Fatigue and brittle fracture assessment of Götaälvbron

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2017-05-29

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BBT Project: Advanced assessment of welded bridges for fatigue and brittle fracture

Project partners

TRAFIKVERKET

Göteborgs Stad

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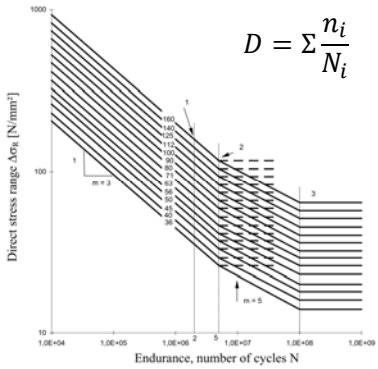
Fatigue dilemma for existing bridges

Using conventional S-N curve method



$$D = \Sigma \frac{n_i}{N_i}$$

Unanswered questions:

- Is the bridge safe after $D \geq 1$?
- What if a crack (or defect) is detected in the bridge?
- The method gives 0 or 1 answer

Case a: Despite predictions ($D \geq 1$) fatigue cracking is not observed in the structure

VS.

Case b: fatigue cracking occurs in unexpected locations

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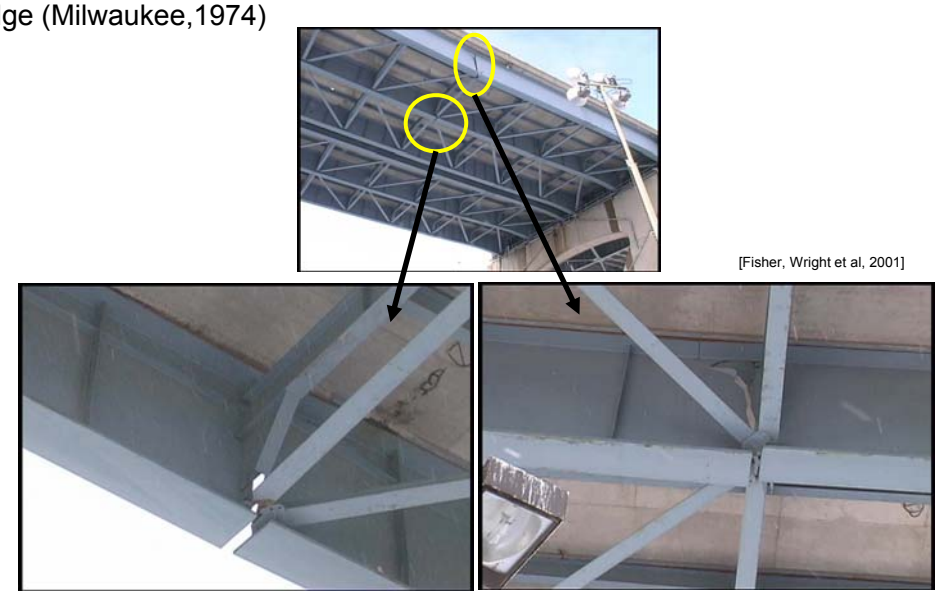
Brittle fracture due to fatigue cracking

Hoan bridge (Milwaukee,1974)



[Fisher, Wright et al, 2001]

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Problem statement

- Safety issues regarding **aging** of large stock of existing steel bridges
- Conventional structural assessment shows that the life span of the bridge is consumed. **Inspections show no sign of damage**
- On the other hand, **fatigue and fracture damage is reported** for unforeseen reasons (low service load stresses) (as in Götaälvbron)

Shortcoming of current assessment methods

- Non-realistic assumptions for loads (such as assessment based on normative loads)
- Simplified models for estimation of load effects (overestimate primary load effects, but neglect or overlook some important load effects)
- Using characteristic values for material strength data (also from norm)

Suggested improvements

- Determine methodology (and required input data) for more accurate safety assessment against fatigue and brittle fracture
- Advanced assessment methods require more (and more accurate) information
- This in turn also means higher cost, but more realistic estimation of remaining service life

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Issue previously addressed by a number of projects:

- Sustainable bridges (2007) – Technical report D3.4
- BriFaG (2009)
- Kühn et al (2008), Assessment of Existing Steel Structures-Recommendations for Estimation of Remaining Fatigue Life

- Current project aims at deliver a synthesis of the research with a multi-step procedure to practicing engineers

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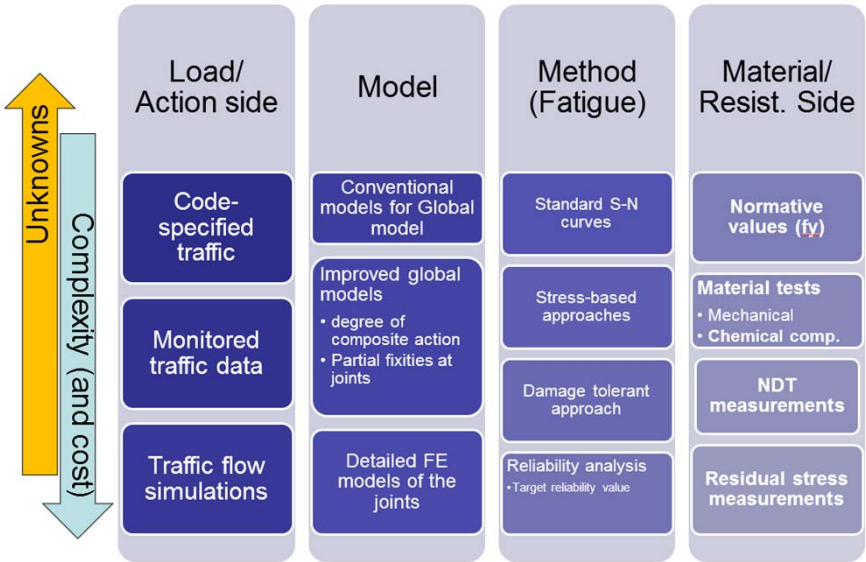
Condition assessment

Multi-level approach



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Condition assessment

Multi-level approach

Phase I – Preliminary assessment

- *Using simple analysis. The bridge is considered as if it is being designed as new.*

Phase II – Advanced assessment

- *Refined analyses on the critical members.*
- No new data collection

Phase III – Expert investigation

- Advanced analysis techniques
- Extensive data collection (Resistance side+Action side

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Phase I – Preliminary assessment

- Data collection by review of existing documentation (original design +maintenance), Site visit
- Resistance side:
  - Basic material data (geometry, steel grade, available test data,…)
- Action side:
  - Normative loads
- Calculation models:
  - Hand calculations, simple global FE models
- Fatigue assessment:
  - Equivalent damage factor (λ-factors)
- Brittle fracture:
  - EN 1993 part 1-10 permissible thickness table

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Phase II – Advanced assessment

- (Almost) no new data needs to be collected; just refinement of analyses
- Resistance side:
  - Basic material data (geometry, steel grade, available test data,…)
- Action side:
  - Normative loads /Traffic loading history (if available)
- Calculation models:
  - Refined global FE models (beam and shell elements, ideal support conditions)
- Fatigue assessment:
  - Damage accumulation
  - Structural hot-spot stress method, Effective notch stress method (Al-Emrani & Aygül 2014)
- Brittle fracture:
  - EN 1993 part 1-10, using Charpy test (or K_{Ic}) data , $T_{Ed} < T_{Rd}$

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Brittle fracture treatment in EN 1993

$K_{Ed} \leq K_{Rd}$ → Transformation → $T_{Ed} \geq T_{Rd}$

$T_{Ed} \geq T_{Rd}$

Action side

$$T_{Ed} = T_{min,d} + \Delta T_r + \Delta T_\sigma + \Delta T_R \left[+ \Delta T_{\dot{\varepsilon}} + \Delta T_{\varepsilon pl} \right]$$

- Lowest air temperature in combination with q_{Ed}
  $T_{min,d}$ =- -25°C
- Radiation loss
  ΔT_r =- -5°C
- Influence of stress, crack imperfection and member shape and dimension

$$\Delta T_\sigma = -52 \cdot \ln \left[\frac{(K_{Ed} - 20)\left(\frac{b_{eff}}{25}\right)^{1/4} - 10}{70} \right] \left[{}^0C \right]$$

- Additive safety element
  ΔT_R =- +7°C (with β = 3.8)

Resistance side

- Influence of material toughness
  $T_{100} = T_{27J} - 18$ [°C]

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Phase III – Expert investigation

- Extensive collection of new data (NDT, material tests, load monitoring)
- Resistance side:
  - Fracture toughness data, crack propagation properties
  - Defect size data (NDT)
- Action side:
  - Load monitoring (load history is not important anymore)
- Calculation models:
  - Refined global and local FE models
  - Linear Elastic Fracture Mechanics (LEFM)
- Fatigue assessment:
  - LEFM (Handbooks, XFEM, BEM,…)
- Brittle fracture:
  - EN 1993 part 1-10, $K_{Ed} < K_{Rd}$

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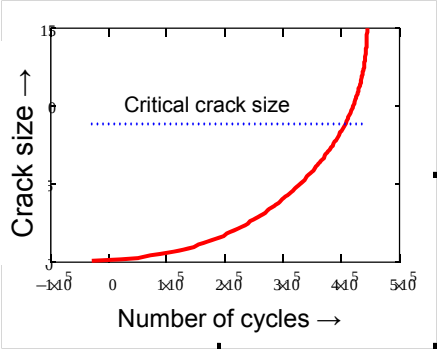
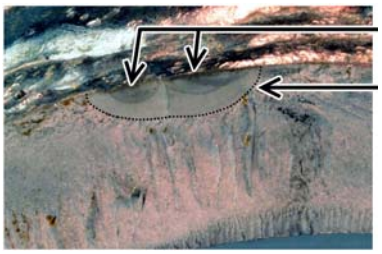
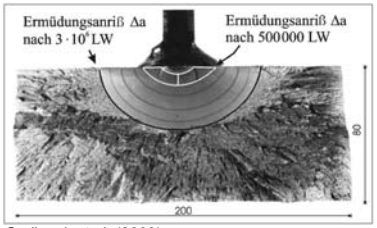
Failures due to cracking

Brittle fracture in contrast to ductile fracture







Sedlacek et al. (2003)

- A large-enough fatigue crack can lead to sudden and brittle fracture
- Source of brittle fracture can also be a defect (e.g. smältdike)

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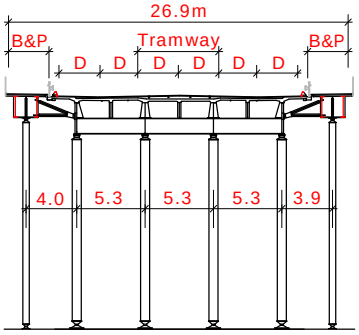
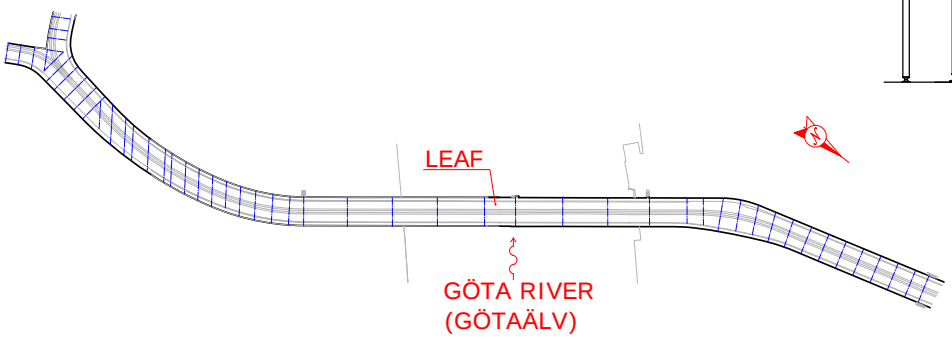
Götaälvbron (built 1939)

Steel bridge with concrete deck



CROSS SECTION



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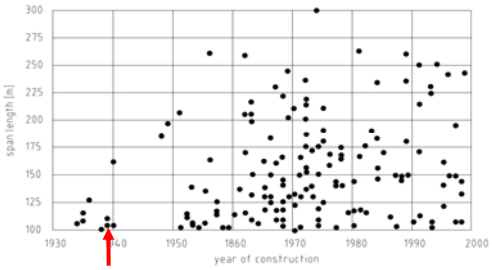
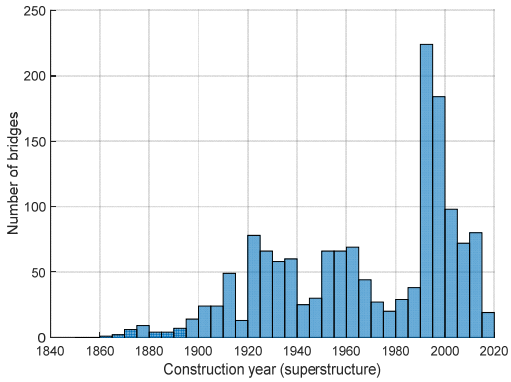
Welded bridges history



Albert bridge (BE) , welded bridge, failed due to brittle fracture



Existing steel road and railway bridges managed by Trafikverket

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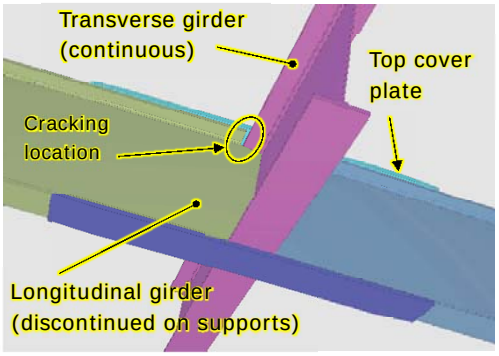
Previously observed cracking



D>1 for some details (since 2004!)

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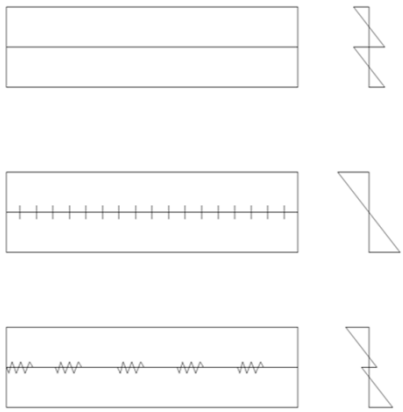
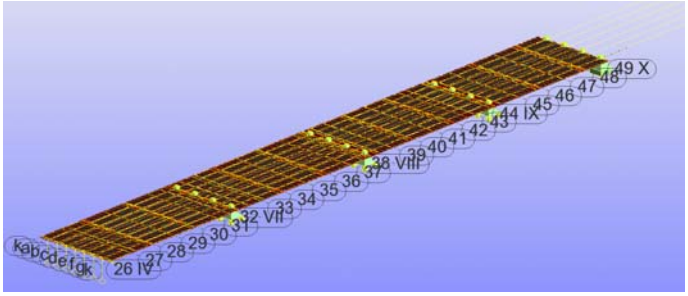
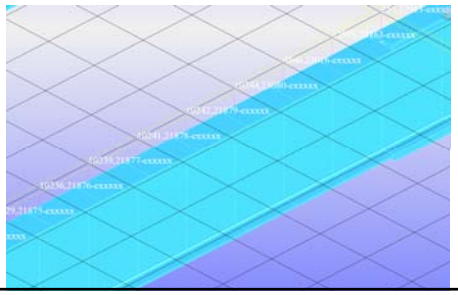
FEM Model calibration







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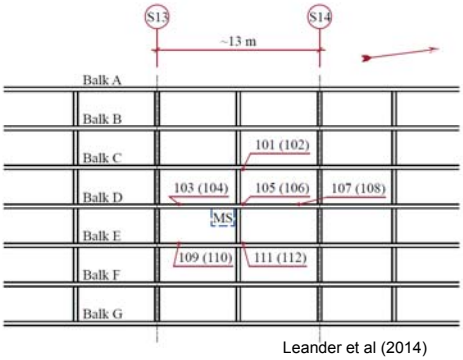
FEM Model calibration



Leander et al (2014)

Givare	Balk	Placering		MÄTNING	FULL	SEMI
101	C	Fält	ÖF	2,0	2,2	1,9
102	C	Fält	UF	16,2	21	21
103	D	Stöd	ÖF	0	-0,6	-0,3
104	D	Stöd	UF	0	-1	-0,7
105	D	Fält	ÖF	1,5	0,6	0,4
106	D	Fält	UF	17,4	18,1	18,6
107	D	Stöd	ÖF	1,6	-0,7	0,8
108	D	Stöd	UF	-1,2	-4,4	-3,2
109	E	Stöd	ÖF	1,5	-0,2	0,1
110	E	Stöd	UF	-0,3	-1,3	-0,2
111	E	Fält	ÖF	2,6	0,8	1
112	E	Fält	UF	12,4	12,9	13
GENOMSNITTLIG SKILLNAD MOT MÄTNING:					1,6 MPa	1,2 MPa

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NDT Crack sizing

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UT/MT/PT inspections

Location	Test	No. Locations	No. tests
Pilar connections	MT	4	8
Longitudinal beam connections (N. Viaduct)	MT	7	18
Stiffener connections (N. Älvdel)	MT	4	6
Beam supports (N. Älvdel)	PT	2	4

Cracks detected only in one location (longitudinal beam connection N3-b' in N. Viaduct)

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Detected crack

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Repair

- The remaning length fillet weld was enough for static strength of the structure
- The cracked fillet weld was removed by careful grinding
- The crack had not grown into the connection plate, therefore no further action deemed necessary.

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Summary of previous tests

Test	Laboratory and date	Governing code	No. of specimnes	Sampling data
Fracture toughness	SP (2003)	BVS 583.12 ASTM 813	9pcs	Viaduct ST-44
Chemical analysis	SP (2003)	BVS 583.12	3pcs	Viaduct
Tensile test				
Chemical ana				n
Tensile test				n
Charpy V (tra temp.)				
Chemical analysis	KTH(1956)		4pcs	Älvbron ST-52 & ST-44
Charpy V (trans. Temp.)	KTH(1956)	SIS 112350	4pcs	Älvbron ST-52 & ST-44

t 6.1 Krav på åtgärd utifrån brottseghet J_c

x x x			1. Byte snarast Åtgärder enligt särskild utredning.
x x x	x x x		2. Byte inom 5 år Åtgärder enligt särskild utredning.
	x x x x x x	x x x	3. Inspektionsintervall enligt BV anvisningar
		x x x	4. Inga särkilda åtgärder
	20	50	Brottseghet J_c kN/m

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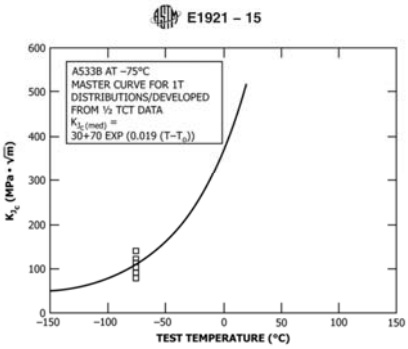
Analysis according to MC approach

For fracture toughness measurement of ferritic steels

- Proposed by Wallin (VTT-1992) and implemented in ASTM E1921 to deal with the large scatter in transition region.
- All toughness transition curves for ferritic steels have similar shape (theoretic justification by weakest link theory)
- As few as 6 samples are needed to construct the curve.

$$K_{Jc(median)} = 30 + 70\exp\left[0.019(T - T_o)\right]$$



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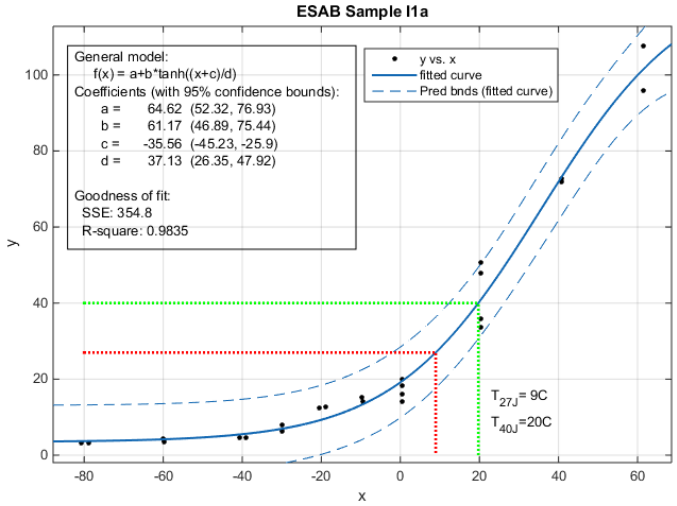
1956 ESAB tests (Charpy test results)



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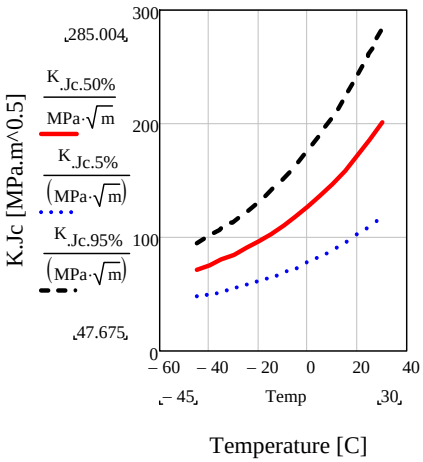
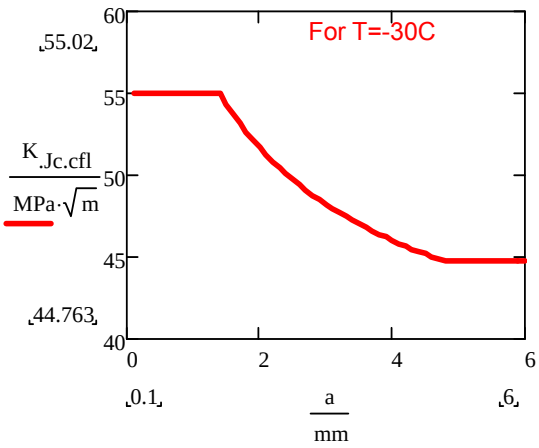
Analysis according to MC approach

According to ASTM E1921 (MC method)



Temperature dependency



Thickness dependency

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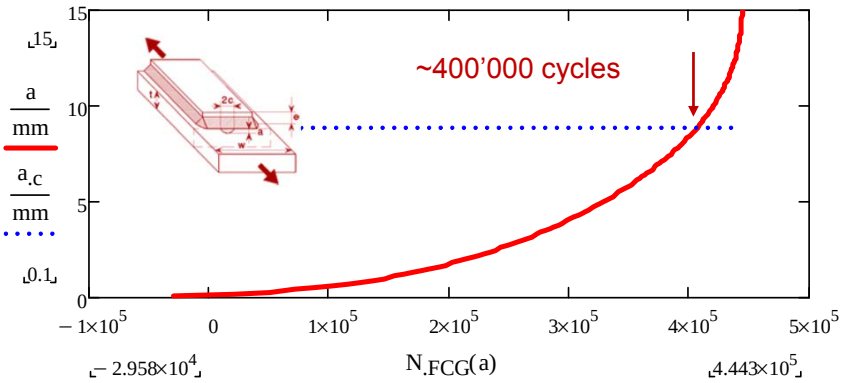
Estimated inspection intervals



- Assumed a detectable crack size of 2c=1.2mm (crack depth: **a=0.15mm**)
- Analysis is based on a constant amplitude cyclic stress range of Δσ=15 Mpa
- Stresses from calibrated 3D-FEM model

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Ongoing work

Monitoring using WSN

- A wireless sensor network is being installed on the bridge
- Monitor Traffic load and environmental loads (construction work)
- Strain gages (traffic actions, settlement effects)
- Accelerometers (piling effects)
- No data yet!

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Conclusion

- While conventional methods are satisfactory for design of new structures, a multi-level condition assessment scheme is the choice for condition assessment of existing bridges.
- The methodology can be developed in accordance to existing Eurocode, it is mature enough to be applied for assessment of existing bridges, with considerable accuracy compared to traditional methods.

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Analysis according to MC approach

- Calculating K0 (scale parameter for Weibul distribution) from maximum likelihood:

$$K_0 := \left[\sum_{i=1}^{N}\left[\frac{\left(K_{Jc.1T_i} - 20MPa\cdot\sqrt{m}\right)^4}{N}\right]\right]^{\frac{1}{4}} + 20MPa\cdot\sqrt{m}$$

$$K_0 = 74.718\cdot MPa\cdot\sqrt{m}$$

$$K_{Jc.med} := 0.9124\cdot\left(K_0 - 20MPa\cdot\sqrt{m}\right) + 20MPa\cdot\sqrt{m} \qquad K_{Jc.med} = 69.925\cdot MPa\cdot\sqrt{m}$$

- Estimated median (50% probability) value:

$$T_0 := T - \frac{1}{0.019}\cdot\log\left(\frac{K_{Jc.med} - 30MPa\cdot\sqrt{m}}{70MPa\cdot\sqrt{m}}\right) \qquad T_0 = -17.165$$

- Reference temperature for which K_{JC} is equal to 100:

$$K_{Jc.50\%_i} := 30\,MPa\cdot\sqrt{m} + 70\,MPa\cdot\sqrt{m}\cdot\exp\left[0.019\cdot\left(Temp_i - T_0\right)\right]$$

- The Master curve is defined as the median (50% probability) toughness for the 1T (25.4mm thick) specimen over the transition

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