

› FRACTURE MECHANICS IN THE PROBABILISTIC MODEL CODE

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REASON FOR RESEARCH

Why are our clients interested?

- › One storm surge barrier is constructed from material with low toughness
- › Old steels are subjected to ageing. Meaning that some bridges are now composed of material with low toughness

What are the reasons to update the fracture mechanics part in the probabilistic model code

- › The assessment procedure in the fracture mechanics society (including BS7910) has changed since drafting the procedure in the model code
- › An assessment with the current procedure in the model code gave a failure probability that does not correspond to actual observations

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FRACTURE MECHANICS FLOW CHART

Start dimensions of a crack: height a_0 , semi length c_0

Consider a crack height extent Δa .

Fatigue crack growth model: Determine # cycles ΔN and semi crack length extend Δc corresponding to Δa due to stress ranges $\Delta \sigma$

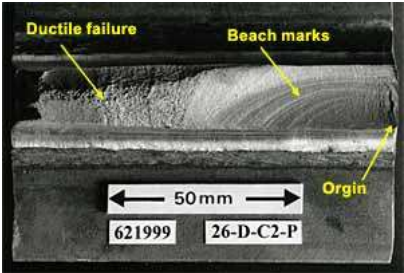
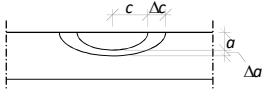
Instable failure model: Determine if remaining ligament fails by interaction of brittle fracture and plasticity due to maximum stress σ_{max} and temperature

failure?

no

yes

Total number of cycles to failure (fatigue life) $N = \Sigma(\Delta N)$.



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STRESS INTENSITY FACTOR (SIF)

› SIF (ΔK) is the basis of the fracture mechanics model. It is a measure for the stress state in the vicinity of the crack front.

› Current probabilistic model code: $\Delta K = C_{glob} C_{scf} C_{sif} \Delta \sigma M_{ellipse(a,c)} M_{weld(a,c)} \sqrt{\pi a}$

Uncertainty	Distr. type	μ	σ
C_{glob}	Lognormal	1	0.1
C_{scf}	Lognormal	1	0.2
C_{sif}	Lognormal	1	0.2 (if based on hand calc.) 0.07 (if based on FEM)

› Result is an extremely large uncertainty factor, which is by far the dominating variable (i.e. large weight factor)

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STRESS INTENSITY FACTOR (SIF)

Uncertainty	Distr. type	μ	σ
C_{glob}	Lognormal	1	0.1
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- › If C_{glob} accounts for engineering model only, and not for uncertainty in load, a comparison between 30 calculated and measured influence lines of 5 bridges (NOTE elastic stress, which is relevant for fract.mech.) yields a normal distribution with $\mu = 0.85$ and $\sigma = 0.12$.
- › C_{SCF} seems too large in case of moderate SCF values. The engineer will always calculate a SCF > 1
- › C_{SIF} based on hand calc. is actually based on FEM by others. BS 7910 and text books indicate an error of less than 1 % for these calculations. This also counts for use of hot-spot stresses in combination with SIF solutions by others.

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STRESS INTENSITY FACTOR (SIF), PROPOSAL

- › **Proposal** If based on the nominal stress

$$K(a, c) = C_{glob} C_{sif} \sigma_{nom} M_{ellipse}(a, c) M_{weld}(a, c) \sqrt{\pi a}$$

- › **Proposal** If based on hot-spot stress (different SIF formulation), where K_{scf} is stress concentration factor

$$K(a, c) = C_{glob} C_{sif} ([K_{scf} - 1] C_{scf} + 1) \sigma_{nom} M_{ellipse}(a, c) M_{weld}(a, c) \sqrt{\pi a}$$

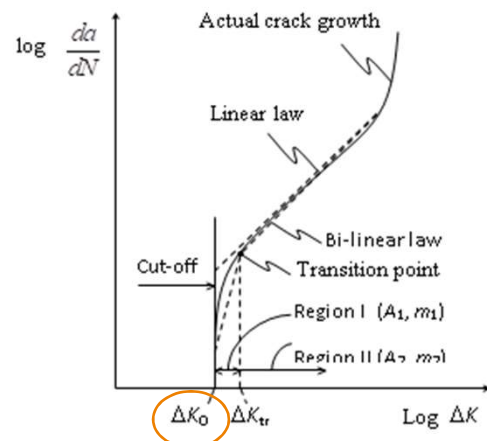
M.U.	Distr. type	μ	σ
C_{glob}	Lognormal Or Normal	1 0.85	0.1 (choice to be discussed) 0.12
C_{scf}	Lognormal	1	0.2
C_{sif}	Lognormal	1	0 (if based on hand book values (proven accuracy) for same geometry) 0.2 (if based on hand book values for approximate geometry) 0.07 (if based on FEM)

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FATIGUE CRACK GROWTH MODEL: THRESHOLD

Distribution crack growth threshold ΔK_0 (below which fatigue crack growth is not assumed)

- › Model code: lognormal, $\mu = 140$, $V = 0.4$. Based on Austin, 1989
- › BS 7910: Characteristic value = 63, scatter within batch 10 % scatter between batches additional 10 % (i.e. $V = 0.1$)
- › Reasons for difference:
 - › Value is very difficult to measure
 - › Value highly depending on stress ratio $R = \sigma_{min} / \sigma_{max}$
 - › Value highly depending on crack height a
- › Models exist that consider R and a . However, not implemented in BS 7910.
- › How to proceed (for the probabilistic model code)?



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EXAMPLE CALCULATIONS

$B = 40 \text{ mm}$, $L = 2000 \text{ mm}$, $W = 1000 \text{ mm}$

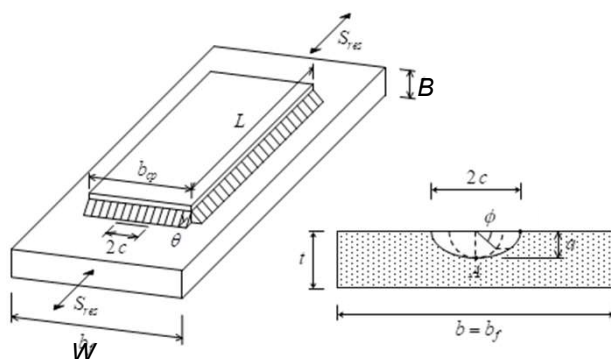
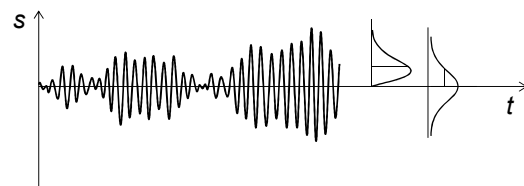


Fig. 2: Cover plate detail on a bridge and crack type.



$$f_s(x) = \frac{x}{\sigma_r^2} \exp\left(-\frac{x^2}{2\sigma_r^2}\right)$$

$$f_{\Delta s}(x) = \frac{x}{4\sigma_r^2} \exp\left(-\frac{x^2}{8\sigma_r^2}\right)$$

n = number of cycles (load)

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RESULTS INFLUENCE MODEL UNCERTAINTIES

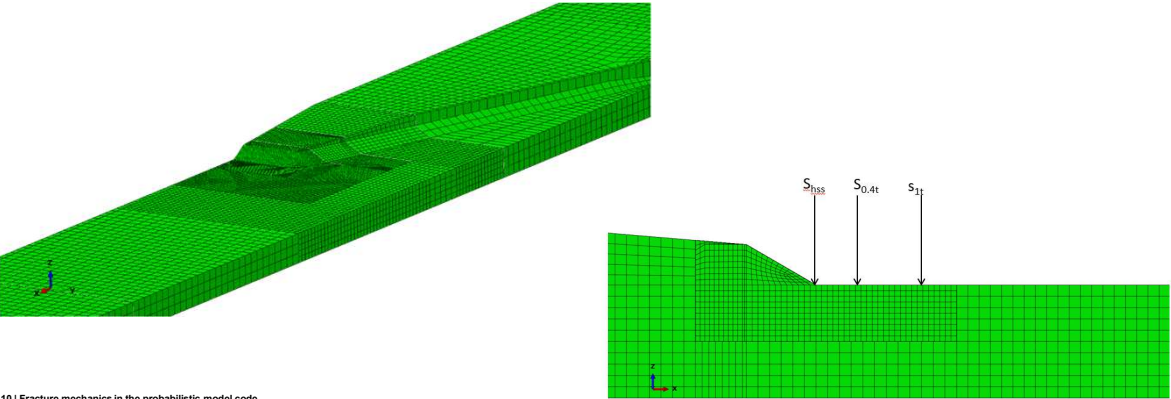
- › $B = 40\text{ mm}, L = 2000\text{ mm}, W = 1000\text{ mm}$ $\Delta K = C_{glob} C_{scf} C_{sif} \Delta \sigma M_{ellipse(a,c)} M_{weld(a,c)} \sqrt{\pi a}$
- › $\sigma_r = 10\text{ MPa}, n = 750.000$
- › Analysis using FORM

Case	1	2	3	4	5
V_{load}	0.1	0	0	0	0
V_{Cglob}	0.1	0.1	0.1	0.1	0.1(normal)
V_{Cscf}	0.2	0.2	0.2	0	0
V_{Csif}	0.2	0.2	0	0	0
β	3.43	3.56	4.32	6.17	6.35
$\alpha (\Pi C)$	-0.89	-0.88	-0.81	-0.56	-0.46

- › Hence enormous influence of the combined uncertainty factors

COVER PLATE

- › FEM analysis performed for various cover plate terminations: $1.4 < K_{SCF} < 1.8$ (usually close to 1.8)



RESULTS COVER PLATE MODEL UNCERTAINTIES

- › $B = 40 \text{ mm}$, $W = 1000 \text{ mm}$ $K(a, c) = C_{glob} C_{sif} ([K_{scf} - 1] C_{scf} + 1) \sigma_{nom} M_{ellipse}(a, c) M_{weld}(a, c) \sqrt{\pi a}$
- › $\sigma_r = 14 \text{ MPa}$, $n = 1.5 \cdot 10^6$
- › Analysis using FORM

Case	6	7	8	9	10	11
K_{scf}	-	-	1.4	1.4	2	2
$L \text{ (mm)}$	20	2000	-	-	-	-
V_{Cglob}	0.1	0.1	0.1	0.1	0.1	0.1
V_{Cscf}	-	-	0.2	0	0.2	0
V_{Csif}	0	0	0	0	0	0
β	4.91	3.28	3.02	3.13	1.15	1.25
$\alpha \text{ (ITC)}$	-0.54	-0.56	-0.62	-0.55	-0.69	-0.55

- › Hence, since using the hot-spot method is already conservative in FM, I believe we do not need C_{SCF}

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RESULTS DISTRIBUTION OF THE THRESHOLD VALUE

- › $L = 2000 \text{ mm}$, $B = 40 \text{ mm}$, $W = 1000 \text{ mm}$, $K_{scf} = 1.0$
- › Analysis using FORM

Case	7	12	13	14
$\sigma_r \text{ (MPa)}$	14	14	9	9
n	$1.5 \cdot 10^6$	$1.5 \cdot 10^6$	10^7	10^7
$\Delta K_0 (\mu; V)$	(140 ; 0.4)	(69.3 ; 0.1)	(140 ; 0.4)	(69.3 ; 0.1)
β	3.28	3.24	2.94	2.75
$\alpha (\Delta K_0)$	0.076	0.001	0.283	0.01

- › Increasing influence for larger number of cycles with lower stress ranges

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FRACTURE MODEL: FRACTURE TOUGHNESS

$$F_{K_{mat}}(k) = 1 - \exp \left[- \left(\frac{k - K_0}{\sigma} \right)^\lambda \right] \quad (4.1)$$

where

- λ is the shape parameter, taken as 4 on the basis of experiments (Wallin, 1984).
- K_0 is the threshold parameter, recommended is 20 MPa m^{1/2} (Burdekin & Hamour, 2000).
- σ is the scale parameter and may be obtained from the following correlation attributed to Wallin (Burdekin & Hamour, 2000):

$$\sigma = \left\{ 11 + 77 \left[\exp \left(\frac{T - T_{27J} + T_0}{52} \right) \right] \right\} \left(\frac{25}{B} \right)^{1/4} (K_{mat} \text{ in MPa m}^{1/2}) \quad (4.2)$$

where:

- T operating temperature (°C) (random FBC process: $\mu = 10^\circ\text{C}$, $\sigma = 8^\circ\text{C}$, $\Delta = 10$ days)
- T_{27J} temperature (°C) corresponding to a CVN of 27 J (safe value)
- T_0 temperature (random variability of T_{27J} : $\mu = 18^\circ\text{C}$, $\sigma = 15^\circ\text{C}$)
- B plate thickness in [mm]

T_{27J} often unknown;

- CVN are known at certain temperature
- What if CTOD values are available?
- A limited (often 3) CVN or COTD values is available only
- What is a safe value?

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FRACTURE MODEL: FRACTURE TOUGHNESS

› Proposal $F(K_{mat}) = 1 - \exp \left[- \left(\frac{K_{mat} - K_{min}}{K_{m,B} - K_{min}} \right)^\lambda \right]$ Note: equations not valid for upper shelf!

$$K_{m,B} = K_{min} + [K_m - K_{min}] \left(\frac{25\text{mm}}{C_l} \right)^{1/\lambda}$$

$$K_m = K_{min} + [11 + 77 \exp(0.019[T - T_0])] \quad \text{Note: units MPa}\sqrt{\text{m}}$$

- › C_l is the crack length. In a (CTOD) test: $C_l = B$. In a semi-elliptical crack: $C_l = 2c$
- › T_0 is the actual material property (temperature at a median fracture toughness of 100 MPa√m for a 25 mm plate thickness). To be based on CTOD / KJC tests (and using the above equations) or estimated based on Charpy tests. In the latter case:

$$T_0 = T_{27J} + T_c$$

where T_c is a correlation temperature with mean $\mu_{T_c} = -18^\circ\text{C}$ and standard deviation $\sigma_{T_c} = 15^\circ\text{C}$.

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FRACTURE MODEL: FRACTURE TOUGHNESS

- › Determine the estimate of T_0 (iteratively) from the following equation, using n tests with (thickness-corrected) fracture toughness $K_{m,Bi}$ per test i :

$$\sum_{i=1}^n \frac{\delta_i \exp(0.019[T - T_0])}{11 + 77 \exp(0.019[T - T_0])} - \sum_{i=1}^n \frac{(K_{m,Bi} - 20)^4 \exp(0.019[T - T_0])}{[11 + 77 \exp(0.019[T - T_0])]^5} = 0 \quad \text{Note: units MPa}\sqrt{\text{m}}$$

where δ_i is a censoring parameter (Kronecker delta), equal to 1 for a valid test and 0 for an invalid test

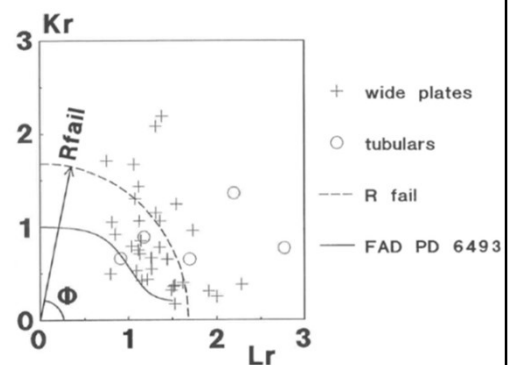
- › Note: equations not valid for upper shelf!
- › The fact that the estimate of T_0 is often based on a limited number of tests only (three) is considered in the FAD model uncertainty, see next slide

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FRACTURE MODEL: FAILURE ASSESSMENT DIAGRAM (FAD)

- › K_r (vertical axis) is (brittle) fracture ratio
- › L_r (horizontal axis) is plastic failure ratio
- › Model according to the probabilistic model code:

$$g = R - \sqrt{(K_r^2 + L_r^2)}$$
- › R is normal distributed, $\mu = 1.7$, $V = 0.18$



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FRACTURE MODEL: FAILURE ASSESSMENT DIAGRAM (FAD)

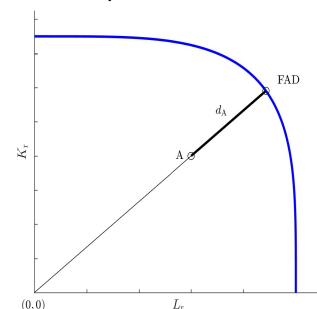
However, many aspects have changed in BS 7910 since assessment of the distribution of R:

- › Fracture toughness K_{mat} obtained from CTOD using more accurate procedure
- › Crack size correction introduced for K_{mat}
- › Triaxial stress state correction (T-stress) introduced for K_{mat}
- › Plastic failure ratio distinction between local failure and global failure (complete rupture)
- › ...

Therefore, tubular joint and wide plate tests carried out in the past have been re-evaluated with the current version of BS 7910. Per test, a limited number of material characterization (CTOD) tests have been carried out.

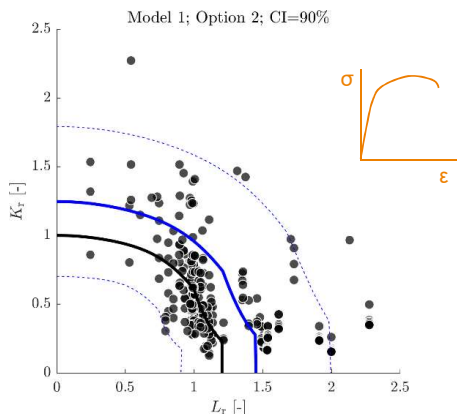
FRACTURE MODEL: FAILURE ASSESSMENT DIAGRAM (FAD)

- › Approach followed to assess the FAD MU:
 - › Re-evaluate old CTOD & Wide plate / tubular joint tests with the current version of BS 7910 (incl. residual stresses)
 - › For each test combination, determine the radial distance d_A between the failure point and the FAD (using polar coordinates)
 - › Model 1: Additive normal distributed MU, independent of polar angle
$$D = FAD + E$$
 - › Model 2: Additive normal distributed MU, depending on polar angle
$$D = FAD + E(\varphi)$$
 - › Models are compared using Akaike information criterion (AIC)
 - › Result: same AIC, so simpler model 1 is further elaborated

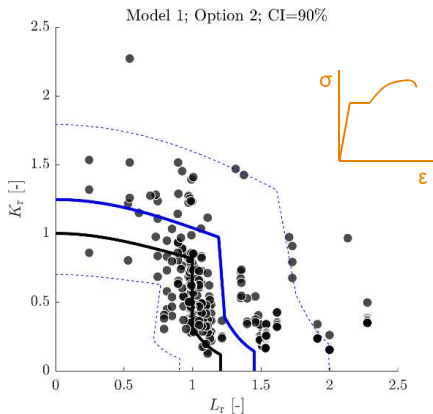


FRACTURE MODEL: FAILURE ASSESSMENT DIAGRAM (FAD)

FAD based on individual CTOD values

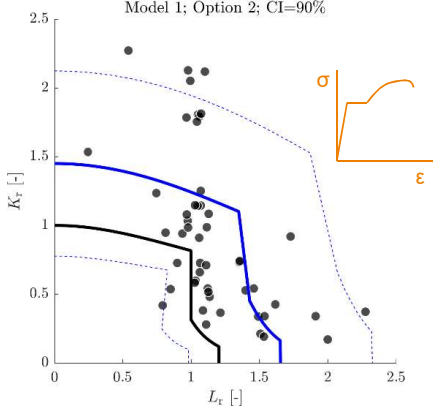


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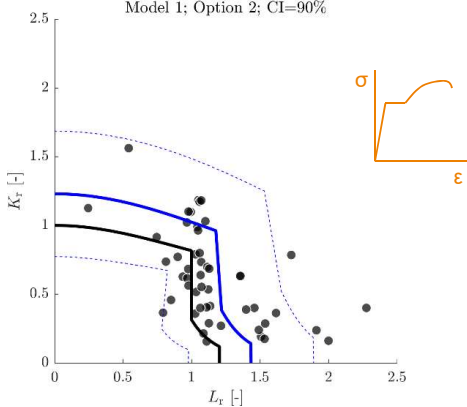
FRACTURE MODEL: FAILURE ASSESSMENT DIAGRAM (FAD)

FAD based on minimum of three CTOD values



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FAD based on average of three CTOD values

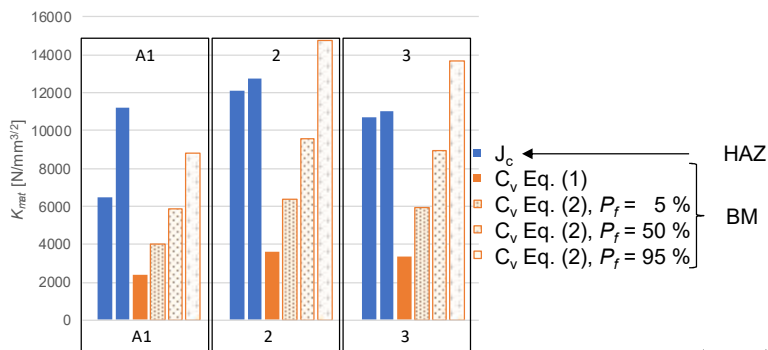


FRACTURE MODEL: FAILURE ASSESSMENT DIAGRAM (FAD)

$D = FAD + E$ If based on the average of three CTOD tests

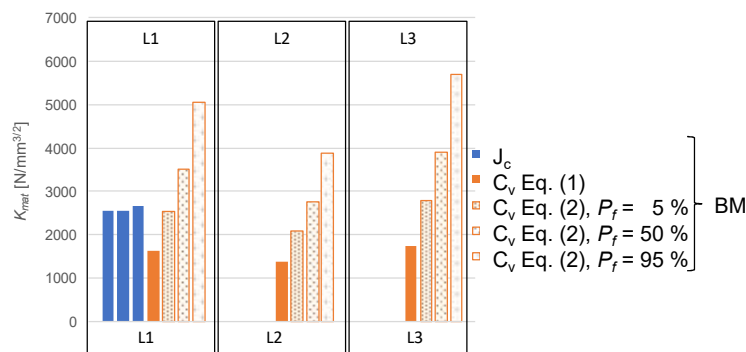
MU	μ_E	σ_E
Point estimate	0.235	0.285
Standard error	0.040	0.028

EXAMPLE: K_{MAT} BASED ON CHARPY OR CTOD



$$(1) K_{mat} = 20 + (12\sqrt{C_v} - 20) \left(\frac{25mm}{B} \right)^{0.25}$$
$$(2) K_{mat} = 20 + \{11 + 77 \exp [0.019(T - T_{27J} - T_k)]\} \left(\frac{25mm}{B} \right)^{0.25} \left[\ln \left(\frac{1}{1 - P_f} \right) \right]^{0.25}$$

EXAMPLE: K_{MAT} BASED ON CHARPY OR CTOD



$$(1) K_{mat} = 20 + (12\sqrt{C_v} - 20) \left(\frac{25mm}{B} \right)^{0.25}$$

$$(2) K_{mat} = 20 + \{11 + 77 \exp[0.019(T - T_{27J} - T_k)]\} \left(\frac{25mm}{B} \right)^{0.25} \left[\ln \left(\frac{1}{1 - P_f} \right) \right]^{0.25}$$

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RESULTS FAD

- › $B = 40 \text{ mm}$, $L = 2000 \text{ mm}$, $W = 1000 \text{ mm}$
- › $\sigma_r = 8 \text{ MPa}$, $n = 10^7$
- › Analysis using FORM

Case	15	16	17	18	19	20
Fracture test	Charpy	Charpy	Charpy	Charpy	CTOD	CTOD
$T_{27J} [^{\circ}\text{C}](\text{m};\text{s})$	(-50;0)	(-50;0)	(0;10)	(0;10)		
$T_o [^{\circ}\text{C}](\text{m};\text{s})$					(-18;10)	(-18;10)
$T [^{\circ}\text{C}](\text{m};\text{s})$	(10;8)	(10;8)	(0;8)	(0;8)	(0;8)	(0;8)
FAD	old	new	old	new	new	new
C_l	B	B	B	B	B	$2c$
$\sigma_{\text{permanent}} [\text{MPa}]$	100	100	220	220	220	220
β	3.38	3.38	3.32	3.18	3.23	3.22

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CONTINUATION

- › If you agree with the headlines of the proposed modifications, I will draft an amended text and equations for the JCSS probabilistic model code

› **THANK YOU FOR YOUR
ATTENTION**

Take a look:
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