J_{el} is the elastic contribution to J.
- σ_{ref} is the reference stress and σ is a characteristic nominal stress.
- H_1, β_1, m_1, and γ_1 are fitting constants that are tabulated in the Handbook.

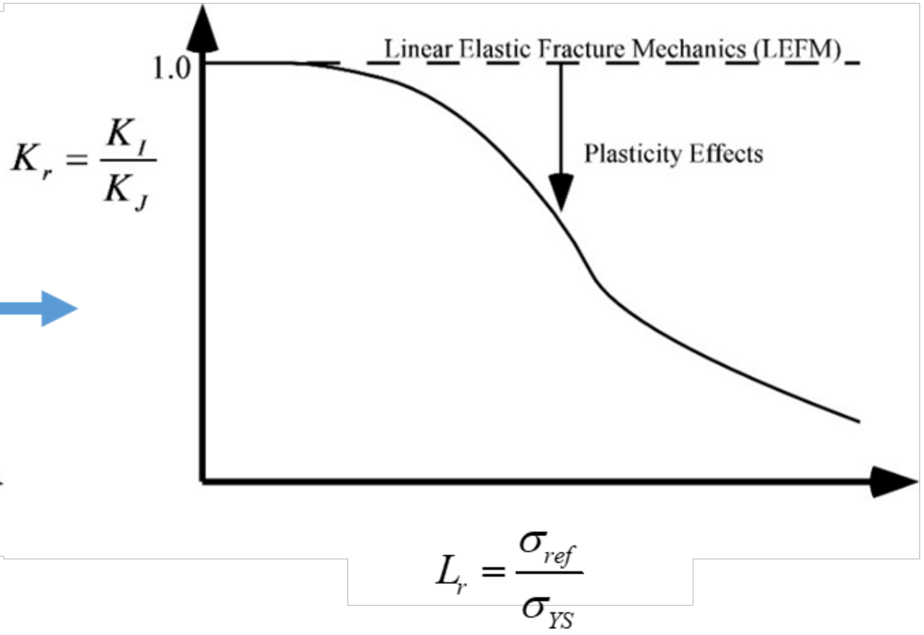
Expressing J as a Dimensionless Failure Assessment Diagram (FAD)

$$K_r = \frac{K_I}{K_J} = \sqrt{\frac{J_{el}}{J}}$$

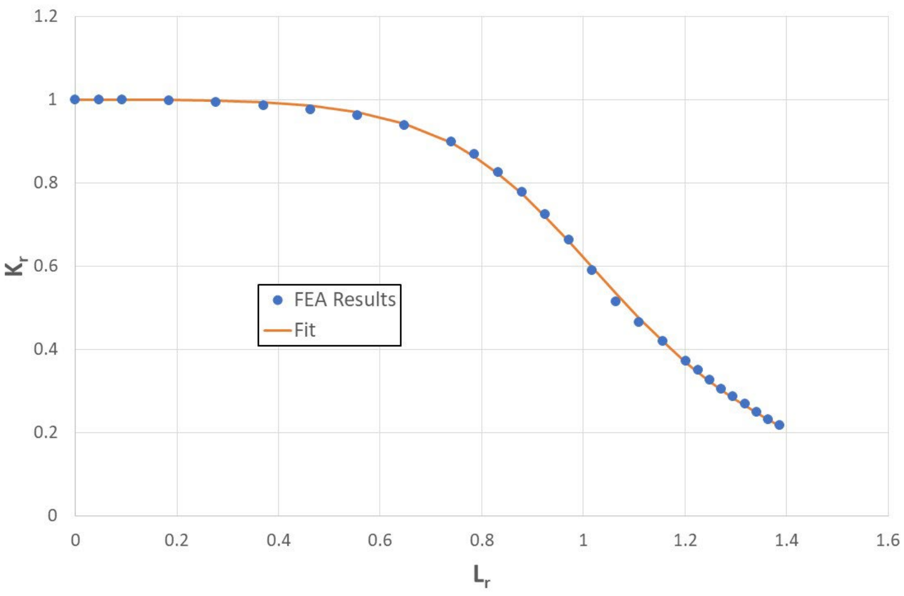
$$L_r = \frac{\sigma_{ref}}{\sigma_{YS}}$$

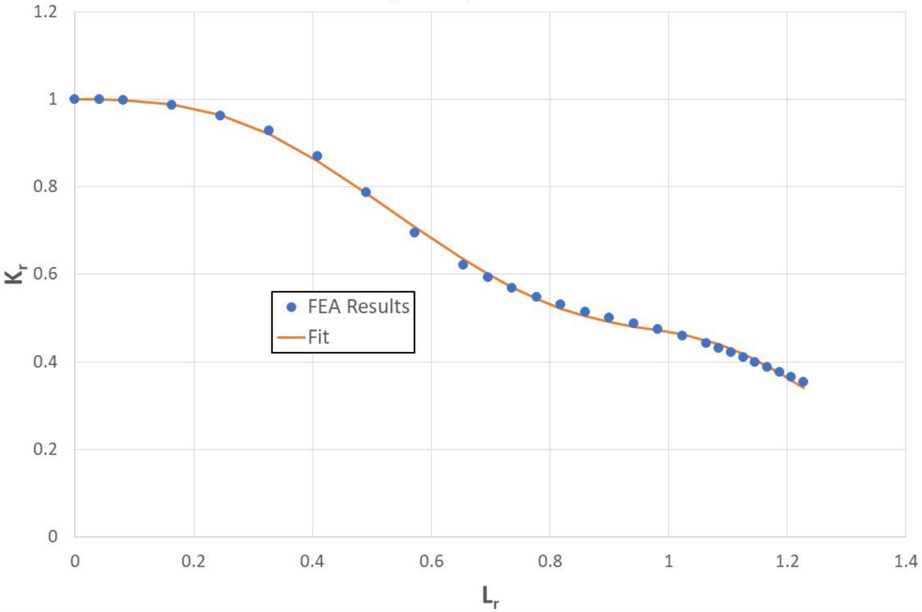
$$K_r = \left[1 + L_r^{\,n-1} + \frac{\beta_1 L_r^{\,m_1}}{1+\left(\gamma_1 L_r\right)^{n-1}}\right]^{-1/2}$$



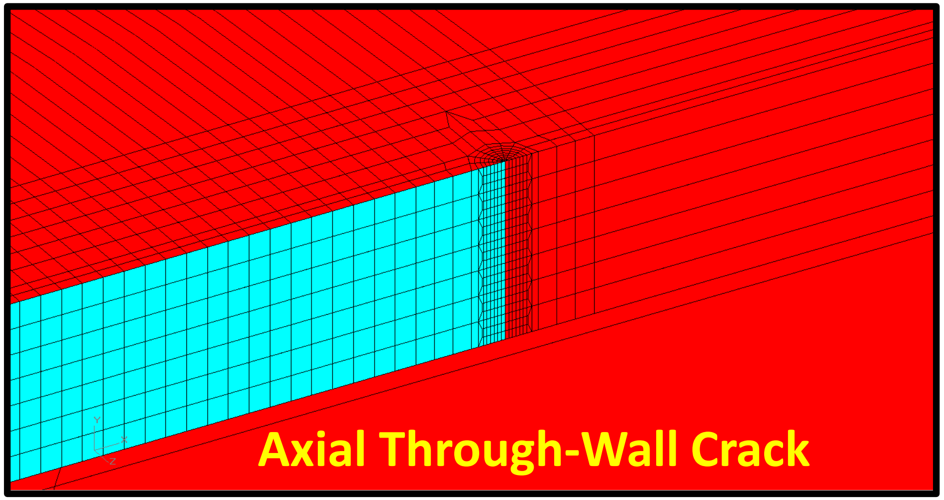


Fitting Examples

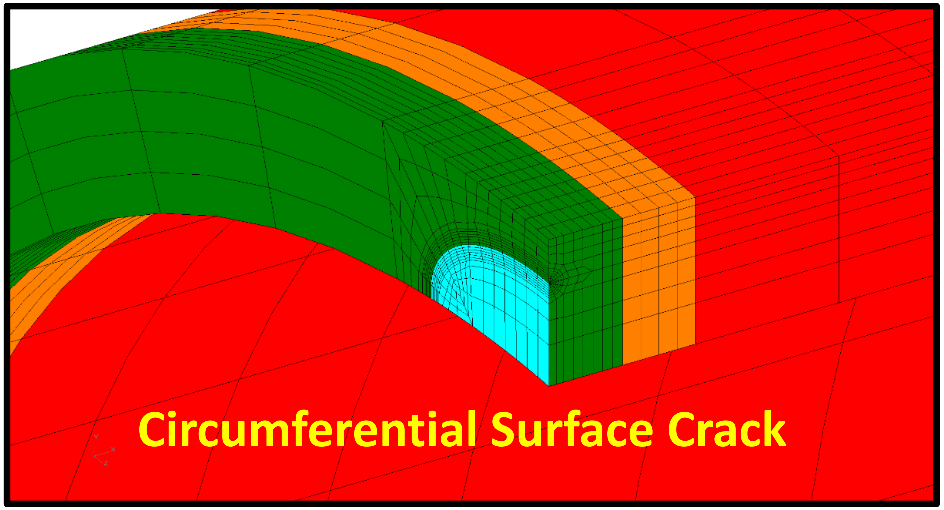

Infinitely Long Axial Surface Crack, Ri/t = 20
a/t = 0.2, n = 10


Infinitely Long Axial Surface Crack, Ri/t = 20
a/t = 0.6, n = 10

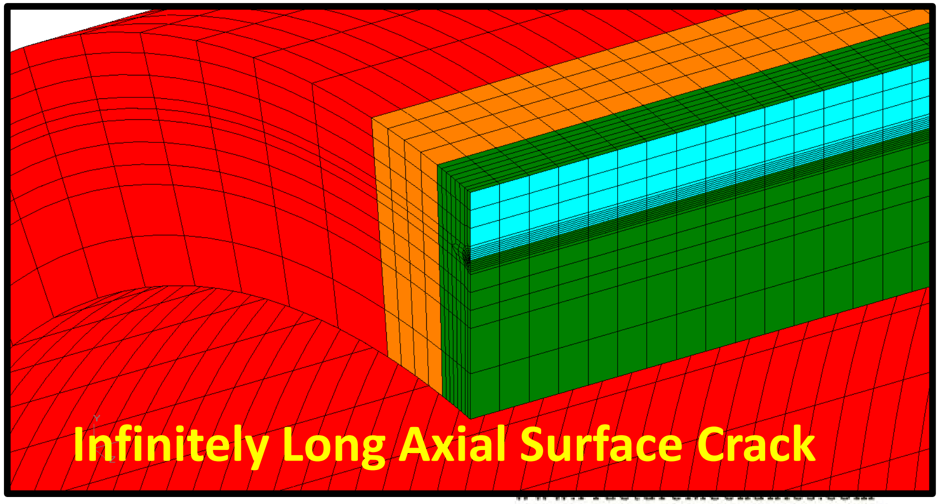
Typical Meshes of Cracks in a Cylindrical Shell



Axial Through-Wall Crack



Circumferential Surface Crack



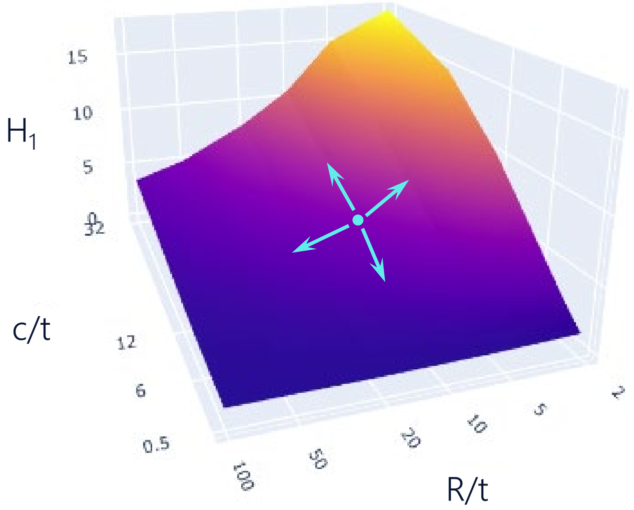
Infinitely Long Axial Surface Crack

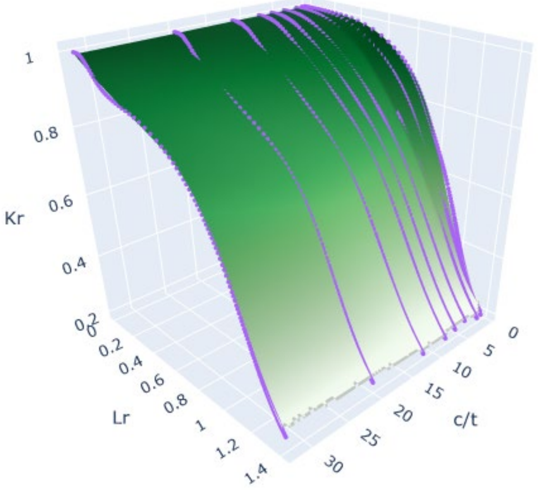
FEA Parametric Study

- Mesh generation with FEACrack software.
- WARP3D nonlinear finite element software.
  - Modified to incorporate adaptive load stepping.
- Various Bash/Python scripts to facilitate automated workflow.
  - Editing and duplicating input files with n = 3, 5, 7, 10, 15.
  - Batch processing and queuing.
  - Post-processing, QA checks.
- Multiple simultaneous WARP3D runs at the Ohio Supercomputing Center

Fitting Solutions to Parametric Equations

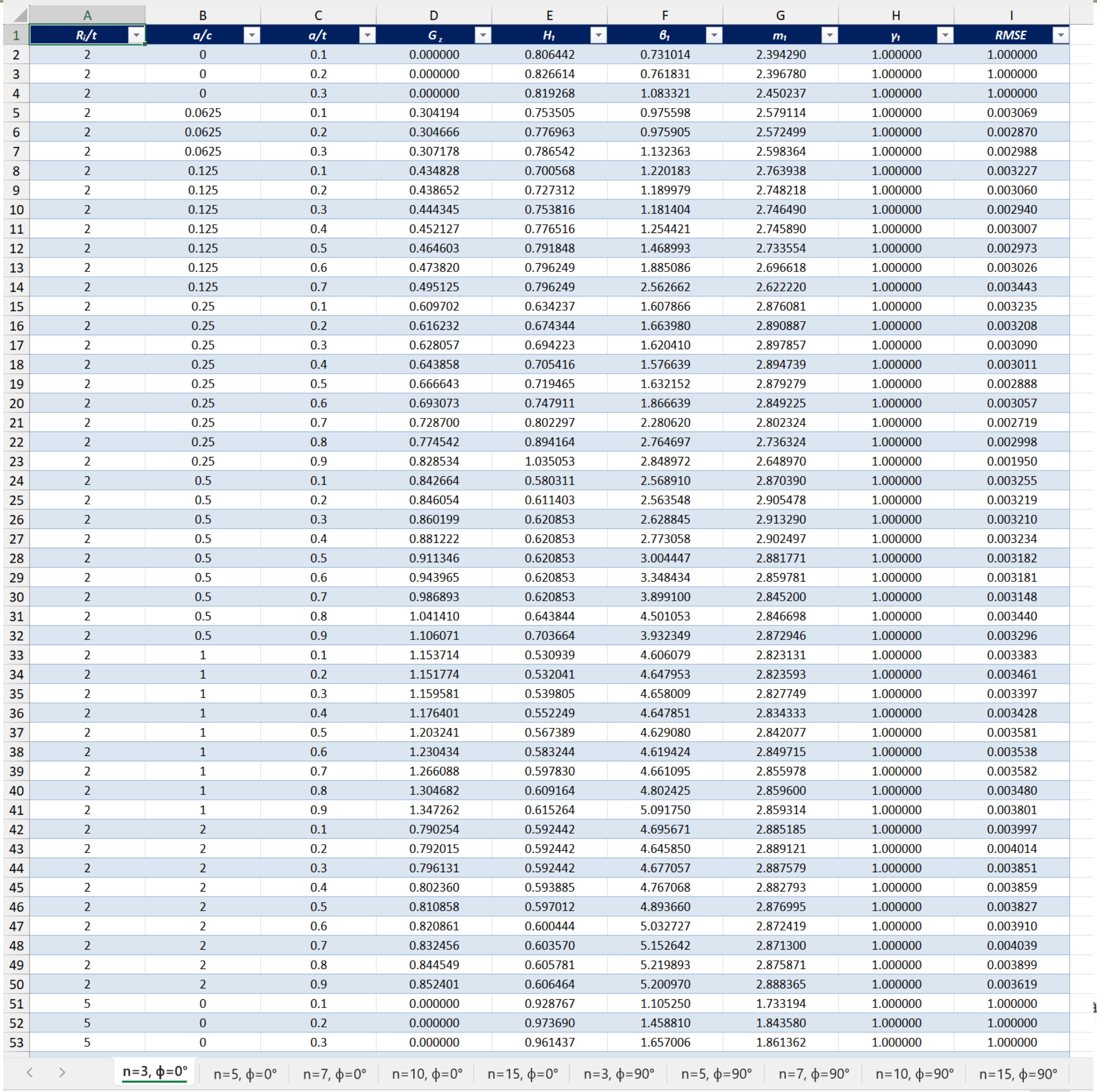
- 4 fitting parameters for J solutions: H_1, β_1, m_1, γ_1.
- These parameters must be fit over a multidimensional space (i.e., component dimensions, crack dimensions, hardening exponent) in a way that enables interpolation in the coefficient tables.
- A radial basis function (RBF) approach is used for optimizing the multidimensional fit of the 4 parameters.





Typical Handbook Table

Excel Files Embedded in the Handbook PDF



	A	B	C	D	E	F	G	H	I
1	R_i/t	a/c	a/t	G_z	H_1	β_1	m_1	γ_1	RMSE
2	2	0	0.1	0.000000	0.806442	0.731014	2.394290	1.000000	1.000000
3	2	0	0.2	0.000000	0.826614	0.761831	2.396780	1.000000	1.000000
4	2	0	0.3	0.000000	0.819268	1.083321	2.450237	1.000000	1.000000
5	2	0.0625	0.1	0.304194	0.753505	0.975598	2.579114	1.000000	0.003069
6	2	0.0625	0.2	0.304666	0.776963	0.975905	2.572499	1.000000	0.002870
7	2	0.0625	0.3	0.307178	0.786542	1.132363	2.598364	1.000000	0.002988
8	2	0.125	0.1	0.434828	0.700568	1.220183	2.763938	1.000000	0.003227
9	2	0.125	0.2	0.438652	0.727312	1.189979	2.748218	1.000000	0.003060
10	2	0.125	0.3	0.444345	0.753816	1.181404	2.746490	1.000000	0.002940
11	2	0.125	0.4	0.452127	0.776516	1.254421	2.745890	1.000000	0.003007
12	2	0.125	0.5	0.464603	0.791848	1.468993	2.733554	1.000000	0.002973
13	2	0.125	0.6	0.473820	0.796249	1.885086	2.696618	1.000000	0.003026
14	2	0.125	0.7	0.495125	0.796249	2.562662	2.622220	1.000000	0.003443
15	2	0.25	0.1	0.609702	0.634237	1.607866	2.876081	1.000000	0.003235
16	2	0.25	0.2	0.616232	0.674344	1.663980	2.890887	1.000000	0.003208
17	2	0.25	0.3	0.628057	0.694223	1.620410	2.897857	1.000000	0.003090
18	2	0.25	0.4	0.643858	0.705416	1.576639	2.894739	1.000000	0.003011
19	2	0.25	0.5	0.666643	0.719465	1.632152	2.879279	1.000000	0.002888
20	2	0.25	0.6	0.693073	0.747911	1.866639	2.849225	1.000000	0.003057
21	2	0.25	0.7	0.728700	0.802297	2.280620	2.802324	1.000000	0.002719
22	2	0.25	0.8	0.774542	0.894164	2.764697	2.736324	1.000000	0.002998
23	2	0.25	0.9	0.828534	1.035053	2.848972	2.648970	1.000000	0.001950
24	2	0.5	0.1	0.842664	0.580311	2.568910	2.870390	1.000000	0.003255
25	2	0.5	0.2	0.846054	0.611403	2.563548	2.905478	1.000000	0.003219
26	2	0.5	0.3	0.860199	0.620853	2.628845	2.913290	1.000000	0.003210
27	2	0.5	0.4	0.881222	0.620853	2.773058	2.902497	1.000000	0.003234
28	2	0.5	0.5	0.911346	0.620853	3.004447	2.881771	1.000000	0.003182
29	2	0.5	0.6	0.943965	0.620853	3.348434	2.859781	1.000000	0.003181
30	2	0.5	0.7	0.986893	0.620853	3.899100	2.845200	1.000000	0.003148
31	2	0.5	0.8	1.041410	0.643844	4.501053	2.846698	1.000000	0.003440
32	2	0.5	0.9	1.106071	0.703664	3.932349	2.872946	1.000000	0.003296
33	2	1	0.1	1.153714	0.530939	4.606079	2.823131	1.000000	0.003383
34	2	1	0.2	1.151774	0.532041	4.647953	2.823593	1.000000	0.003461
35	2	1	0.3	1.159581	0.539805	4.658009	2.827749	1.000000	0.003397
36	2	1	0.4	1.176401	0.552249	4.647851	2.834333	1.000000	0.003428
37	2	1	0.5	1.203241	0.567389	4.629080	2.842077	1.000000	0.003581
38	2	1	0.6	1.230434	0.583244	4.619424	2.849715	1.000000	0.003538
39	2	1	0.7	1.266088	0.597830	4.661095	2.855978	1.000000	0.003582
40	2	1	0.8	1.304682	0.609164	4.802425	2.859600	1.000000	0.003480
41	2	1	0.9	1.347262	0.615264	5.091750	2.859314	1.000000	0.003801
42	2	2	0.1	0.790254	0.592442	4.695671	2.885185	1.000000	0.003997
43	2	2	0.2	0.792015	0.592442	4.645850	2.889121	1.000000	0.004014
44	2	2	0.3	0.796131	0.592442	4.677057	2.887579	1.000000	0.003851
45	2	2	0.4	0.802360	0.593885	4.767068	2.882793	1.000000	0.003859
46	2	2	0.5	0.810858	0.597012	4.893660	2.876995	1.000000	0.003827
47	2	2	0.6	0.820861	0.600444	5.032727	2.872419	1.000000	0.003910
48	2	2	0.7	0.832456	0.603570	5.152642	2.871300	1.000000	0.004039
49	2	2	0.8	0.844549	0.605781	5.219893	2.875871	1.000000	0.003899
50	2	2	0.9	0.852401	0.606464	5.200970	2.888365	1.000000	0.003619
51	5	0	0.1	0.000000	0.928767	1.105250	1.733194	1.000000	1.000000
52	5	0	0.2	0.000000	0.973690	1.458810	1.843580	1.000000	1.000000
53	5	0	0.3	0.000000	0.961437	1.657006	1.861362	1.000000	1.000000

Status

- The first edition of the Handbook has been completed and is in final review.
- A prototype app that implements the solutions in crack stability calculations has been developed with Excel-VBA.
- A second edition with additional cases is planned for 2025.

Related Effort

- The API 579 Fitness-for-Service Standard is being updated with a simplified version of the EPRI J estimation approach.
    - EPRI 4-term equation:

$$J = J_{el}\left[1+\left(\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{n-1} + \frac{\beta_1\left(\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{m_1}}{1+\left(\gamma_1\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{n-1}}\right] \qquad \sigma_{ref} = H_1\sigma\left(\frac{0.002E}{\sigma_{YS}}\right)^{\frac{1}{n-1}}$$

- API 579 2-term equation:

$$J = J_{el}\left[1+\left(\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{n-1} + \frac{\beta\left(\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{2}}{1+\left(\frac{\sigma_{ref}}{\sigma_{YS}}\right)^{n-1}}\right] \qquad \sigma_{ref} = H\sigma\left(\frac{0.002E}{\sigma_{YS}}\right)^{\frac{1}{n-1}}$$


Questions