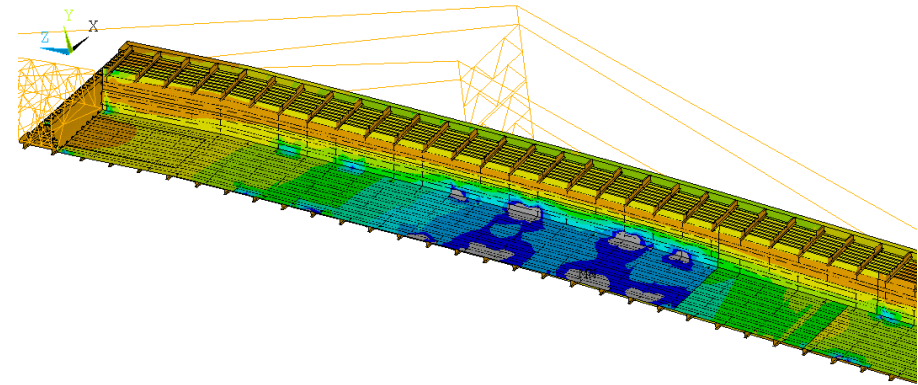


Fatigue design approaches using FEM



Balázs Kövesdi, PhD
Associate Professor
BME Dept. of Structural Engineering

Traditional fatigue analysis

1. Selection of critical structural detail
 - Reference points in standard's tables (EC3-1-9)
2. Determination of loading history
 - Based on standardized fatigue load models
3. Stress range calculation at critical points
4. Fatigue check
 - Fatigue class of critical location
 - Choice of S-N curve and evaluation

Fatigue assessment methods

„Traditional”

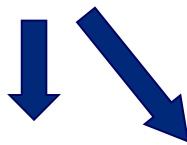
FEM based design

Simple stress analysis

Advanced stress analysis

Nominal stresses

Local stresses (Hot spot / Notch)



S-N curves -- damage accumulation hypothesis

Complex structural detail

Simple structural detail
reduced number of detail classes



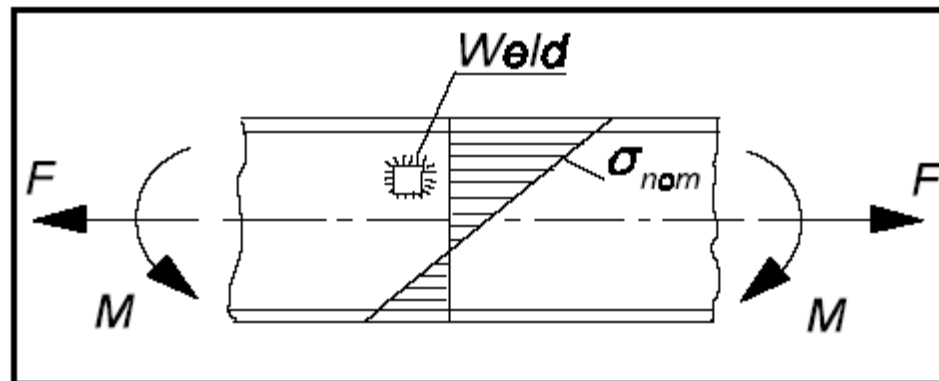
Nominal and geometric stresses

- ◆ Nominal stress: structural detail (basically hand calculation method)
- ◆ Geometric stress: structural point Geometric stress (includes the effect of "macro" change in geometry = Stress concentration)
- ◆ Notch stresses: structural point Local (notch) stress, e.g. at weld toe contains „macro" and „micro" changes
- ◆ S-N curves include:
 - ◆ Structural detail: stress concentration due to weld geometry, residual stresses, effect of welding method, shape and size of micro/macro failures, direction of stresses.
 - ◆ Structural point: local micro/macro failures due to weld geometry, local imperfections.

Nominal stress theory σ_N

nominal stress

is calculated at a potential crack location in the material or in the weld; based on linear elastic calculation excluding any stress concentration

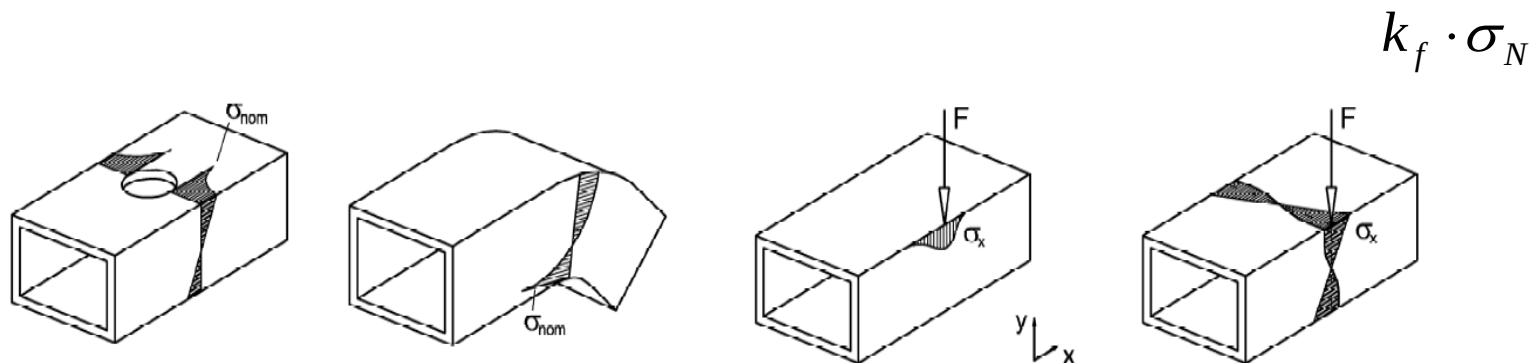


Nominal stress theory σ_N

- Determination of stress amplitude:
- Nominal stress σ_N = based on linear mechanics
 - eg. member in tension

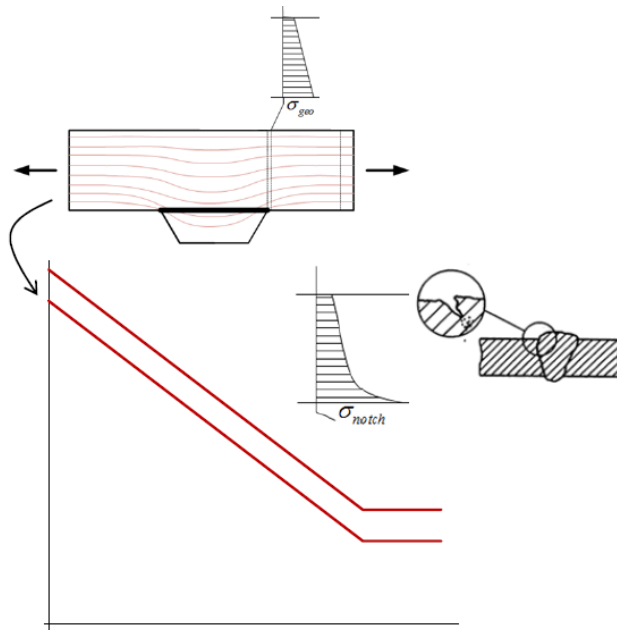
$$\sigma_N = \frac{N}{A}$$

- unplanned excentricities, macrogeometric effects to be included → modified nominal stress:



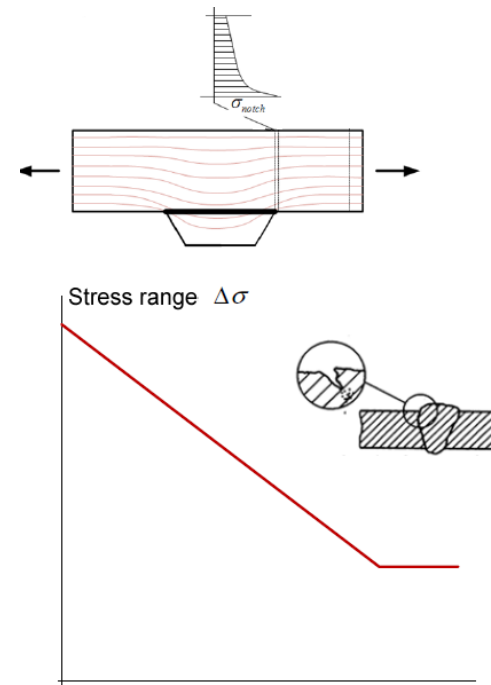
FEM based fatigue assessment

- Fatigue analysis with local approaches



The Hot-spot method

The effect of macro geometry is transferred to the load-effect side



The effective notch stress method

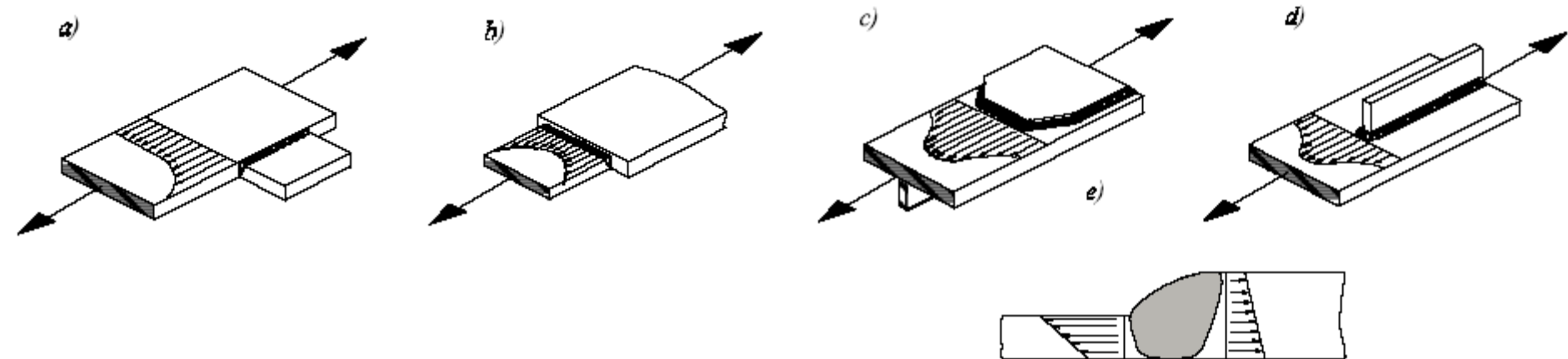
Both macro & micro effects are accounted for on the load-effect side

Geometric stresses

„geometric stress”

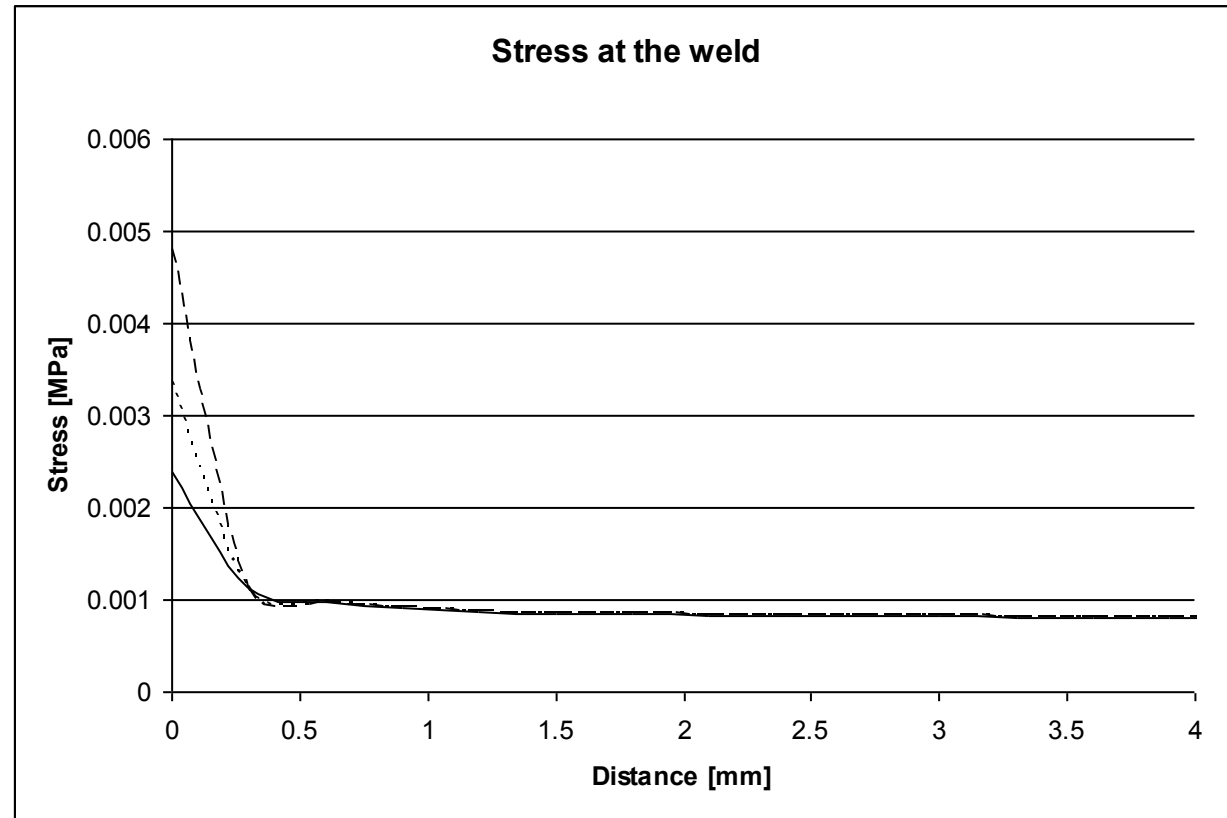
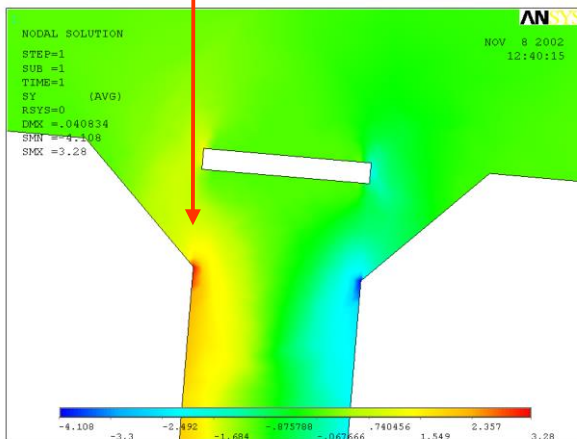
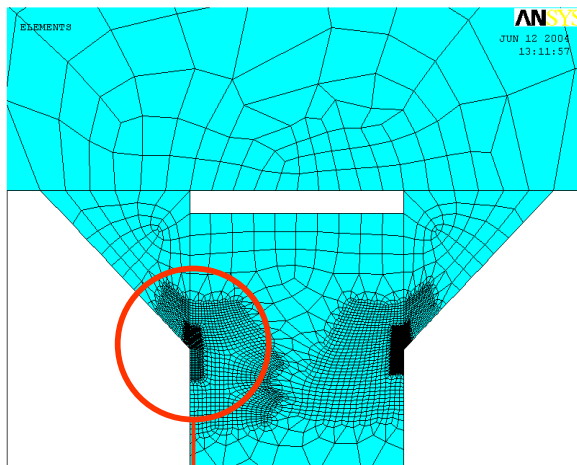
„hot spot stress”

„stress at dangerous point”



Geometric stress

- Stress concentration depends on the mesh size





IIW proposals

INTERNATIONAL INSTITUTE OF WELDING - IIW / IIS

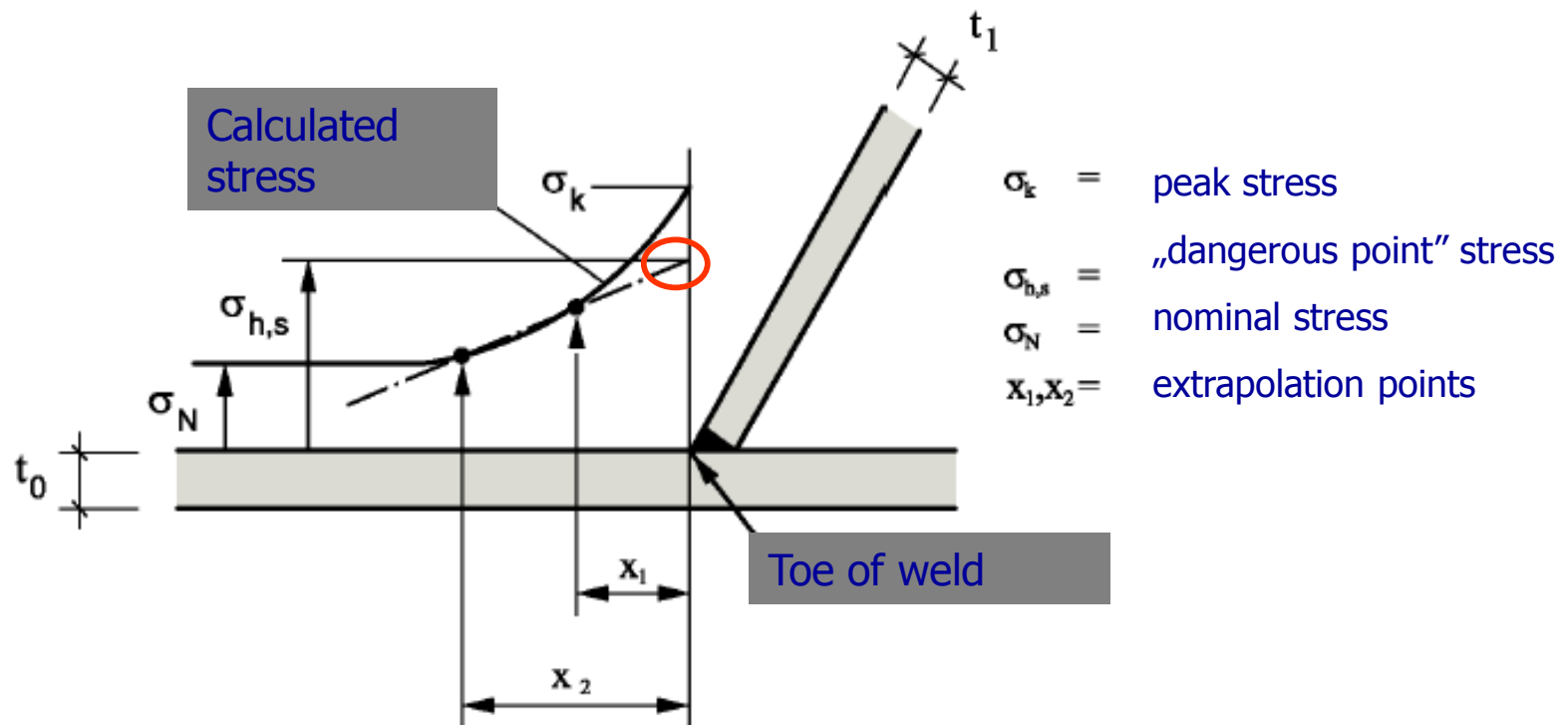
IIW document XIII-1965-03 / XV-1127-03

RECOMMENDATIONS FOR FATIGUE DESIGN OF WELDED JOINTS AND COMPONENTS

IIW proposals

Determination of:

- „dangerous point”
- „stresses at dangerous points” $\sigma_{h,s}$

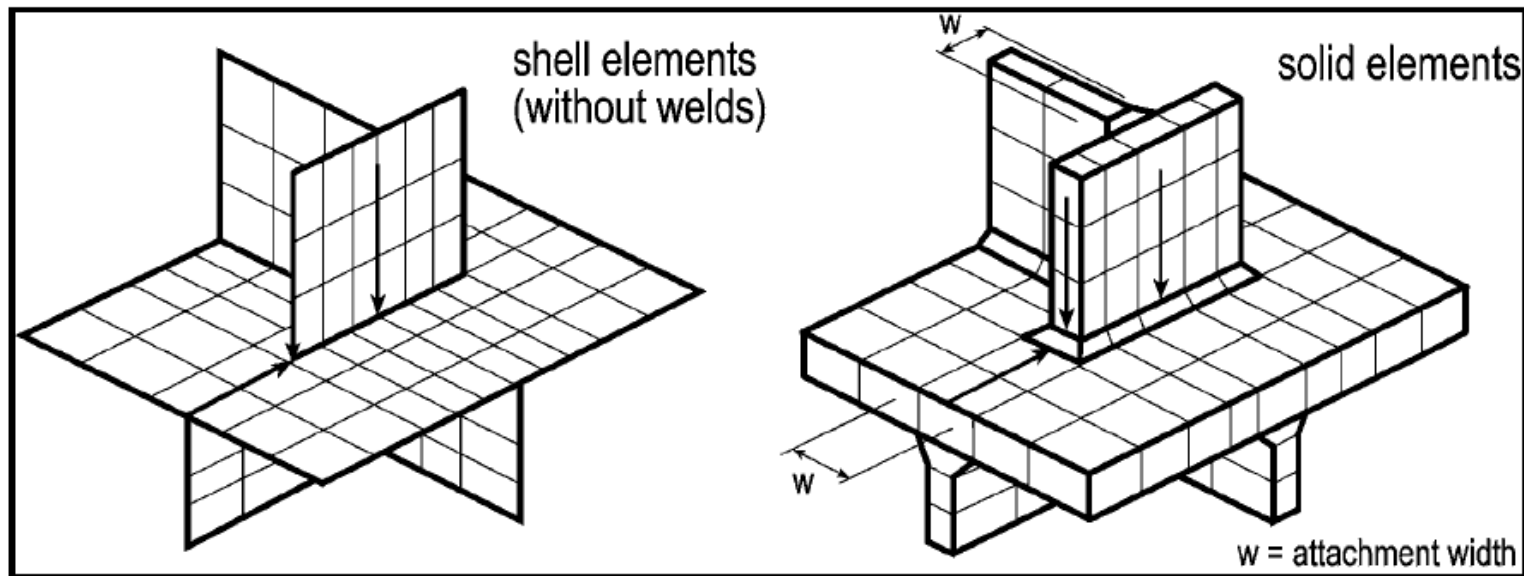
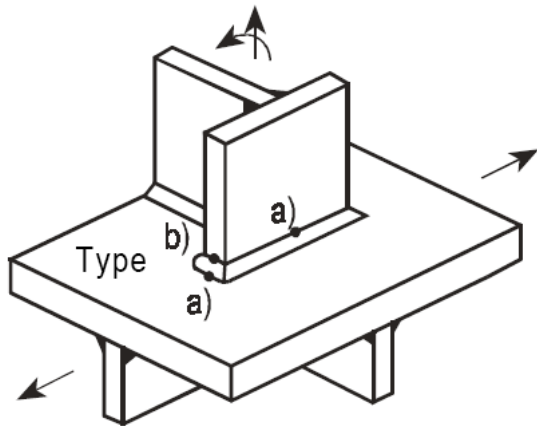


Classification and modelling of „dangerous points”

Shell model

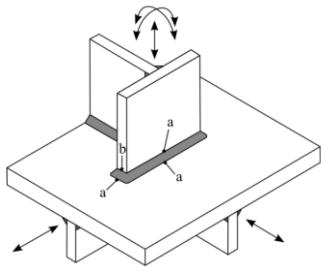
Solid element model

Weld type a) or b) (surface or edge weld)

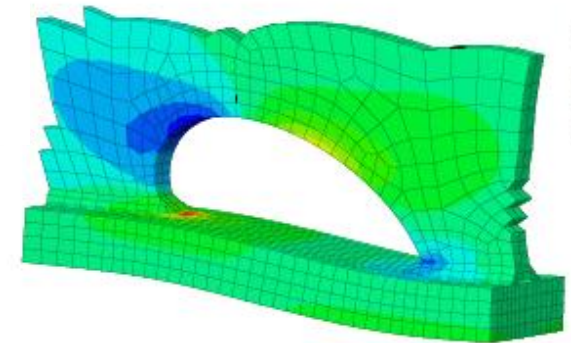


The hot-spot method (geometric stress)

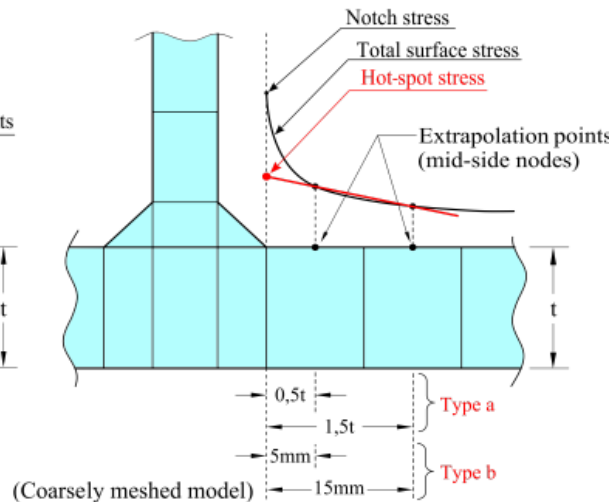
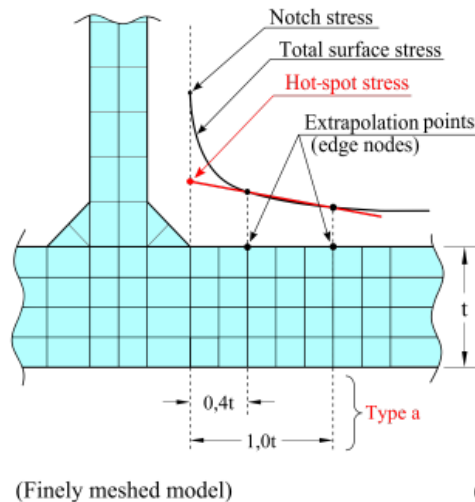
- Stress extrapolation should follow certain "rules" on the basis of which the method was "calibrated/validated"



Type of hot-spot (a or b)



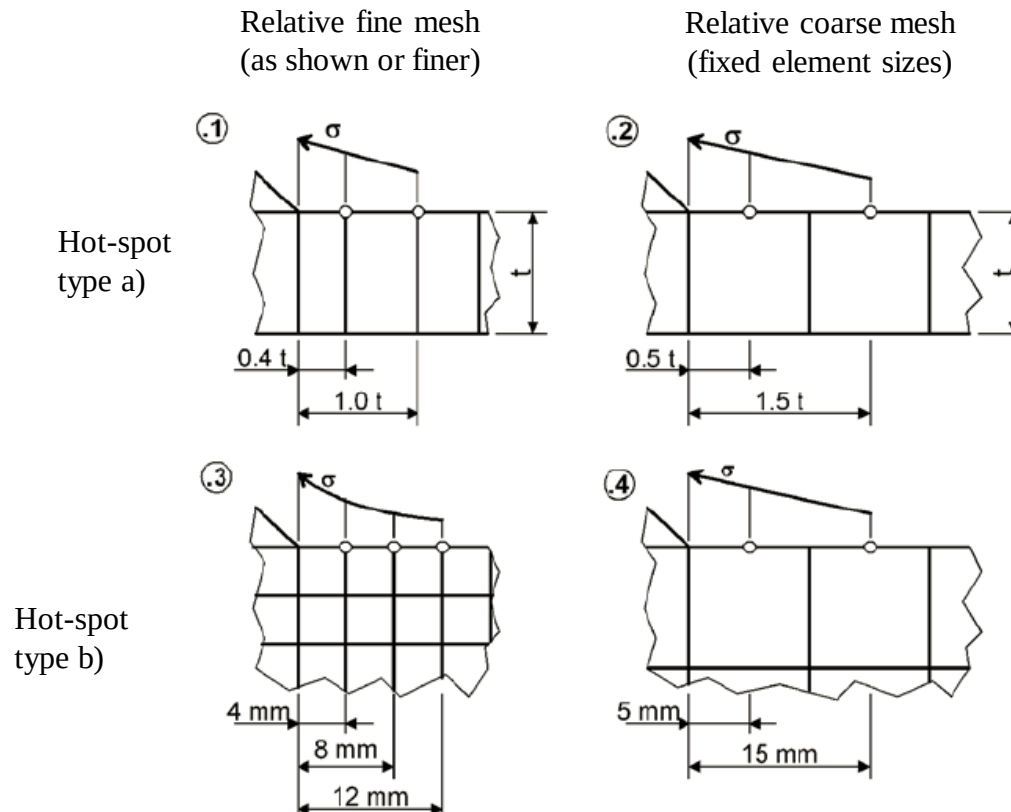
To some degree
Type of detail (stress gradient)



Type of mesh
- "coarse" or "fine"
- linear or quadratic elements

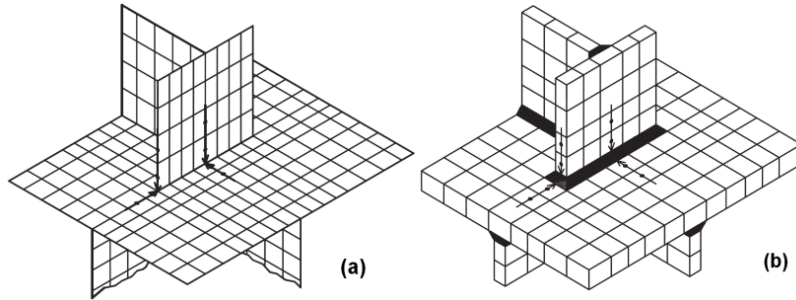
Extrapolation of stresses

- Reference points of dangerous points



Extrapolation of stresses

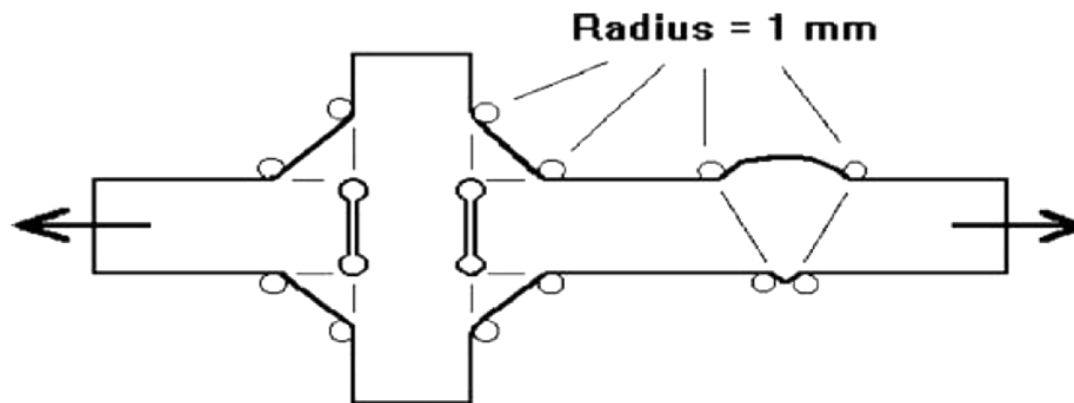
- Rules for stress extrapolation



Type of hot-spots point	Linear extrapolation		Quadratic extrapolation	
	Fine mesh	coarse mesh	Fine mesh	coarse mesh*
Type a	0,4t and 1,0t	0,5t and 1,5t	0,4t, 0,9t and 1,4t	0,5t, 1,5t and 2,5t
	$1,67\sigma_{0,4t} - 0,67\sigma_{1,0t}$	$1,5\sigma_{0,5t} - 0,5\sigma_{1,5t}$	$2,52\sigma_{0,4t} - 2,24\sigma_{0,9t} + 0,72\sigma_{1,4t}$	$1,875\sigma_{0,5t} - 1,25\sigma_{1,5t} + 0,375\sigma_{2,5t}$
Type b	--	5mm and 15mm	4, 8 and 12mm	--
	--	$1,5\sigma_{5mm} - 0,5\sigma_{15mm}$	$3\sigma_{4mm} - 3\sigma_{8mm} + \sigma_{12mm}$	--

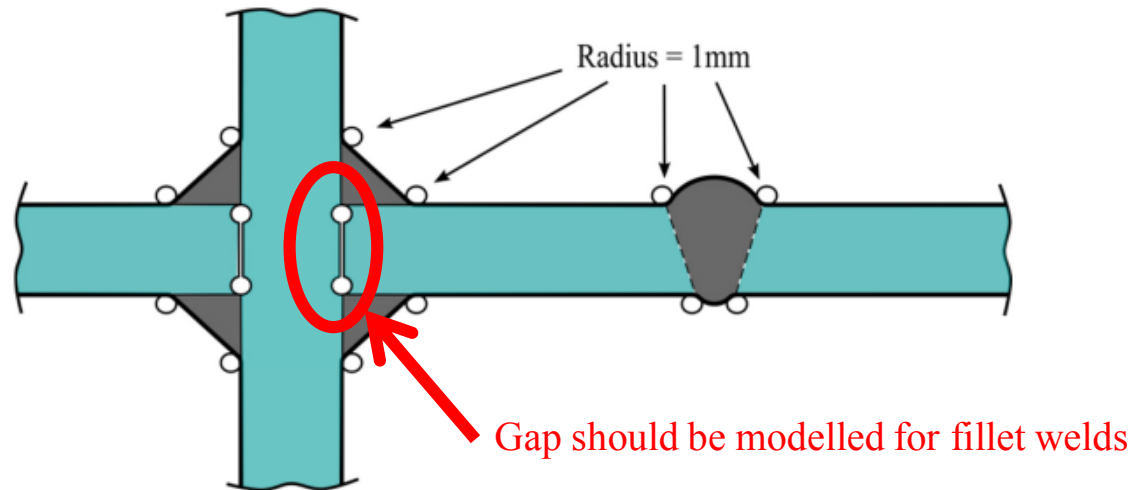
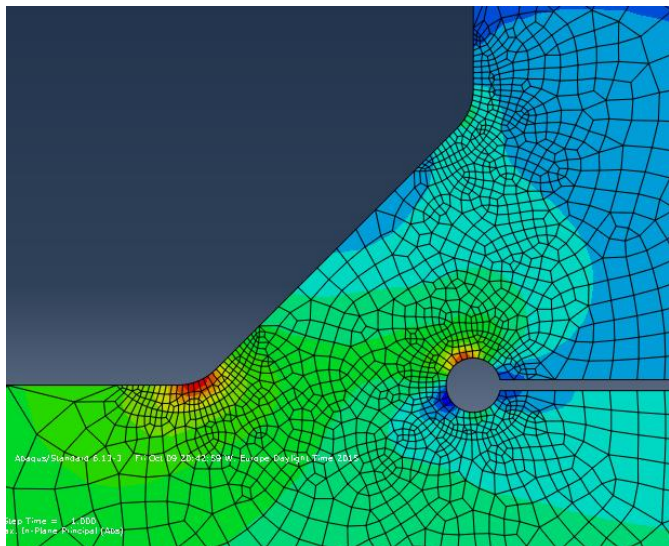
Effective notch stress approach

- „notch stress method”:
 - IIW Update 2006 includes already,
 - Generalization, further development of the hot-spot procedure,
 - Detailed analysis of weld and it's surrounding area
 - Stress calculation inside the weld, at the weld toe
 - Modelling with 1 mm rounding instead of „sharp corner”



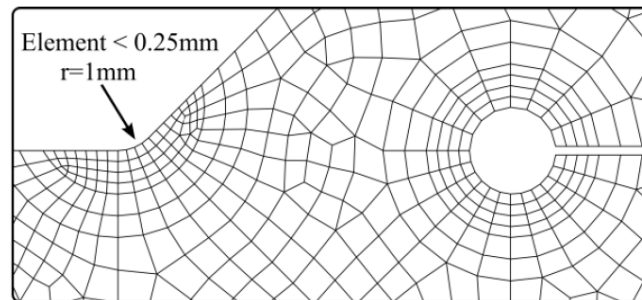
Effective notch stress approach

- Modelling aspects
 - Detail geometry in and around the region of stress concentration (weld toe or root) is required
 - Sufficiently fine FE mesh at the notch region
 - Both toe- and root cracking can be evaluated



Effective notch stress approach

- FE size determination
IIW-recommendations



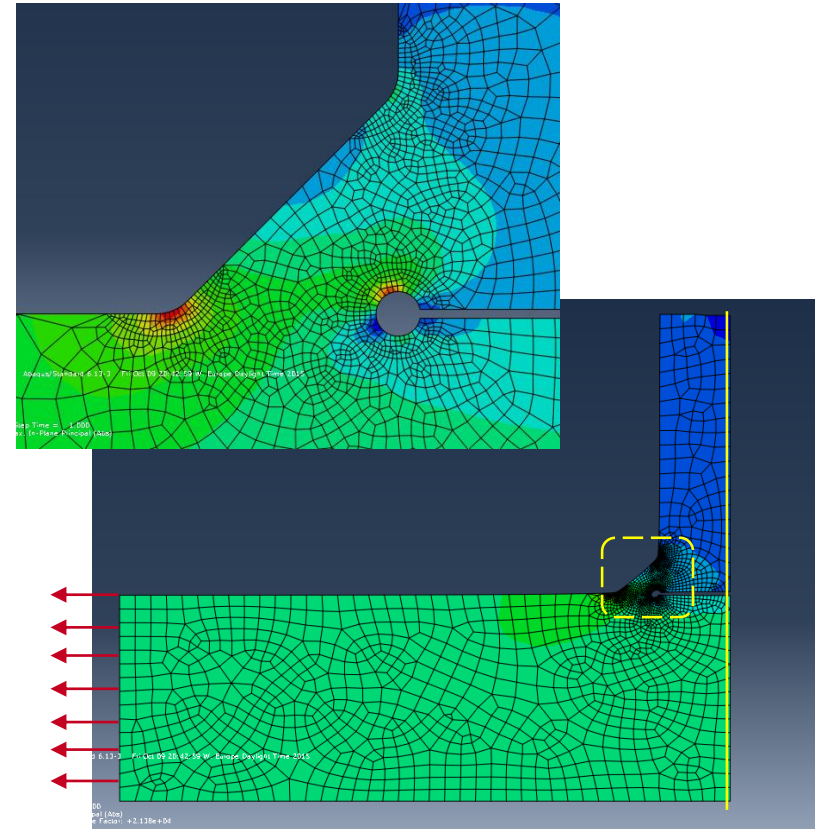
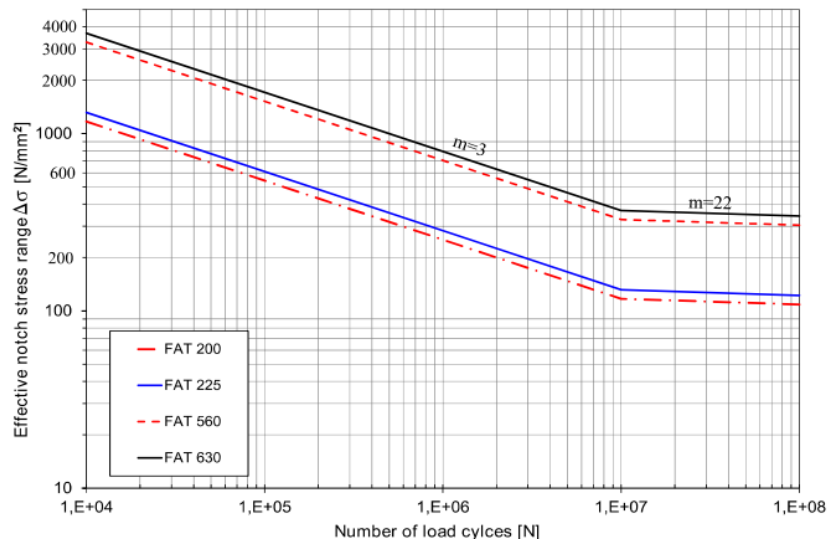
<i>Element type</i>		<i>Element size</i>		
		<i>Relative size</i>	<i>r = 1mm</i> (<i>t</i> ≥ 5mm)	<i>r = 0.05mm</i> (<i>t</i> < 5mm)
Hexahedral	Quadratic	$\leq r / 4$	0.25mm	0.012mm
	Linear	$\leq r / 6$	0.15mm	0.008mm
Tetrahedral	Quadratic	$\leq r / 6$	0.15mm	0.008mm

Effective notch stress approach

- Resistance side – S-N curves

IIW-recommendations

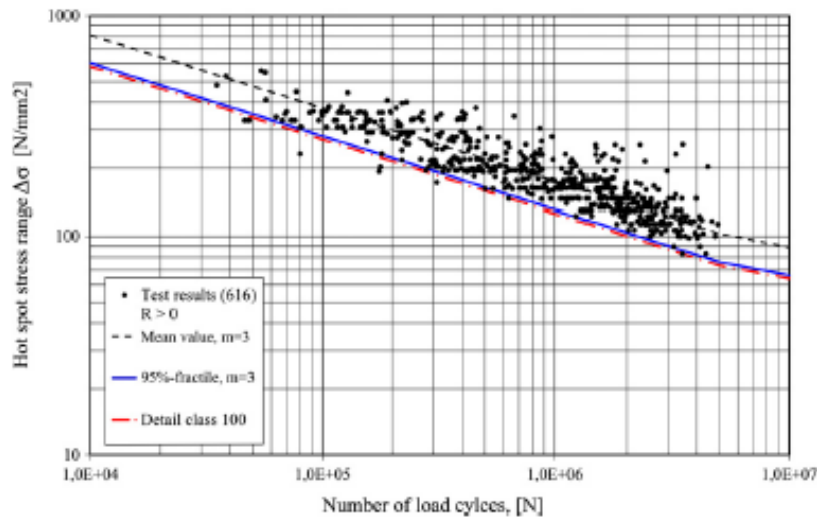
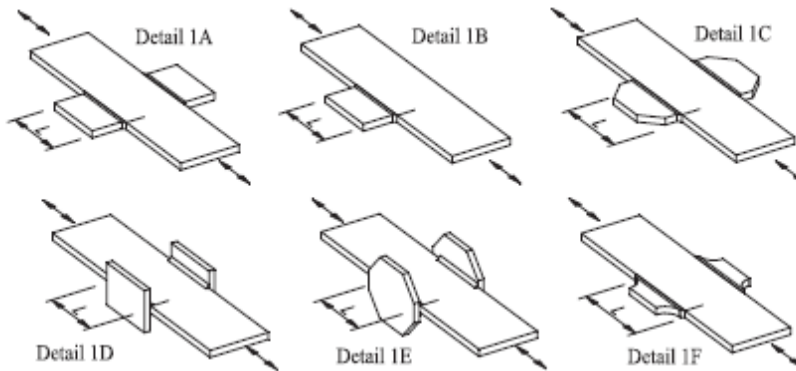
Reference radius	Principal stress	von Mises stress
$r = 1,0\text{mm}$	FAT225	FAT200
$r = 0.05\text{mm}$	FAT630	FAT560



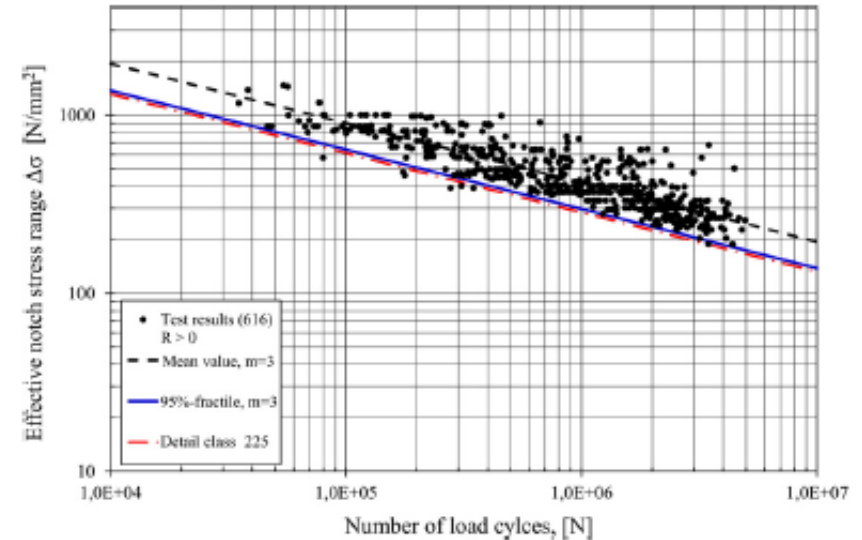
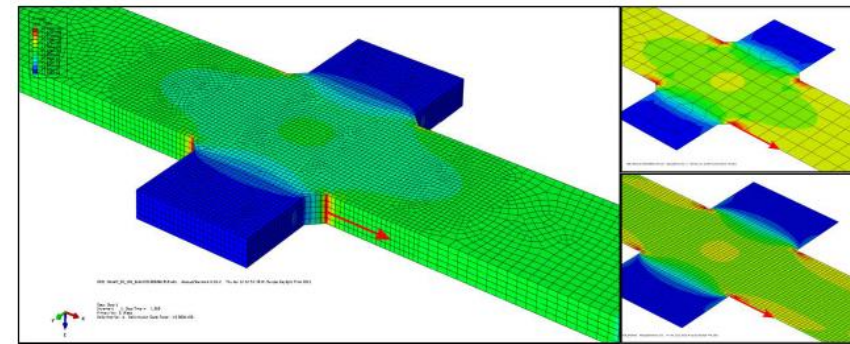
Examples

- verification of the two methods

Hot spot stress method / FAT100



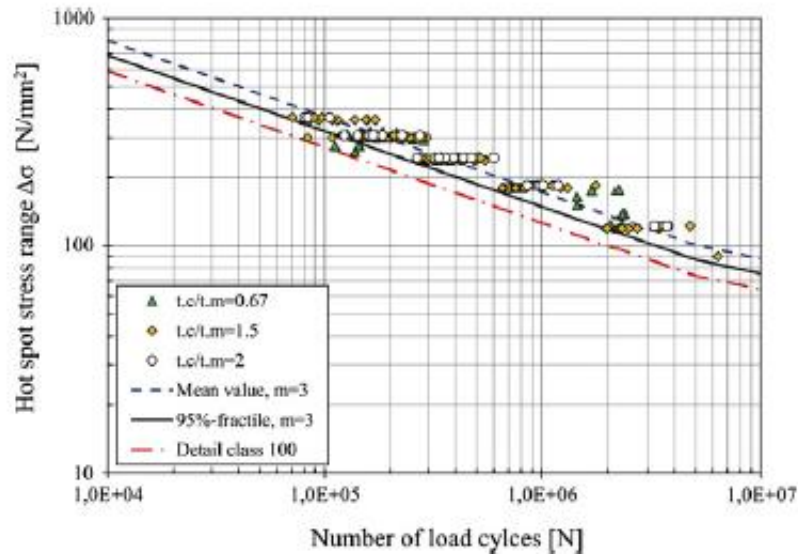
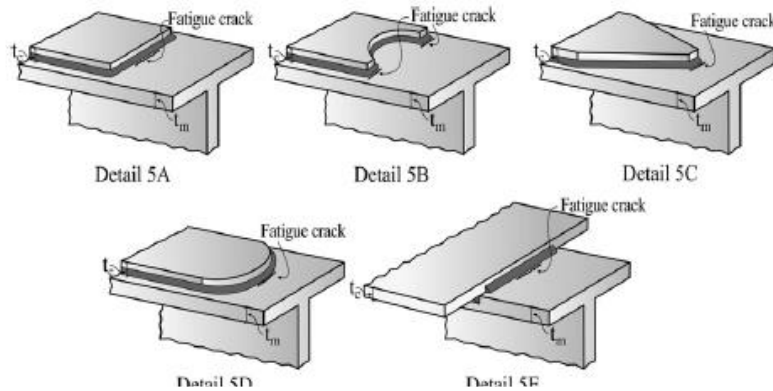
Effective notch stress method / FAT225



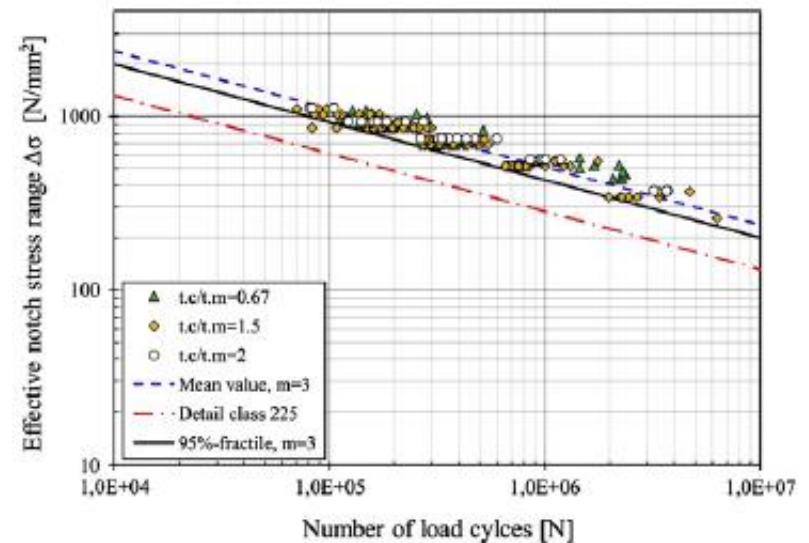
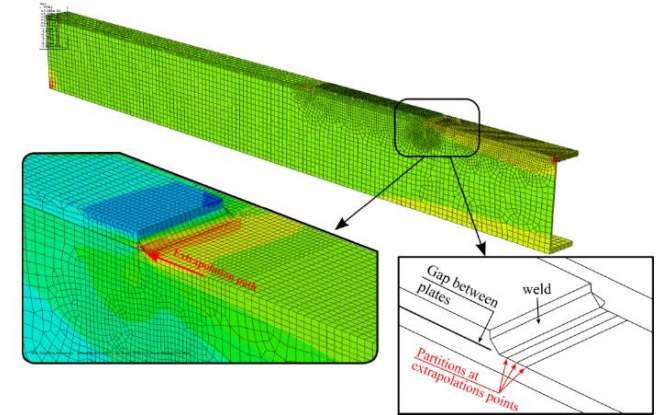
Examples

- Verification of the two methods

Hot spot stress method / FAT100



Effective notch stress method / FAT225



Safety concepts

- Traditional, crackfree, „safe life”:
 - It can be proved (with adequate safety) that no fatigue induced damage occurs during the design lifetime (100 years for bridges) without regular check.
 - Practice: cracks do not occur
- Damage tolerant / crack tolerant:
 - Proves that the structure works properly during its design lifetime
 - Maintenance system is required to detect fatigue cracks and reparation during the structure's whole design lifetime

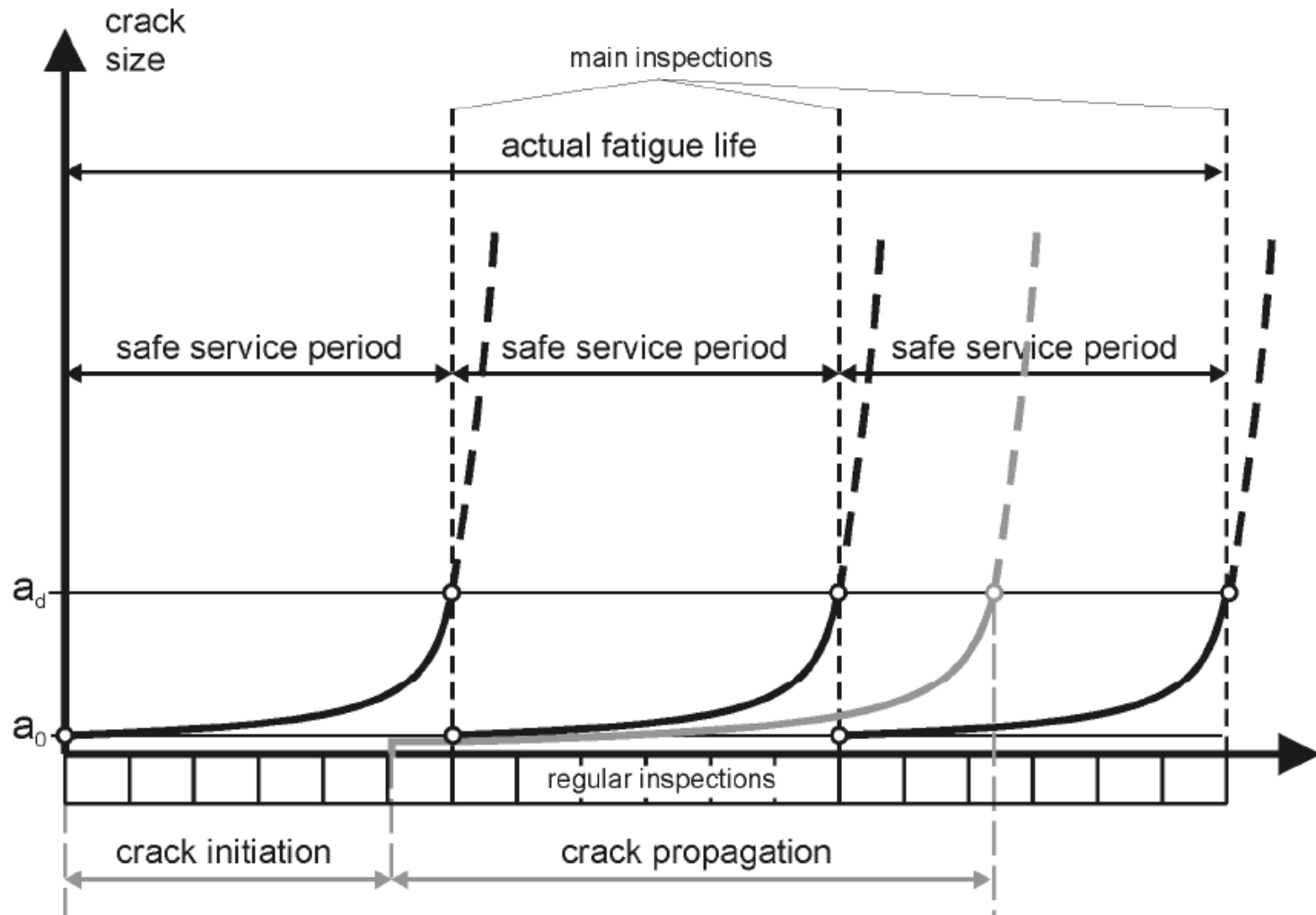
Safety concepts

- Basics
 - Does not depend on the material's grade!
 - Constant stress amplitude independently of the average stress
 - Stress calculation in SLS
 - Safety concepts:
 - Crack-free
 - Damage tolerant
 - Partial safety factors:

 γ_{Mf}

Safety concepts	Consequences of damage	
	Not serious	Serious
Damage tolerant	1,00	1,15
Crack free	1,15	1,35

Maintenance period calculation



Fatigue loads to consider

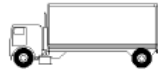
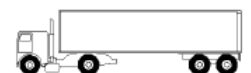
Eurocode1: Actions on structures

different fatigue load models:

- standardized load groups
- example: Traffic loads on bridges, EC1-2
 - FLM1 same than in ULS, smaller wheel load (axle load)
 - FLM5 „statistical value”
 - based on real loads, traffic counts data (recorded traffic),
 - or, from direct stress measuremet

Fatigue loads to consider

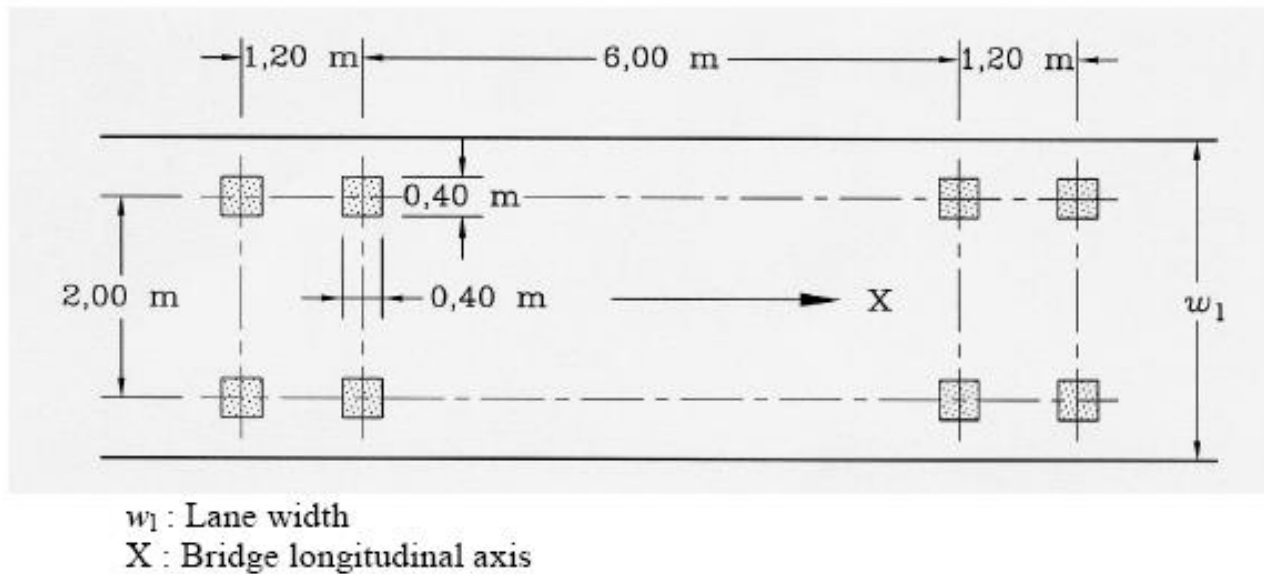
FLM 2 set of „frequent” lorries

1		2	3	4
LORRY SILHOUETTE		Axle spacing (m)	Frequent axle loads (kN)	Wheel type (see Table 4.8)
		4,5	90	A
			190	B
		4,20 1,30	80	A
			140 140	B B
		3,20 5,20 1,30 1,30	90	A
			180	B
			120	C
			120 120	C C
		3,40 6,00 1,80	90	A
			190	B
			140	B
			140	B
		4,80 3,60 4,40 1,30	90	A
			180	B
			120	C
			110	C
			110	C

Fatigue loads to consider

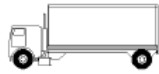
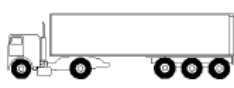
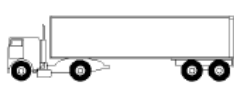
FLM 3 „single vehicle” (heavy vehicle)

- $F_i = 120 \text{ kN}$ (total of 480 kN!!!)
- two trucks in 40 m distance



Fatigue loads to consider

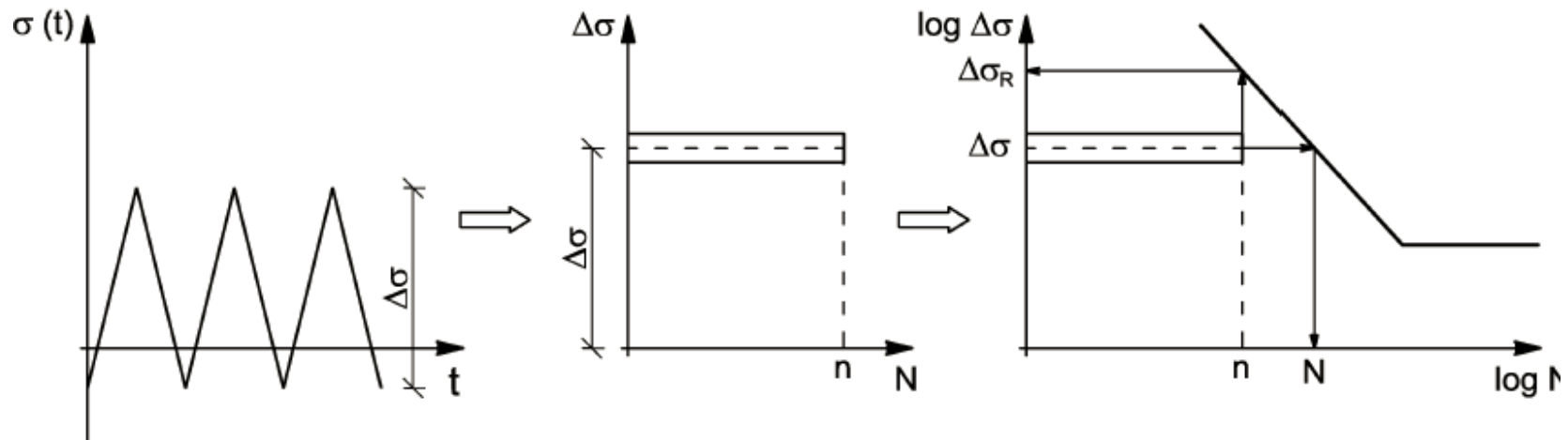
FLM 4 set of „equivalent” lorries

VEHICLE TYPE			TRAFFIC TYPE			
1	2	3	4	5	6	7
			Long distance	Medium distance	Local traffic	
LORRY	Axle spacing (m)	Equivalent axle loads (kN)	Lorry percentage	Lorry percentage	Lorry percentage	Wheel type
	4,5	70 130	20,0	40,0	80,0	A B
	4,20 1,30	70 120 120	5,0	10,0	5,0	A B B
	3,20 5,20 1,30 1,30	70 150 90 90 90	50,0	30,0	5,0	A B C C C
	3,40 6,00 1,80	70 140 90 90	15,0	15,0	5,0	A B B B
	4,80 3,60 4,40 1,30	70 130 90 80 80	10,0	5,0	5,0	A B C C C

Steps of fatigue analysis

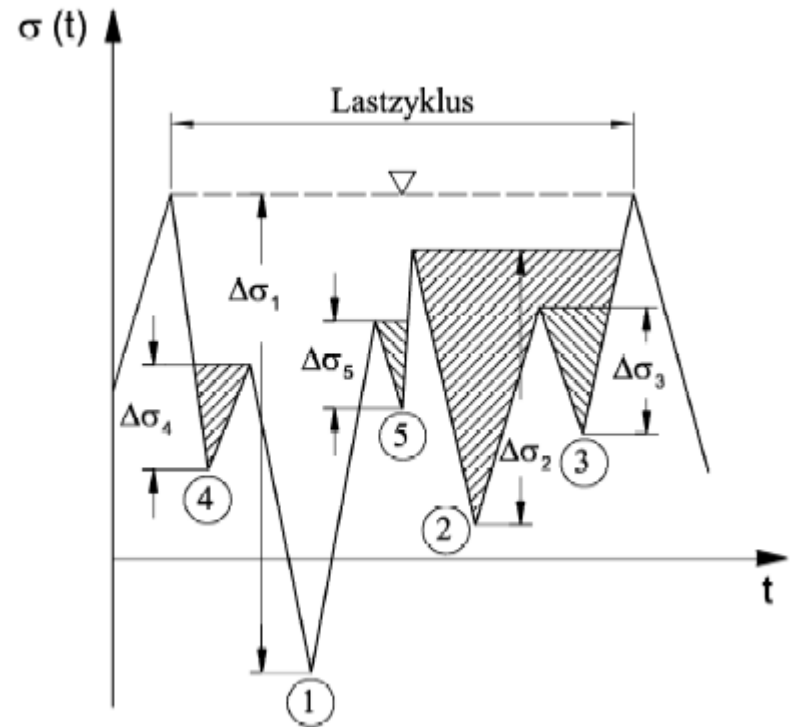
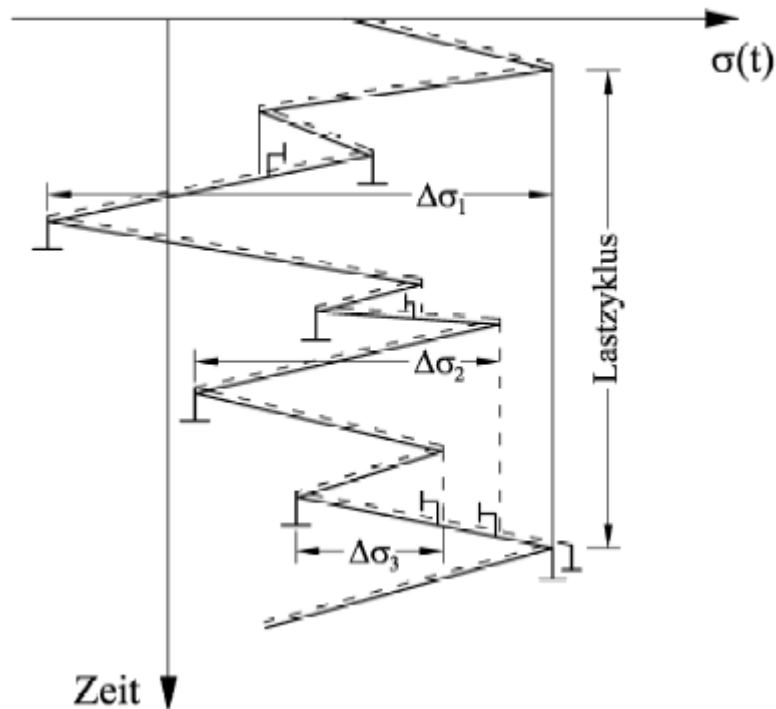
In case of nominal stresses σ_N

– In case of simple repeating load



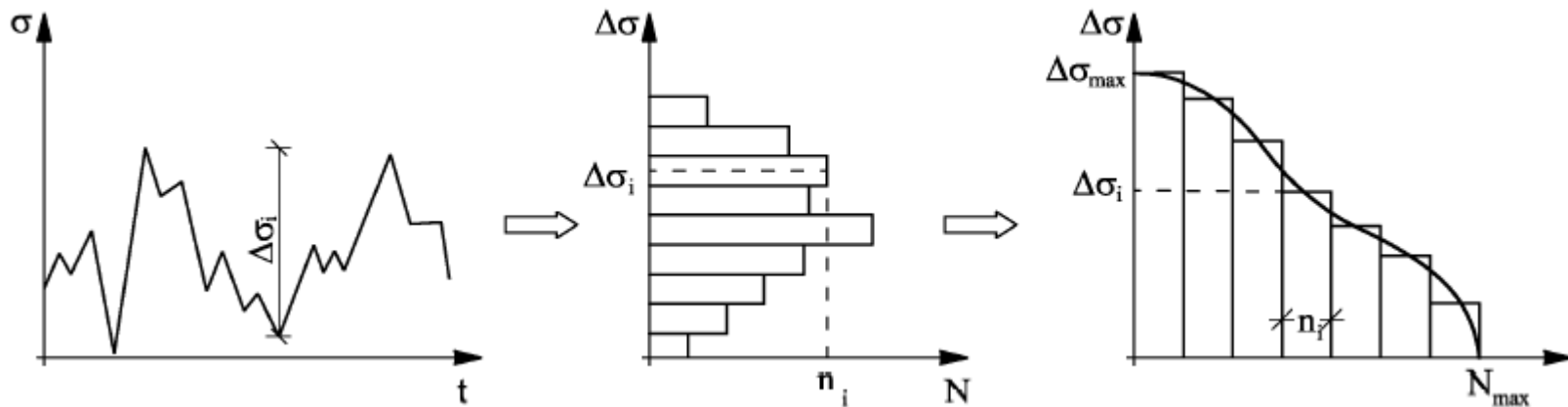
Determination of stress range

In case of nominal stresses σ_N
– Counting methods $\Delta\sigma_i - n_i$



Determination of stress range

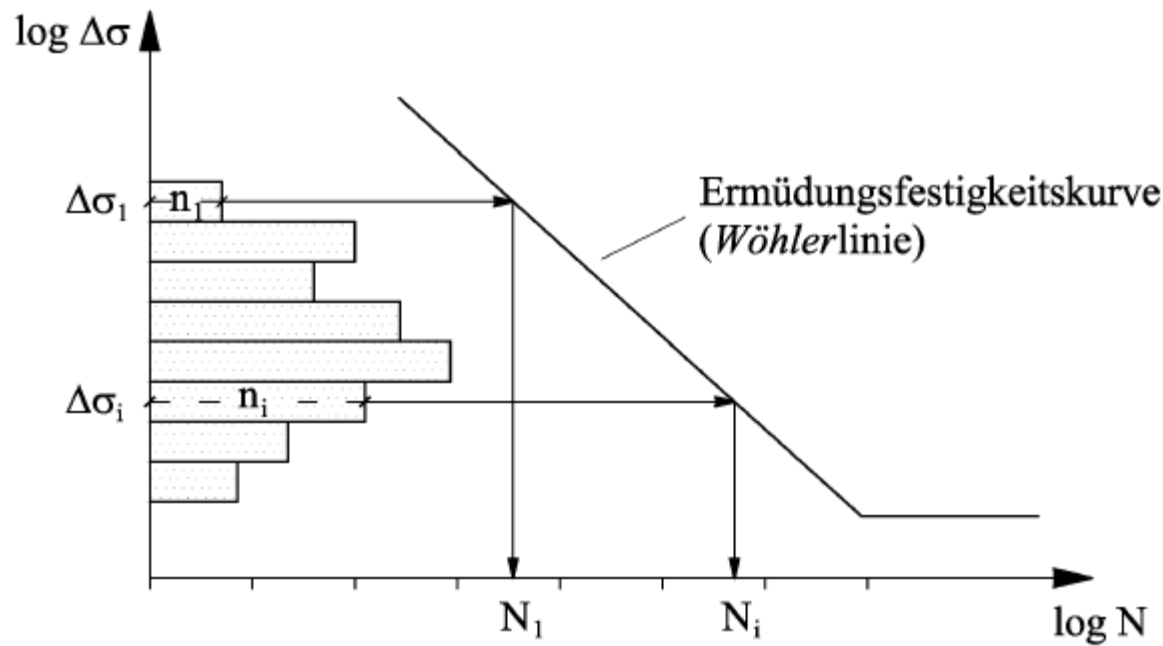
In case of nominal stresses σ_N
– Design stress range spectrum



Steps of fatigue analysis

Linear damage hypothesis:

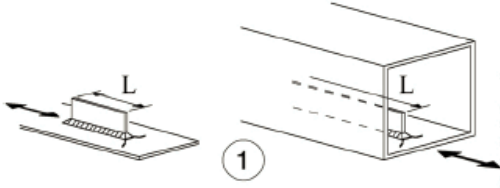
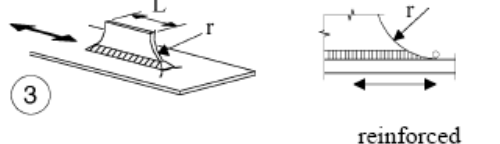
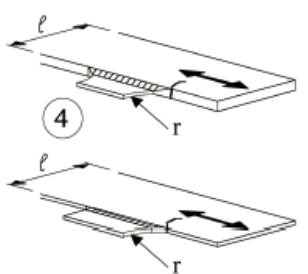
- Palmgren-Miner-rule: linear cumulative damage



$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \dots = \sum \frac{n_i}{N_i} = \int_0^{N_{\max}} \frac{dn}{N} \leq 1,0$$

Fatigue detail classes

Table 8.4: Weld attachments and stiffeners

Detail category	Constructional detail		Description
80	$L \leq 50\text{mm}$		<u>Longitudinal attachments:</u> 1) The detail category varies according to the length of the attachment L .
71	$50 < L \leq 80\text{mm}$		
63	$80 < L \leq 100\text{mm}$		
56	$L > 100\text{mm}$		
71	$L > 100\text{mm}$ $\alpha < 45^\circ$		2) Longitudinal attachments to plate or tube.
80	$r > 150\text{mm}$		3) Longitudinal fillet welded gusset with radius transition to plate or tube; end of fillet weld reinforced (full penetration); length of reinforced weld $> r$.
90	$\frac{r}{L} \geq \frac{1}{3}$ or $r > 150\text{mm}$		4) Gusset plate, welded to the edge of a plate or beam flange.
71	$\frac{1}{6} \leq \frac{r}{L} \leq \frac{1}{3}$		
50	$\frac{r}{L} < \frac{1}{6}$		

L : attachment length as above

Relevant detail category: $\Delta\sigma_c$

Geometric stresses

Detail category	Constructional detail	Description	Requirements
112		1) Full penetration butt joint.	1) - All welds ground flush to plate surface parallel to direction of the arrow. - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides, checked by NDT. - For misalignment see NOTE 1.
100		2) Full penetration butt joint.	2) - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides. - For misalignment see NOTE 1.
100		3) Cruciform joint with full penetration K-butt welds.	3) - Weld toe angle $\leq 60^\circ$. - For misalignment see NOTE 1.
100		4) Non load-carrying fillet welds.	4) - Weld toe angle $\leq 60^\circ$. - See also NOTE 2.

Orthotropic bridge deck

- Pentele bridge, Dunaújváros



Orthotropic bridge deck

- Pentele bridge, Dunaújváros



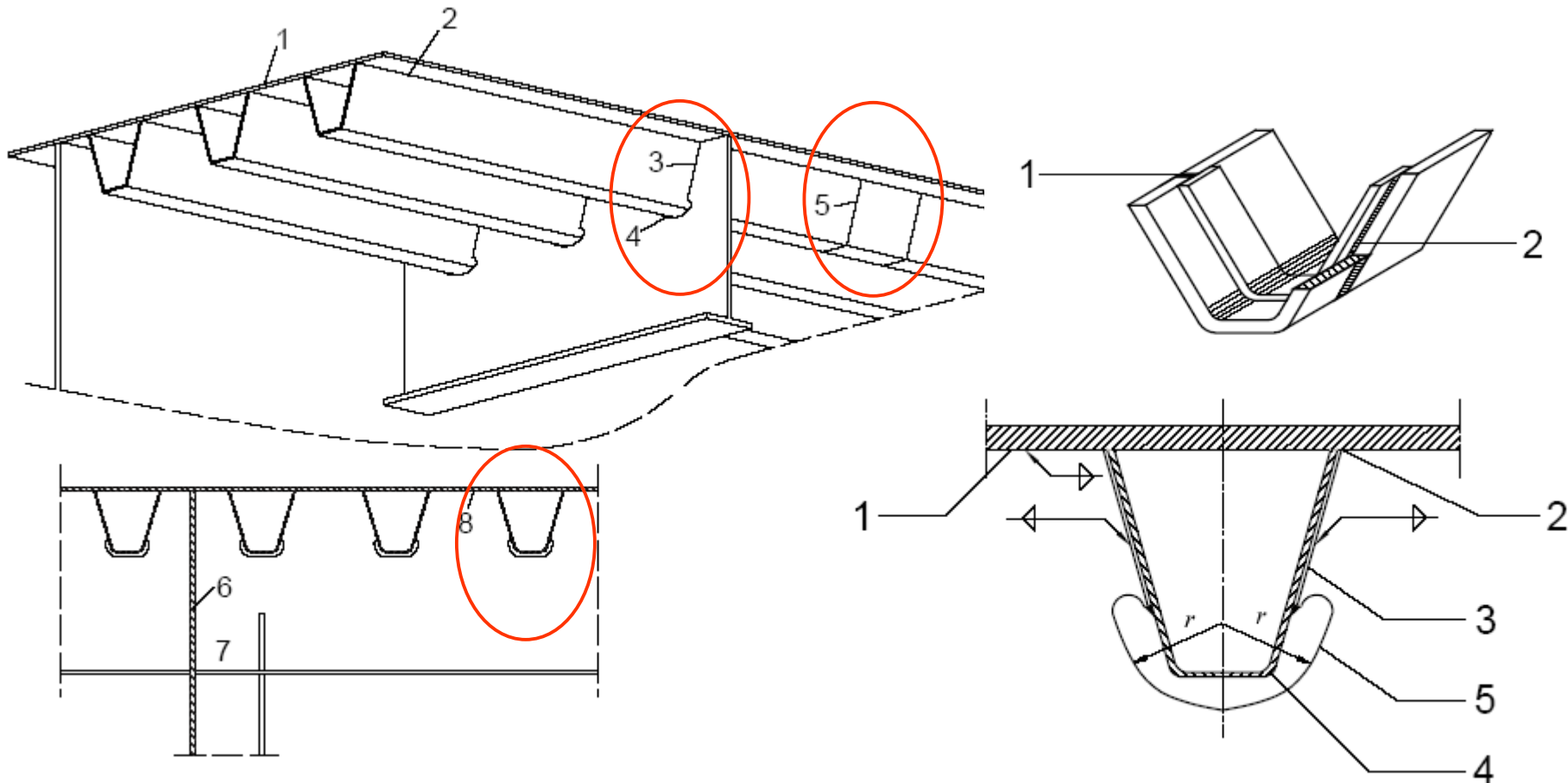
Orthotropic bridge deck

- Pentele bridge, Dunaújváros



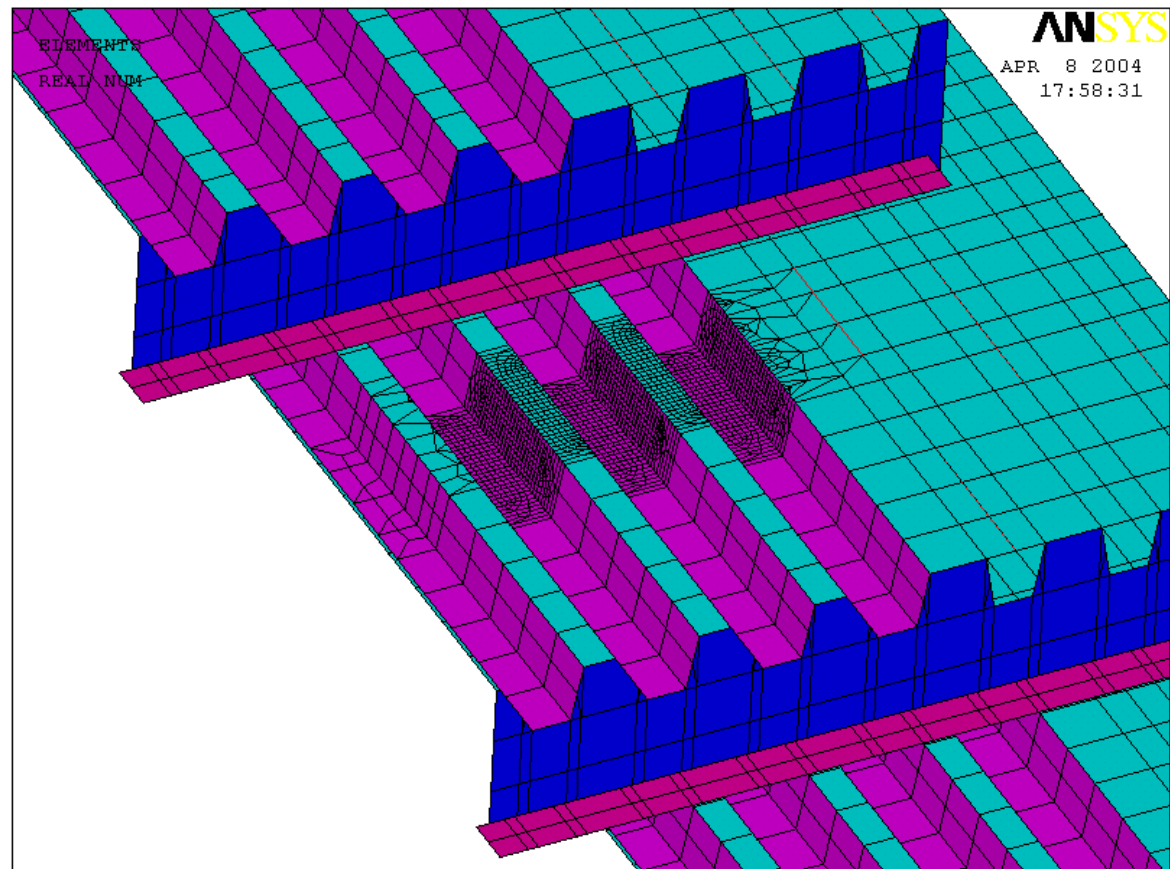
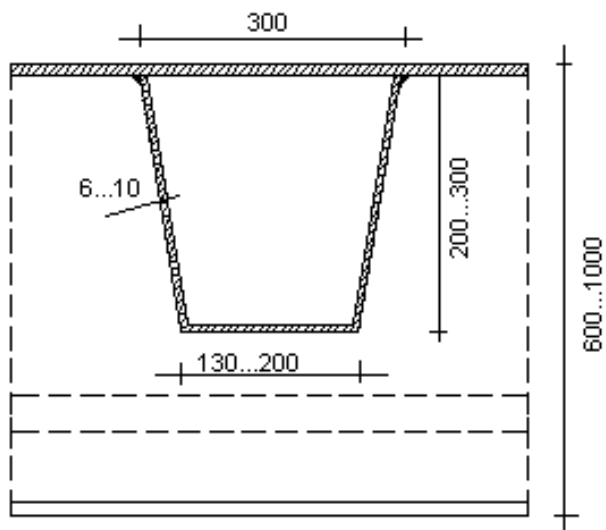
Orthotropic bridge deck

- Ribs → particular fatigue-sensitive parts



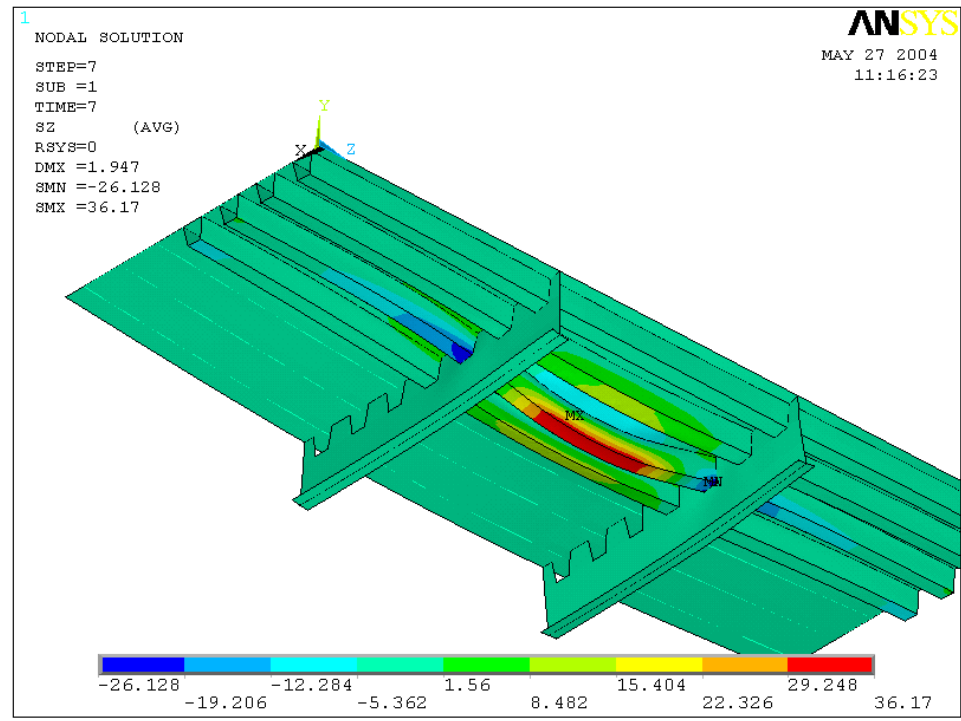
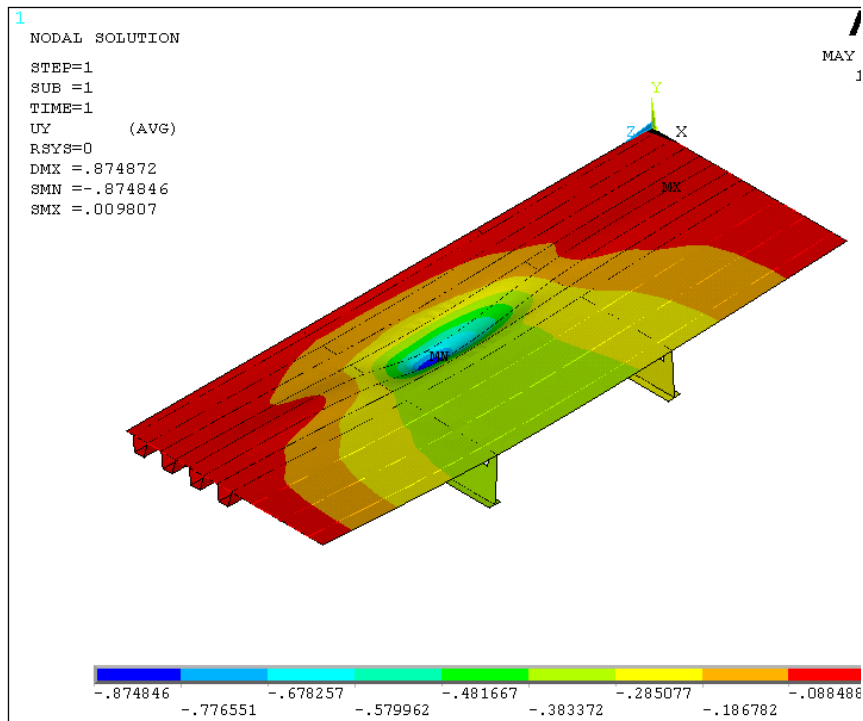
Orthotropic bridge deck

- Submodels and details



Orthotropic bridge deck

- FLM 2 type loading, stresses

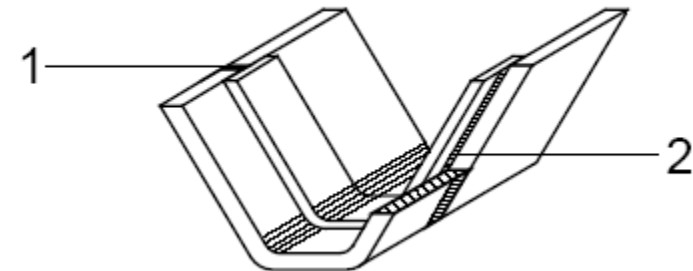


Orthotropic bridge deck

- Stress ranges at the butt weld on the rib

Vehicle type	[MPa]	[MPa]	$\Delta\sigma_i$ [MPa]
A	18,13	-4,47	22,70
B	27,44	-6,92	34,36
C	22,66	-5,72	28,38
B+B	32,04	-10,12	42,16
C+C	28,35	-8,89	37,24
C+C+C	28,10	-10,79	38,89

$$\Delta\sigma_D = 52 \text{ MPa}$$

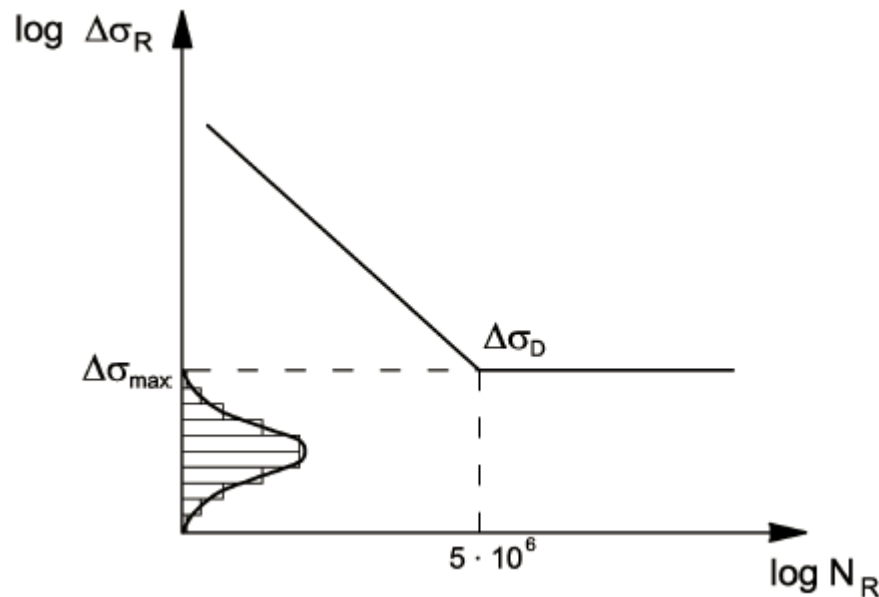


Orthotropic bridge deck

- Simplified fatigue analysis (Dunaújváros)

$$\Delta\sigma_{i,\max} = 42 \text{ MPa}$$

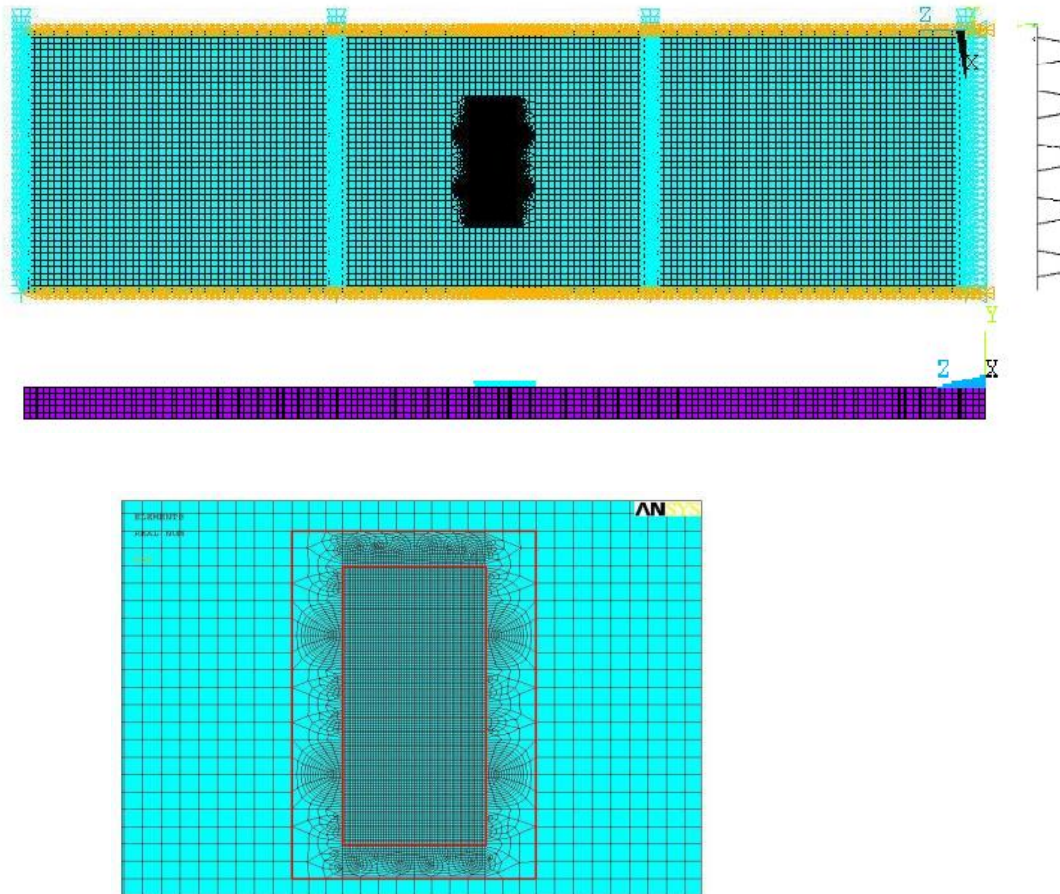
$$\Delta\sigma_D = 52 \text{ MPa}$$



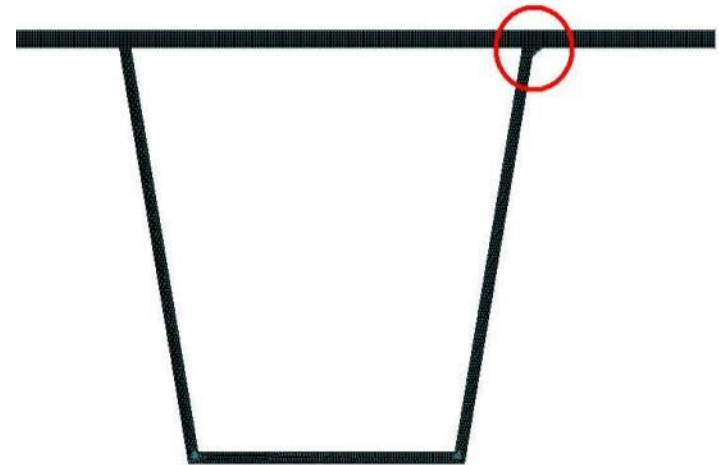
$$\gamma_{Ff} \cdot \Delta\sigma_{\max} \leq \Delta\sigma_D / \gamma_{Mf}$$

Orthotropic deck – two-level-model

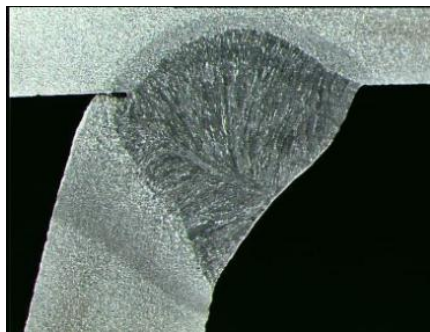
Global model - shell



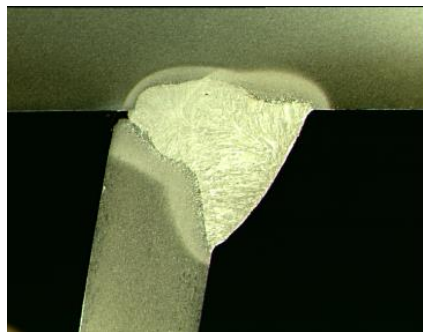
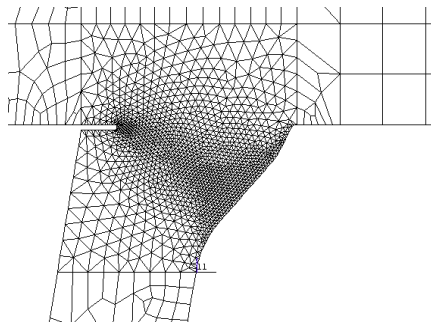
Local model – plane strain



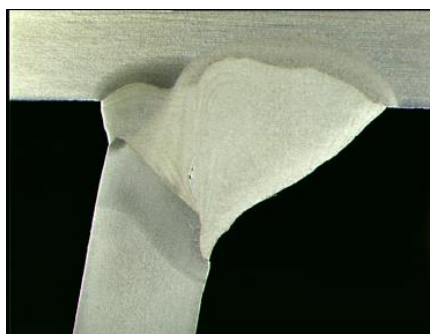
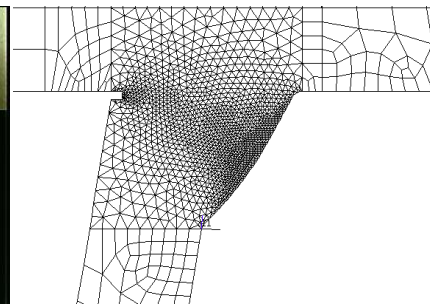
Weld shape and FEM model



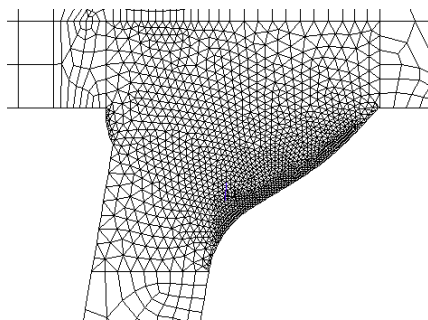
2. weld



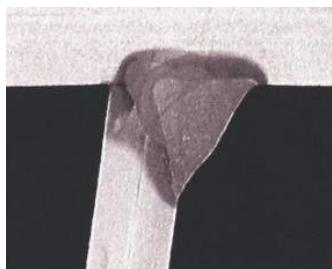
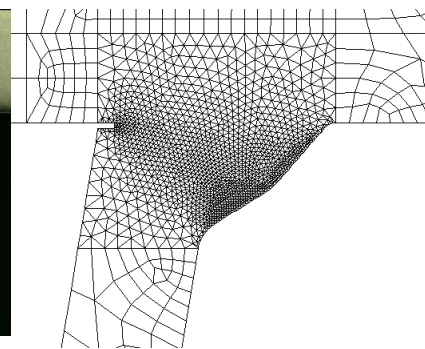
3. weld



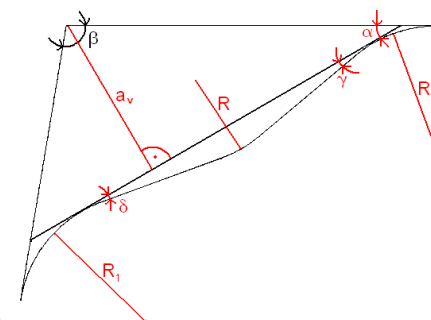
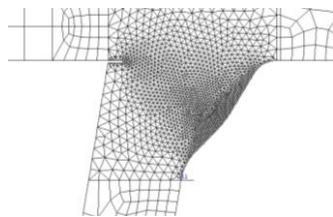
4. weld



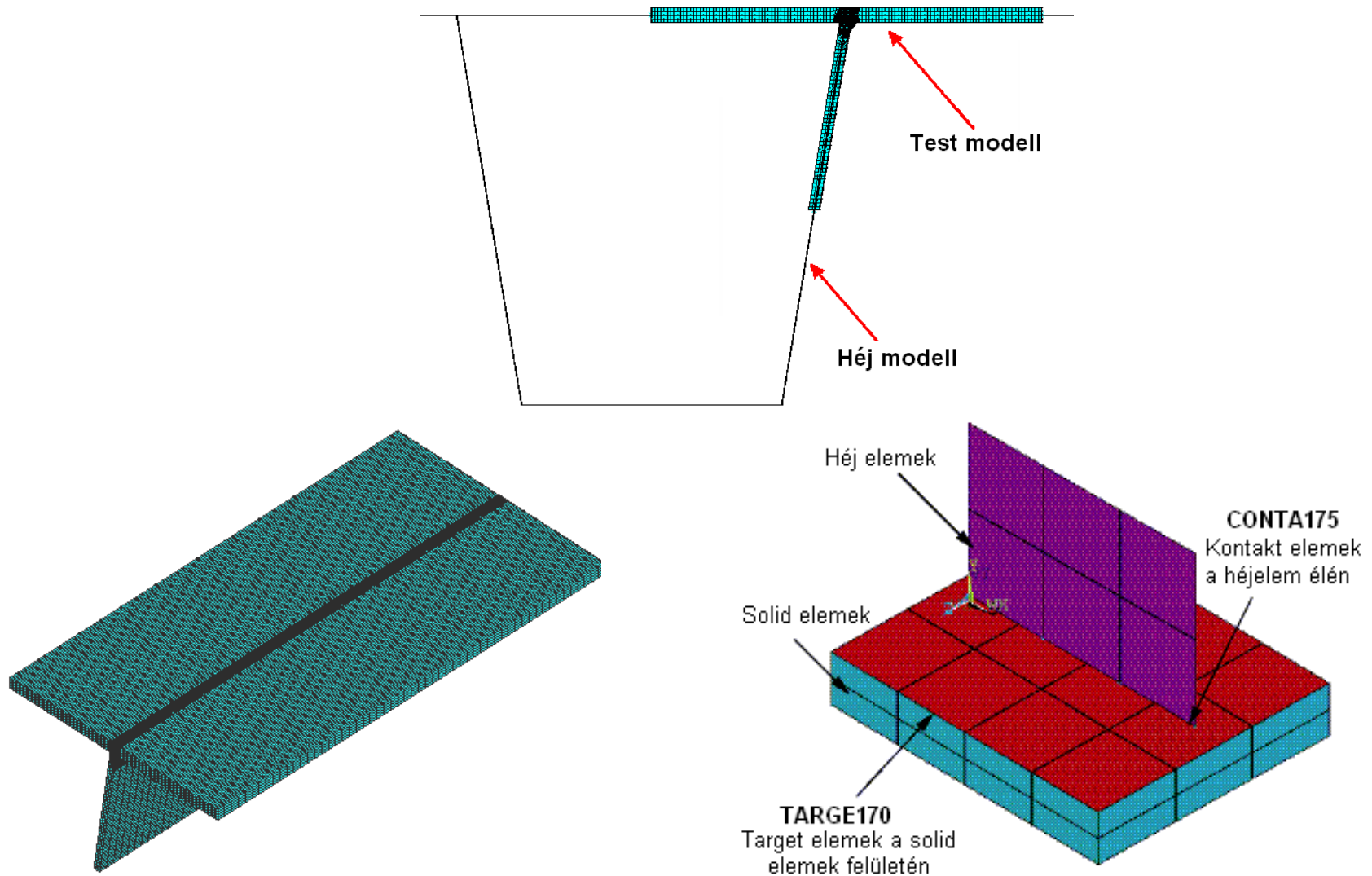
5. weld



6. weld



Global mixed solid-shell model



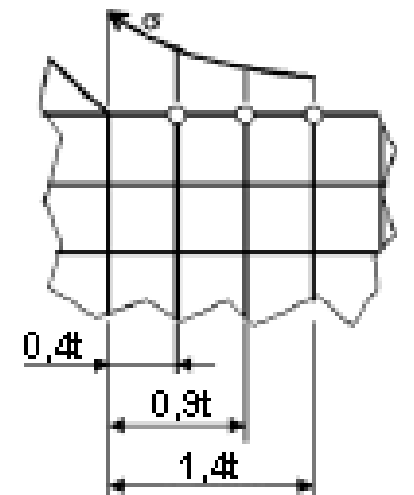
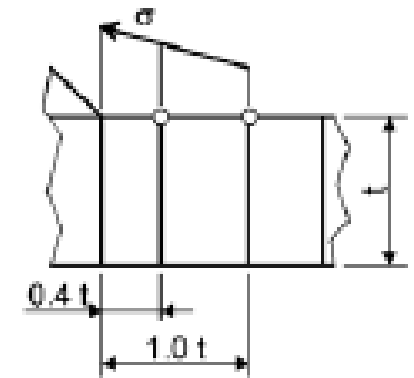
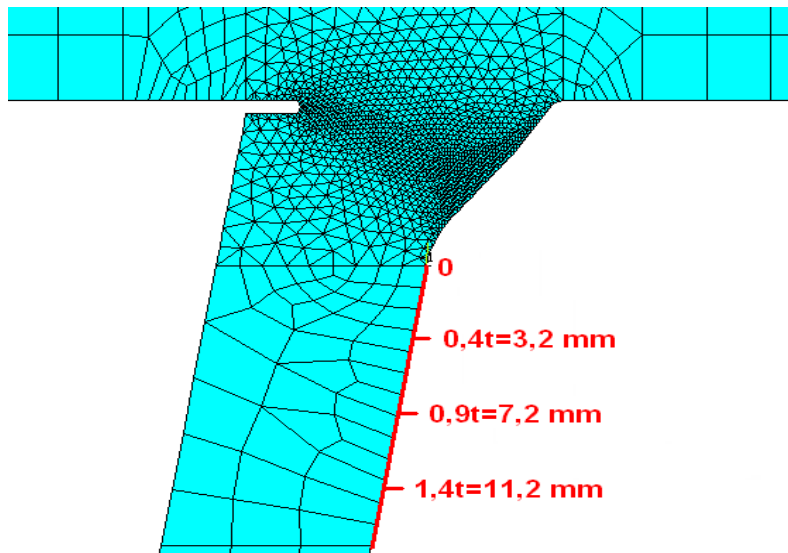
Geometric stress - IIW

- „Fine” mesh: element size $< 0,4t$

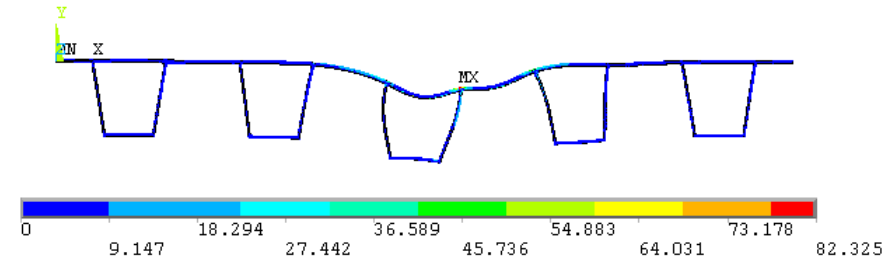
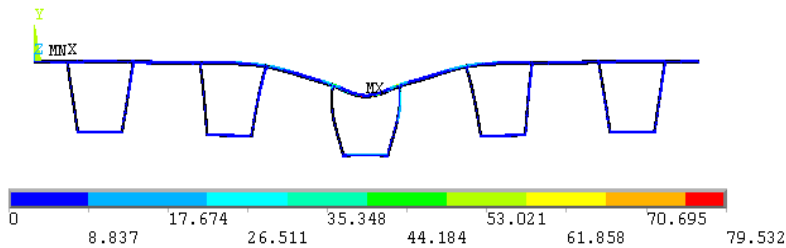
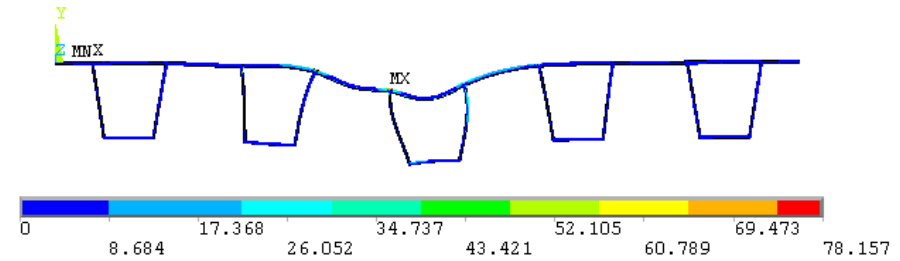
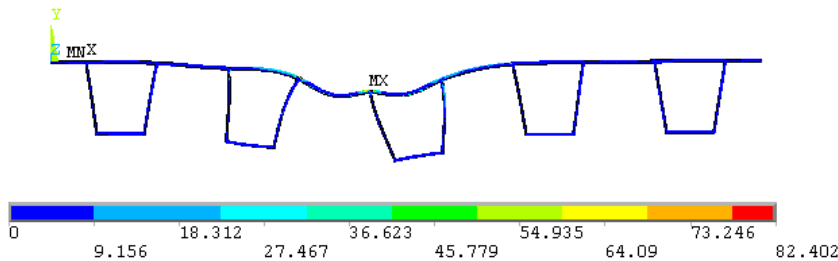
$$\sigma_{hs} = 1,67\sigma_{0,4t} - 0,67\sigma_{1,0t}$$

- „Fine” mesh: element size $< 0,4t$

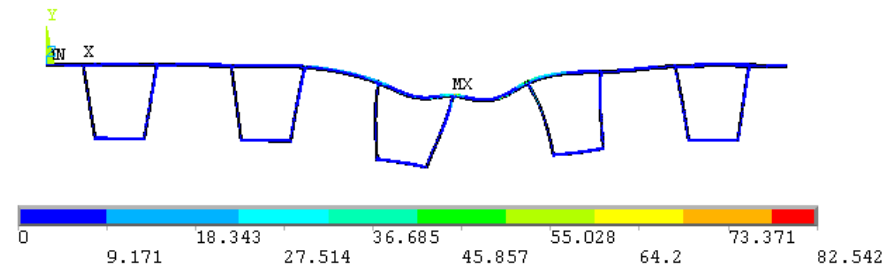
$$\sigma_{hs} = 2,52\sigma_{0,4t} - 2,24\sigma_{1,0t} + 0,72\sigma_{1,4t}$$



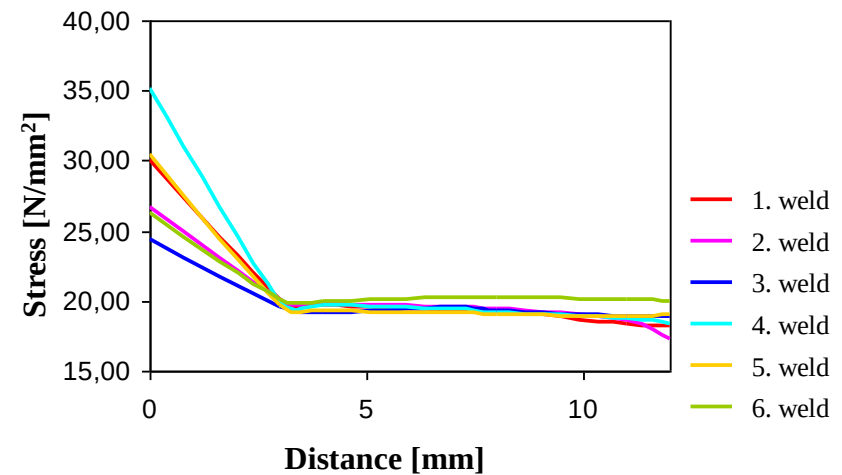
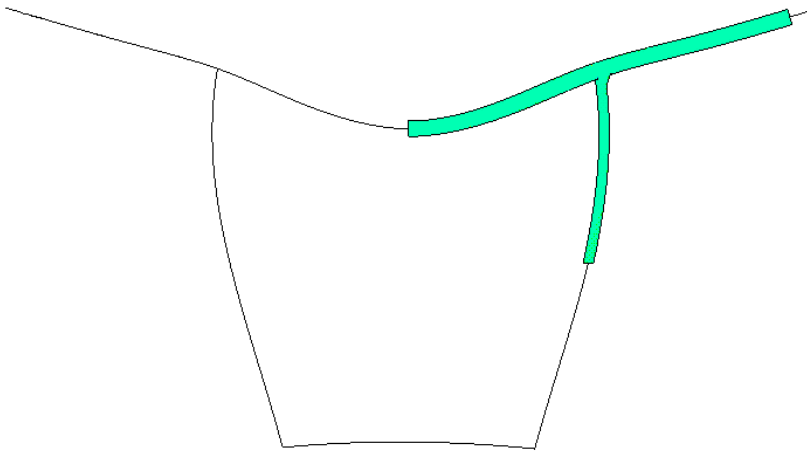
Load cases – cross section



„C” wheel (90 kN)

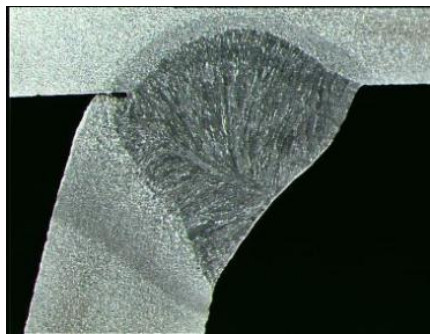


Solid – shell model

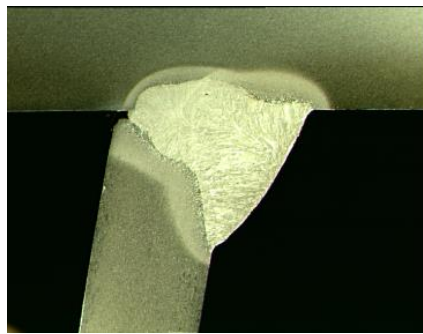
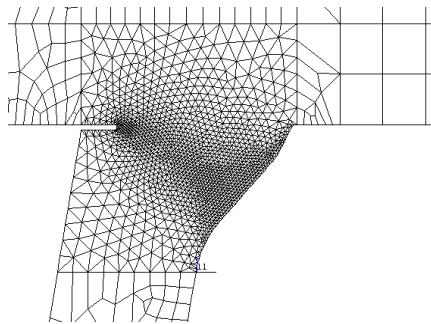


Solid-shell model							Local model						
Kerék	kN		Linear	2 nd order	Weld toe	MAX	Kerék	kN		Linear	2 nd order	weld toe	MAX
B	150	1	20,61	20,52	30,08	44,52	B	150	1	33,91	37,95	41,31	54,98
		2	20,33	19,60	26,70	44,01			2	33,23	33,17	37,82	50,04
		3	19,55	19,05	24,36	33,56			3	35,73	36,51	38,59	44,33
		4	20,41	20,11	35,17	44,23			4	35,04	34,54	49,62	58,59
		5	20,04	20,36	30,45	46,07			5	34,63	34,90	43,88	60,10
		6	20,07	19,95	26,24	39,48			6	33,93	33,51	38,92	48,66

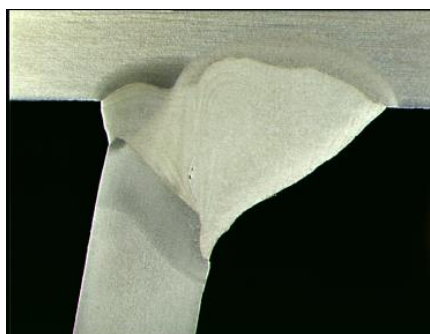
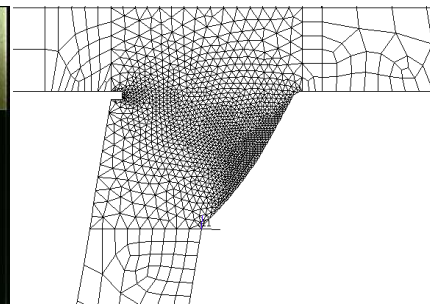
Weld shape and FEM model



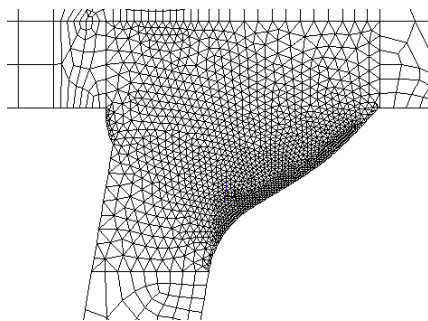
2. weld



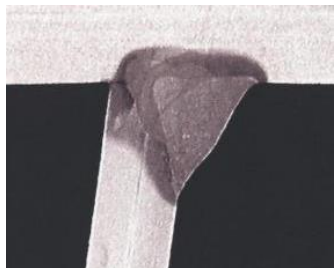
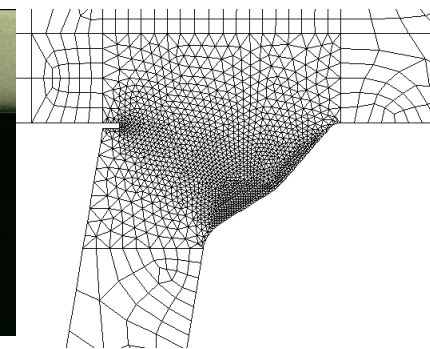
3. weld



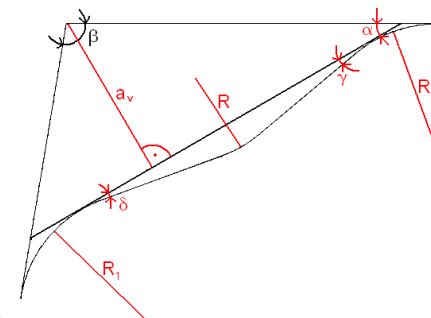
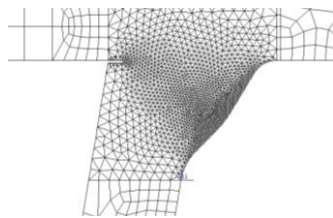
4. weld



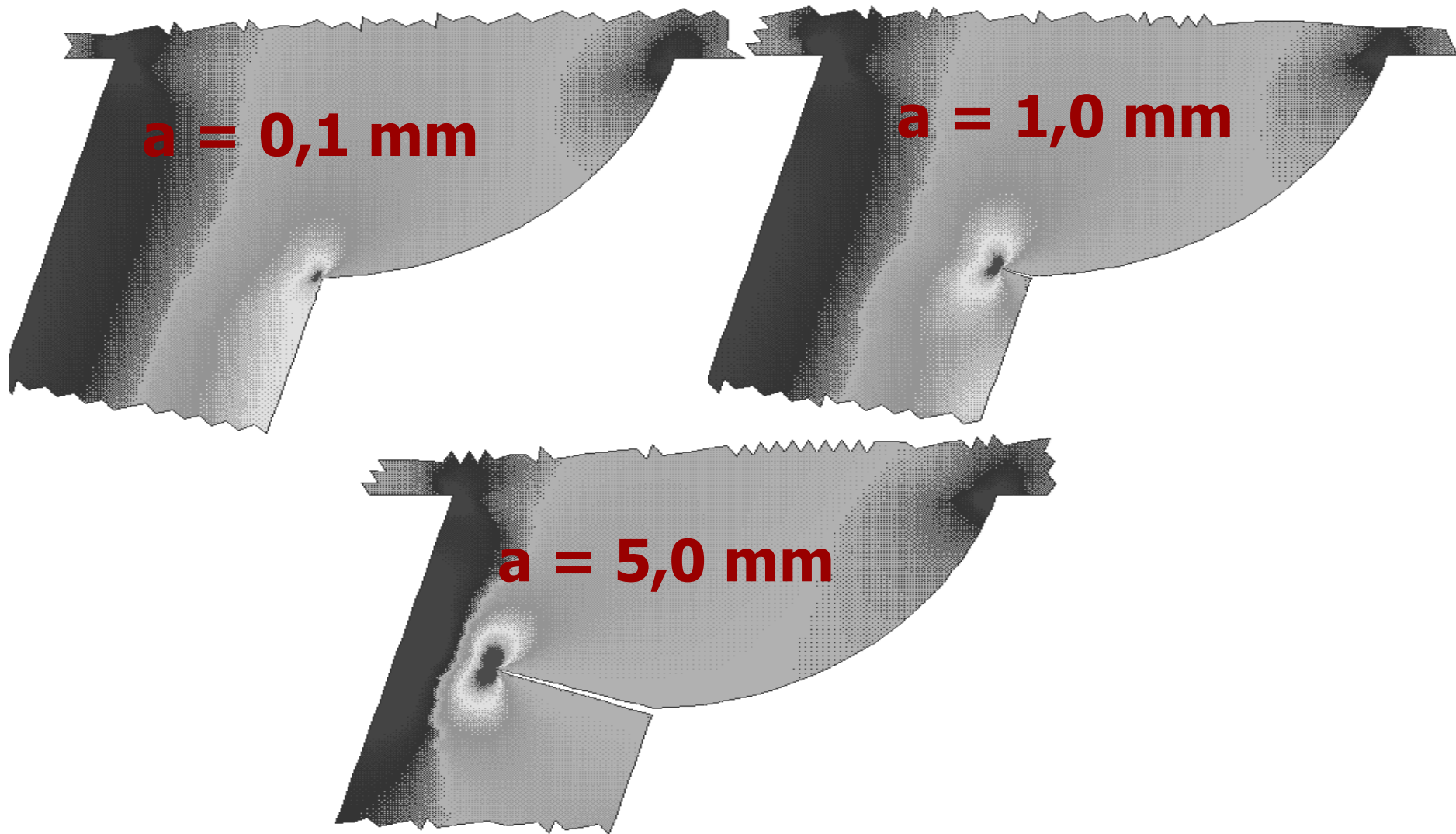
5. weld



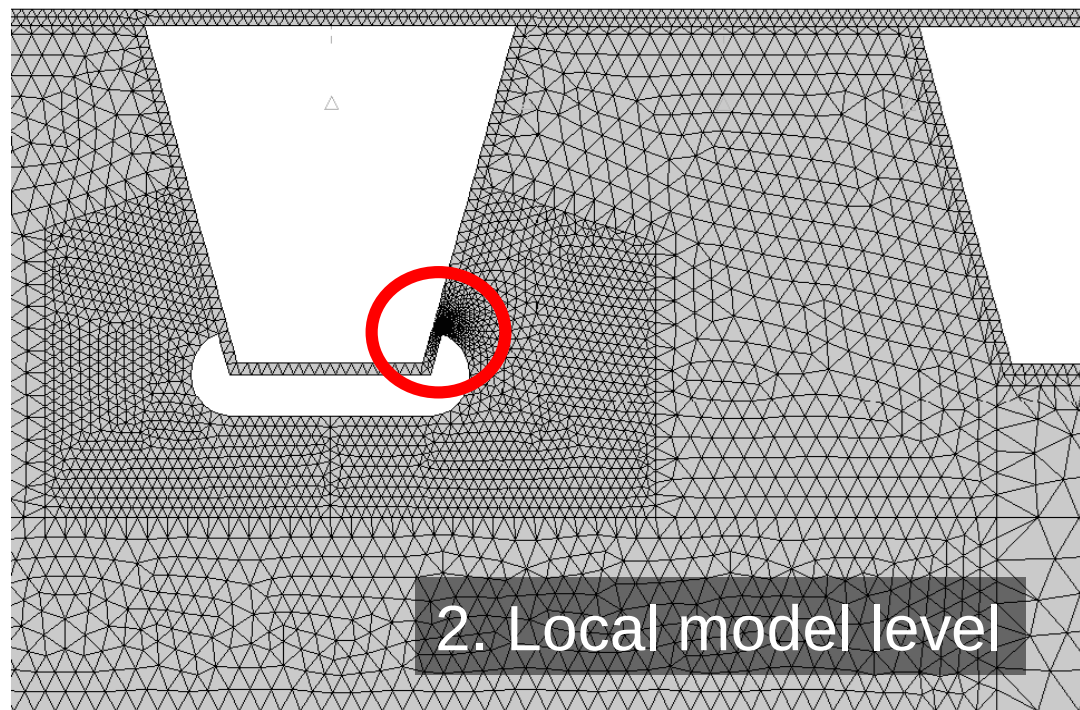
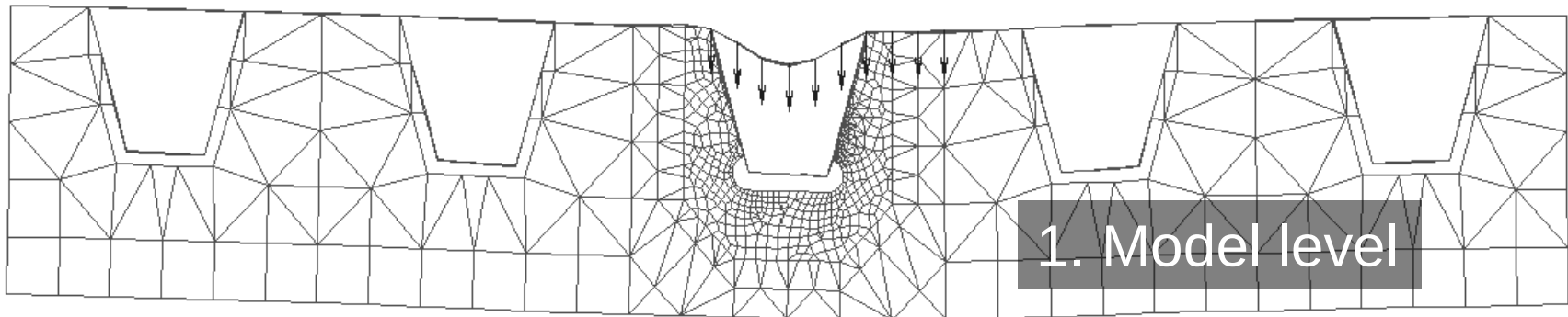
6. weld

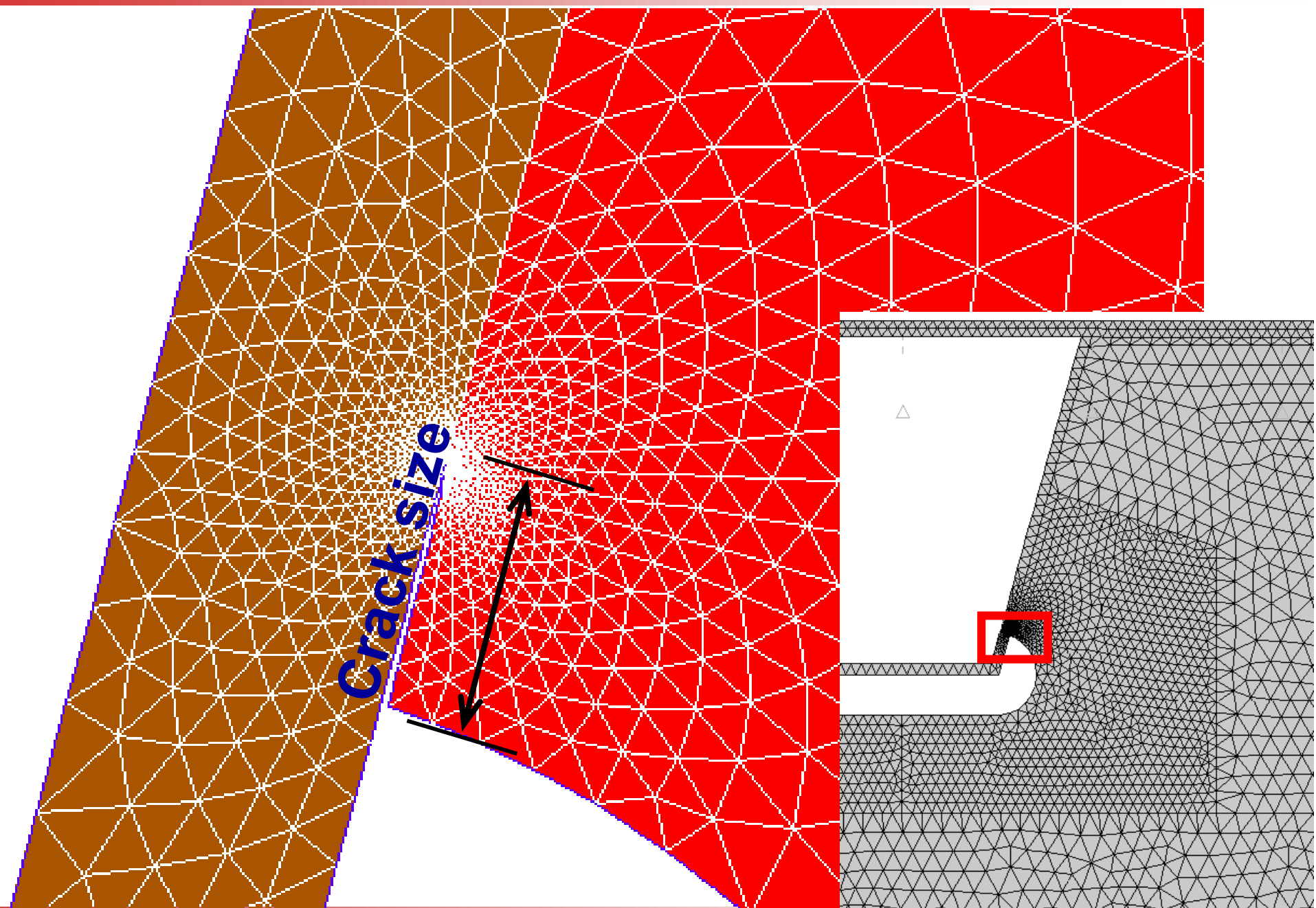


Crack models – fracture mechanics

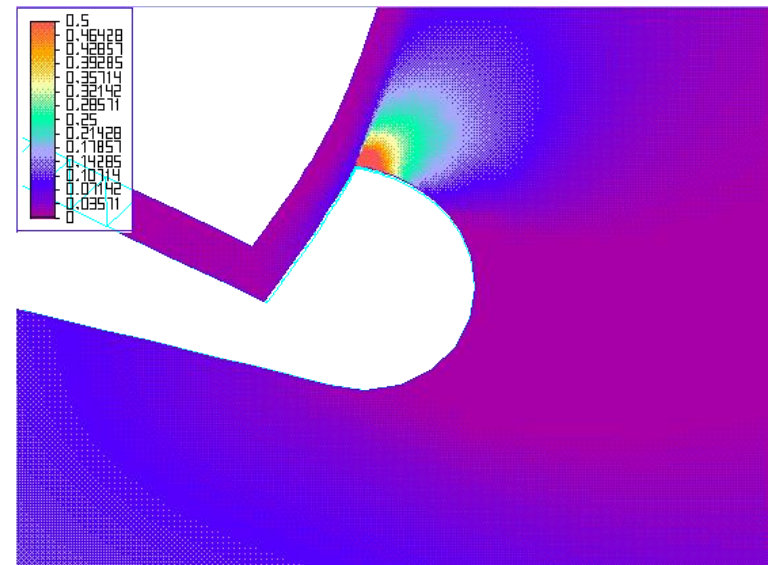
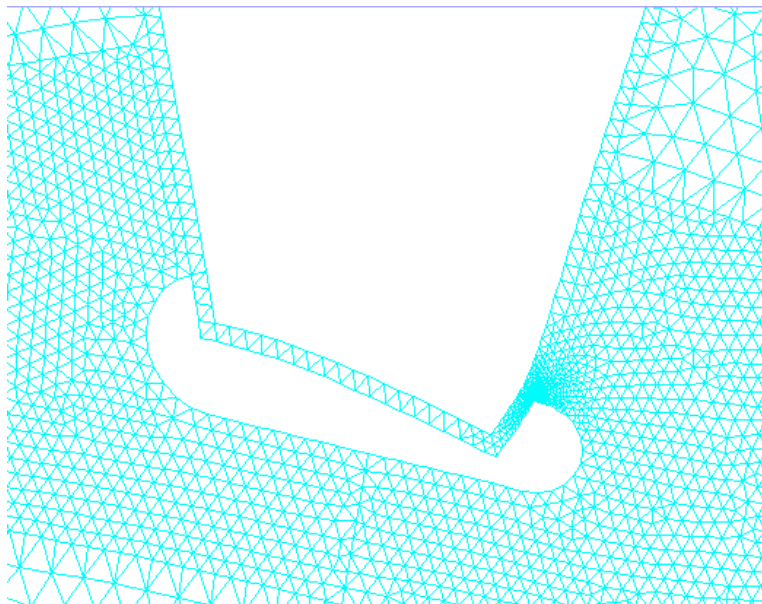
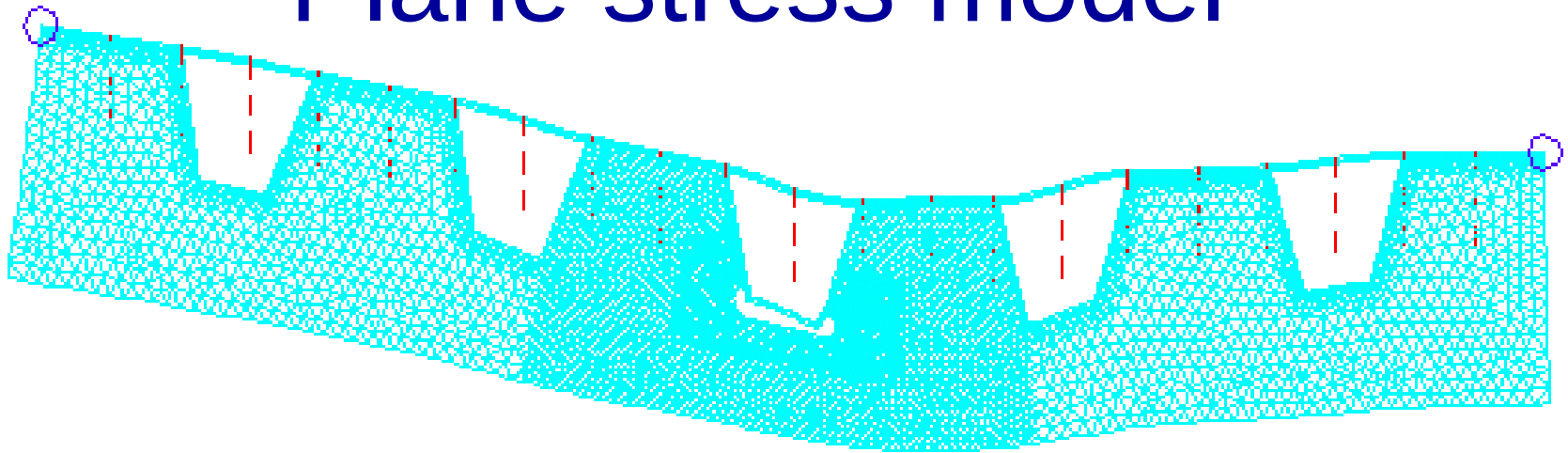


Stiffener – cross beam detail





Plane stress model



Railway bridge over the Danube



Railway bridge over the Danube



Observed failures in the bridge

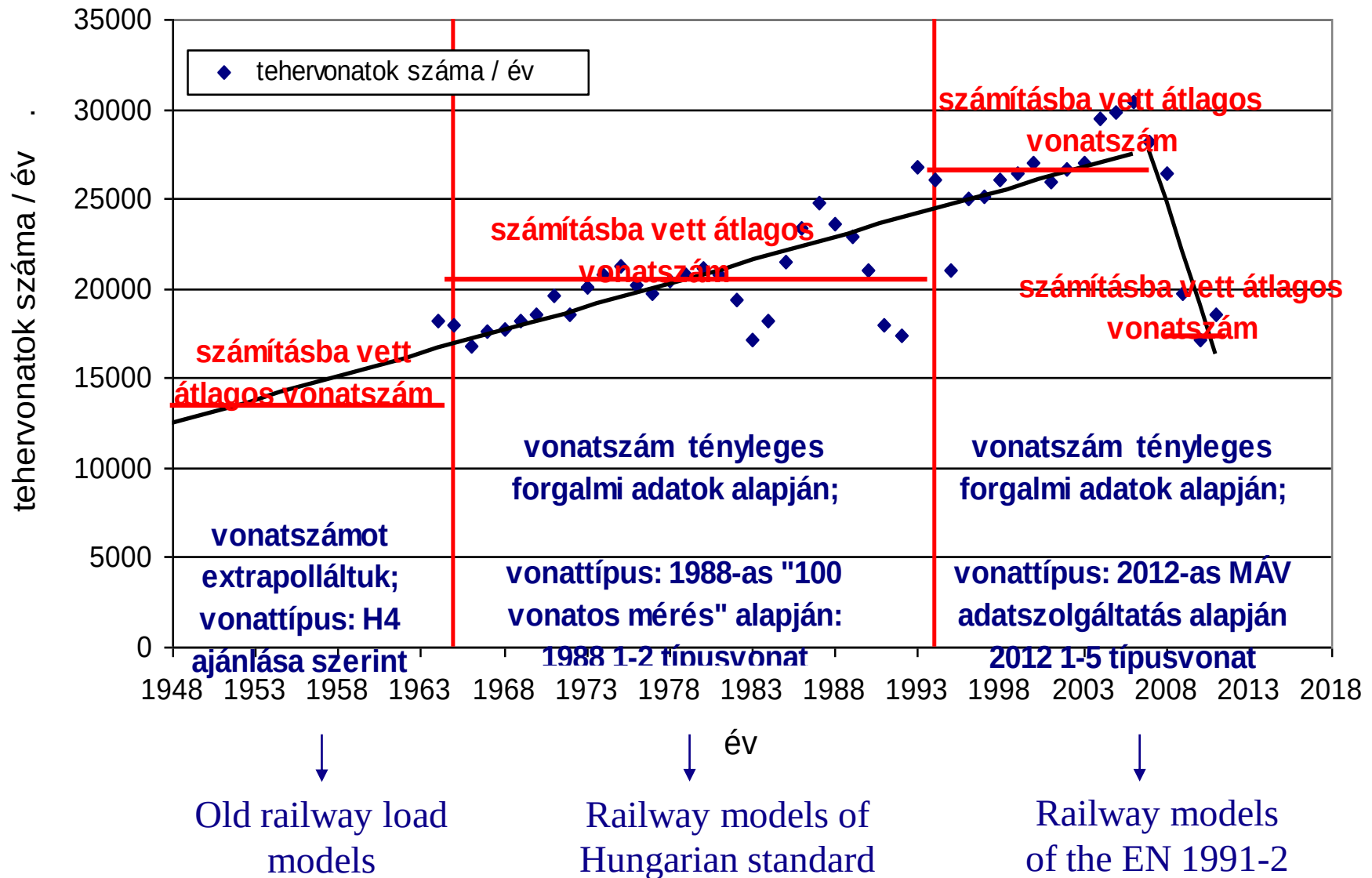
- Corrosion in the main girders - cracks in the stringers



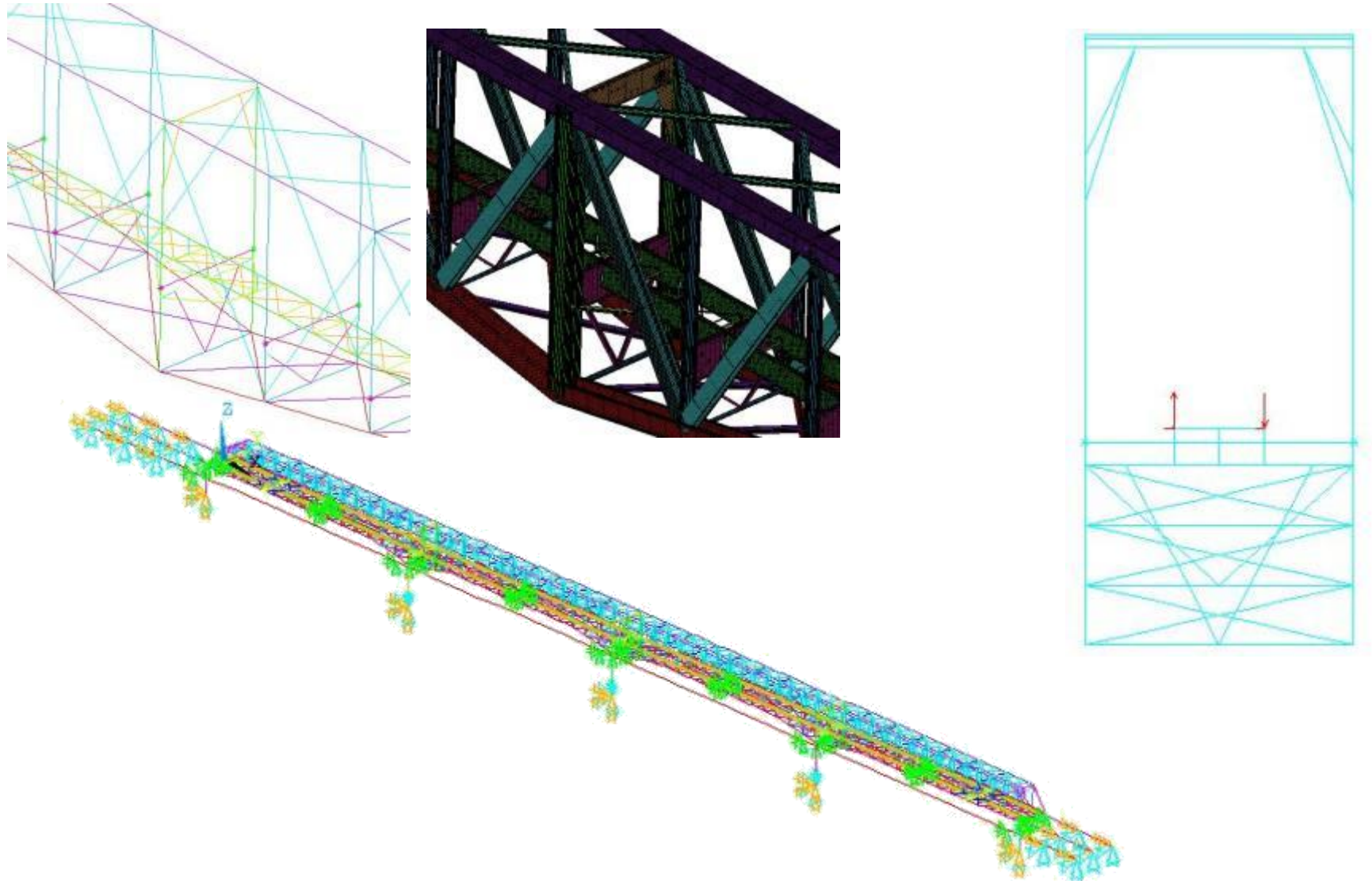
Fatigue cracks in the stringers



Real traffic volume during lifetime



FE model of the bridge

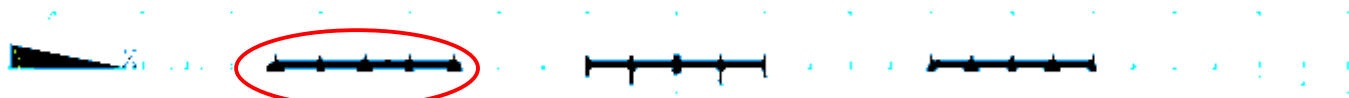


Three stage model of the bridge

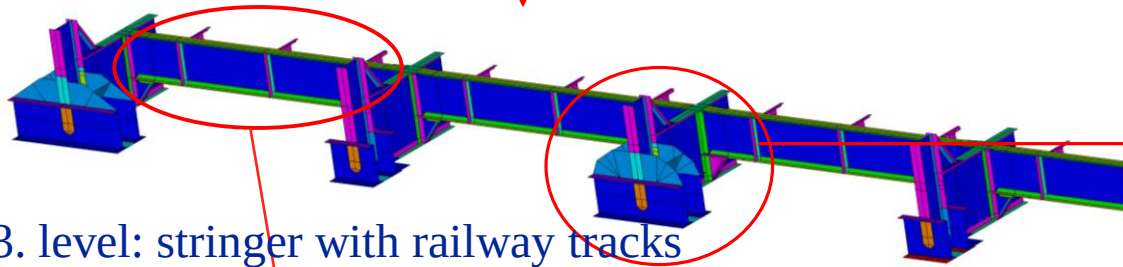
-Shell model integrated in the global beam model
main girder; deck system; joint analysis

-Local model using volume elements

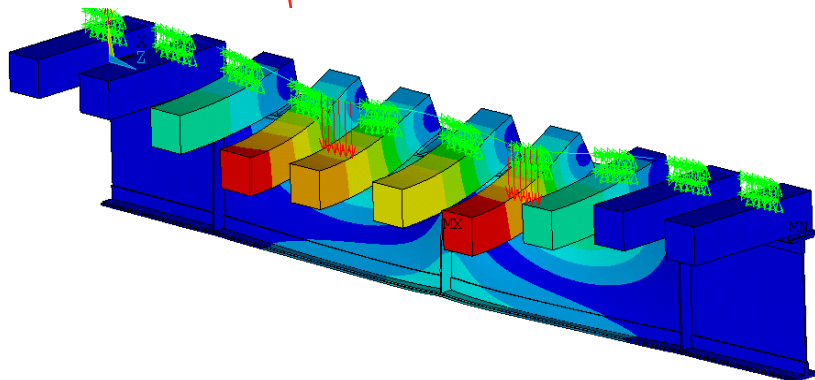
1. level: upper flange of the stringer – crack propagation analysis



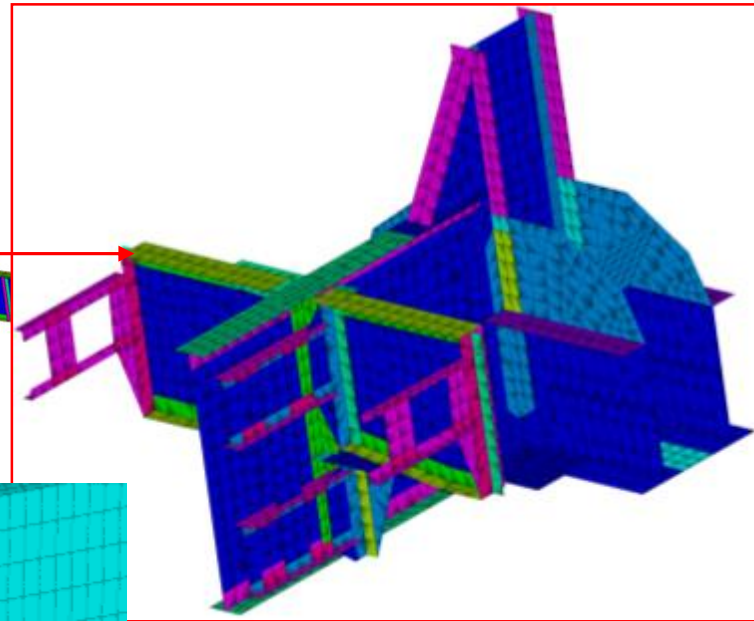
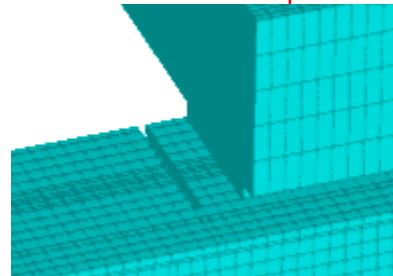
2. level: main girder and deck system parts



3. level: stringer with railway tracks



Crack model



Validation of the model

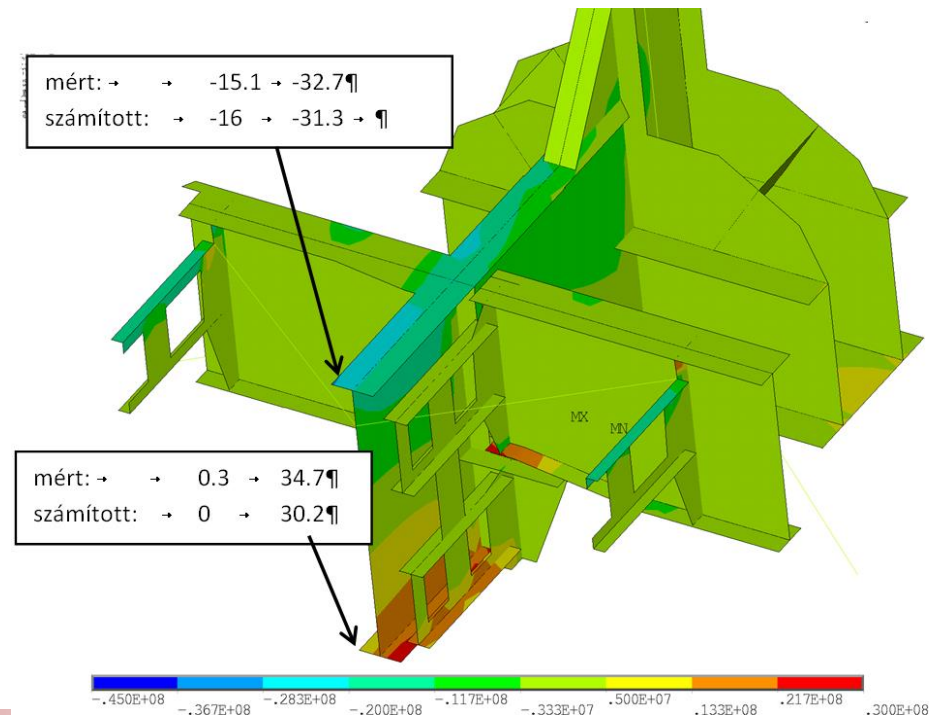
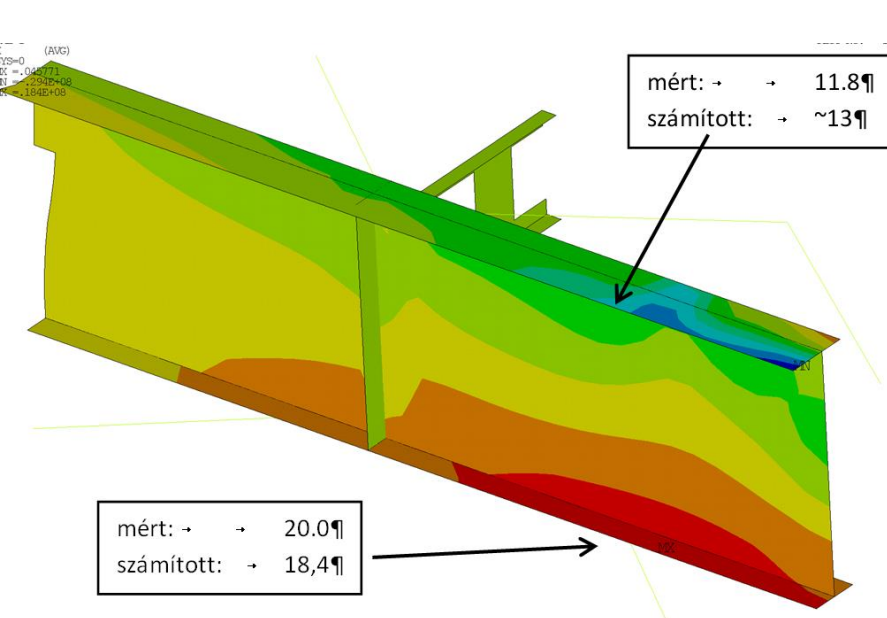
Loading tests results (1995 and 1997 using 4 M62 locomotives)

Lehajlások összehasonlítása: (átlagolt, múlt)

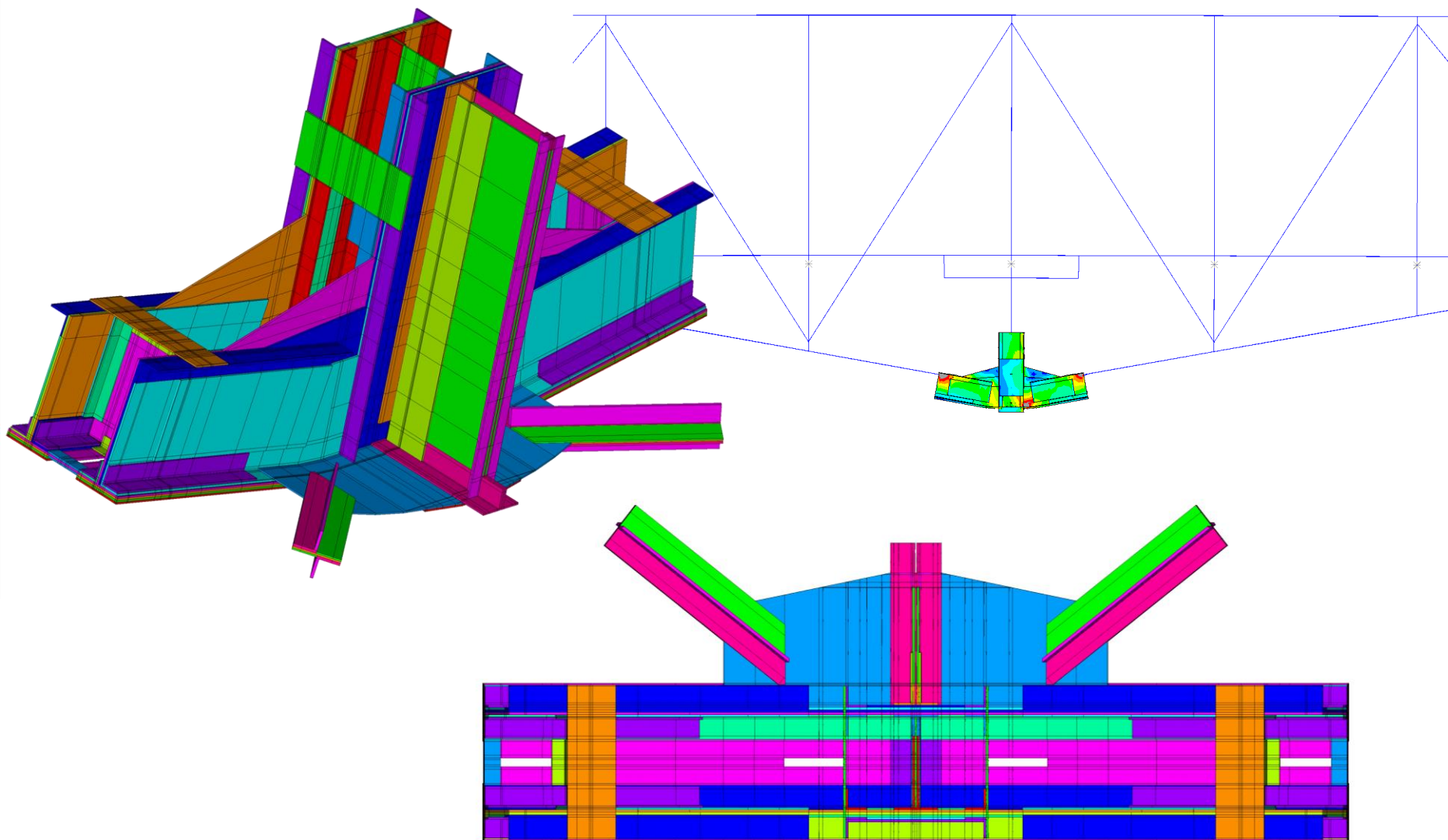
R	M1-teherállás				M2-teherállás			
	mért	kéz	gépi	eltérés	mért	kéz	gépi	eltérés
6R	40.3	45.54	42.8	106%	13.3	15.19	13.9	102%
22R	14.6	17.35	16.7	114%	36.6	42.62	38.2	104%

Rúderök összehasonlítása

7-8-övrúd: → → mért: 3024 kN → számított: 2980 kN → → eltérés: 98%



Local shell model of critical joints



Fatigue check

1. Based on real traffic data
2. Based on EN 1991-2

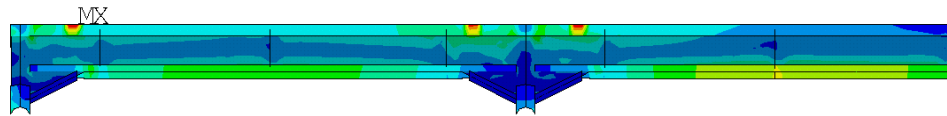
} → Linear damage theory

Analysed structural details:

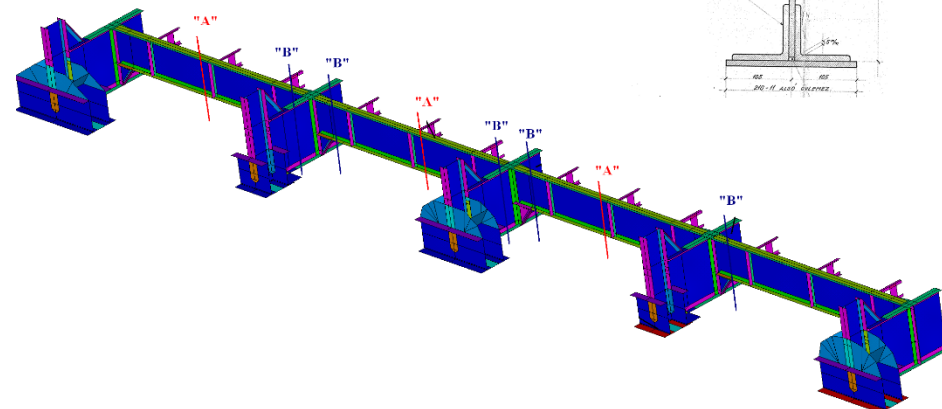
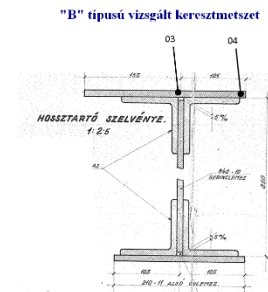
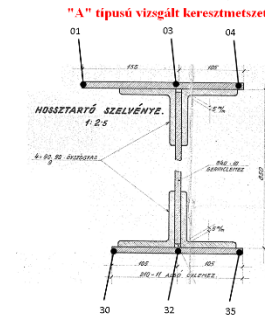
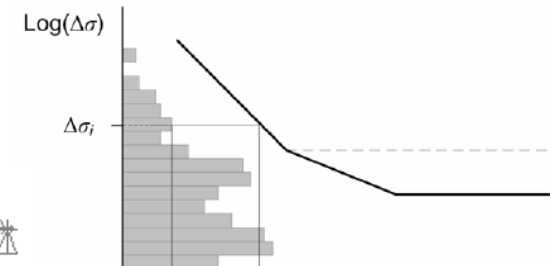
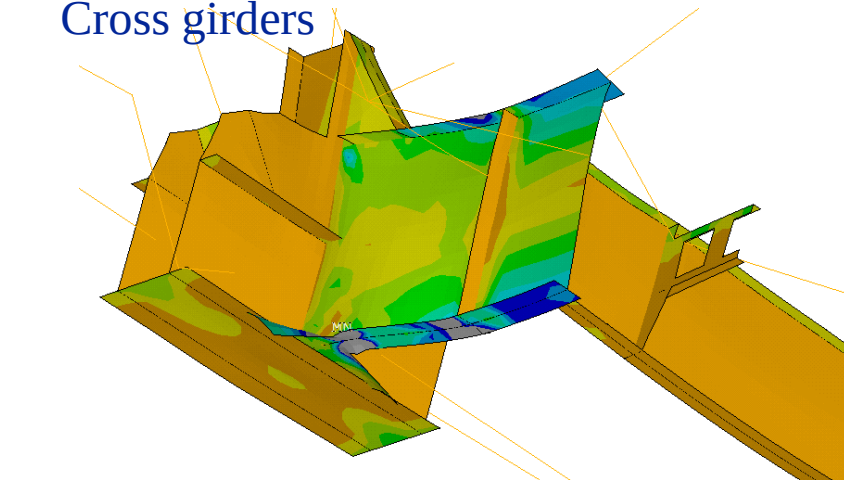
Main girder:



Bridge deck system: Stringers

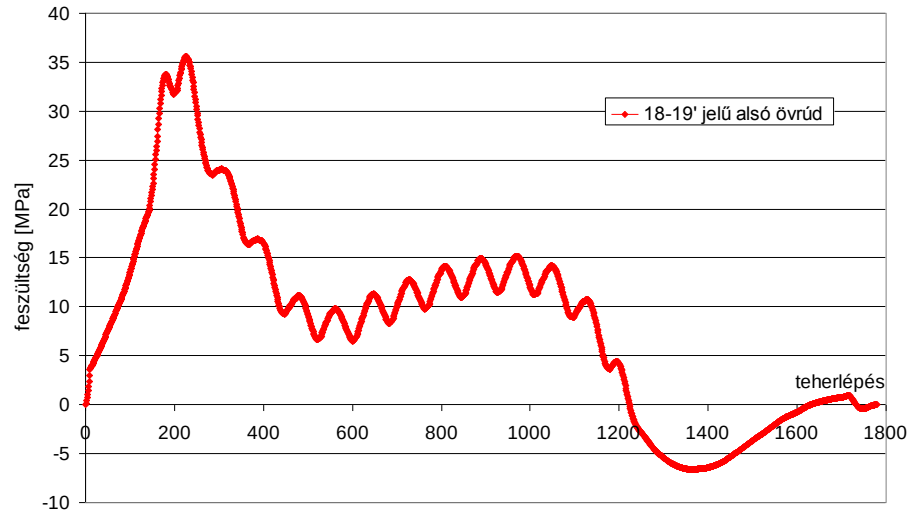


Cross girders

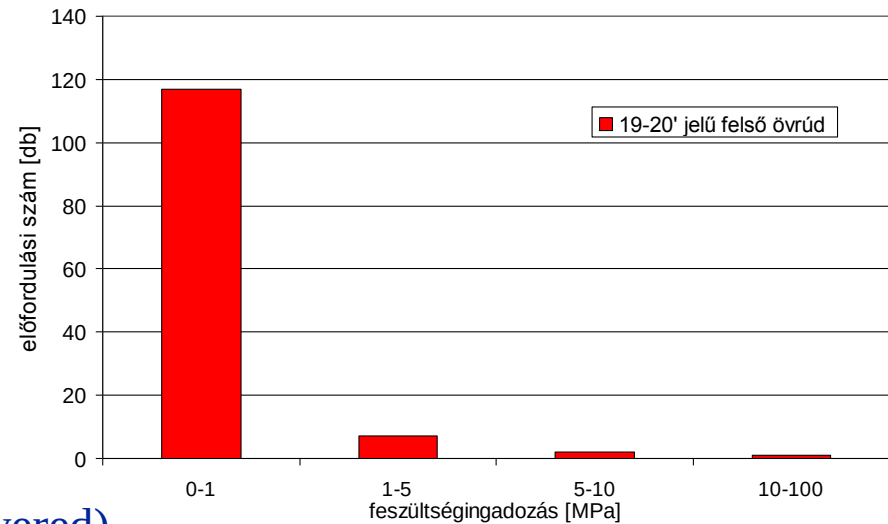


Fatigue assessment process

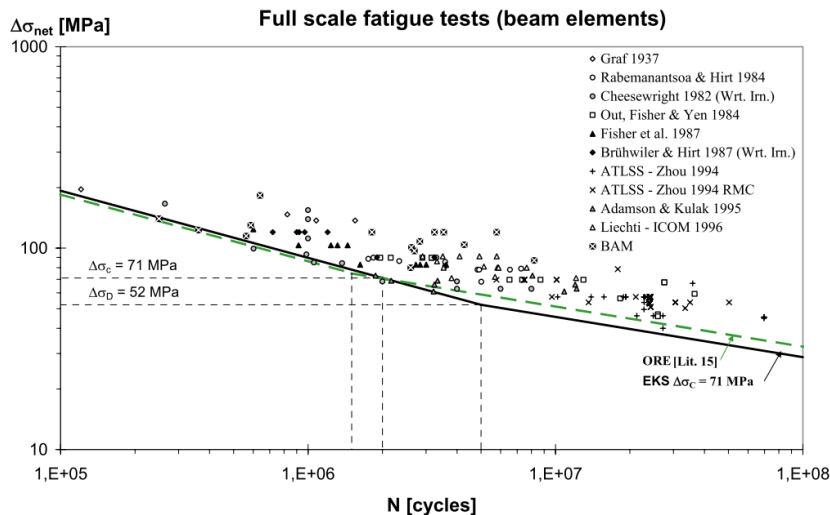
Load stress history



Stress range spectra



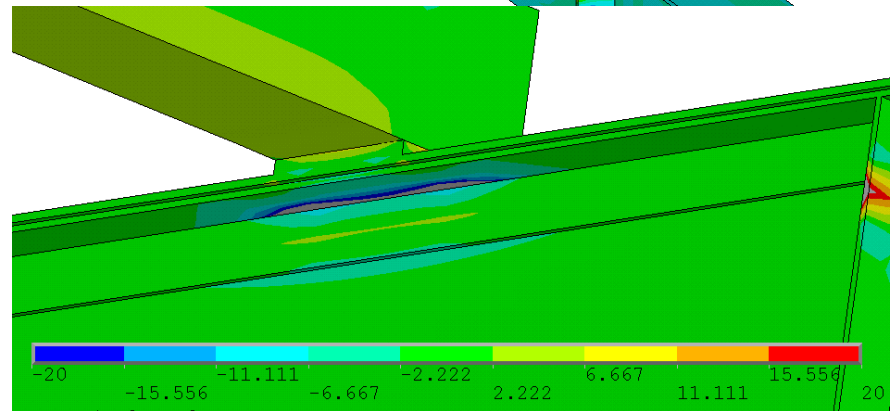
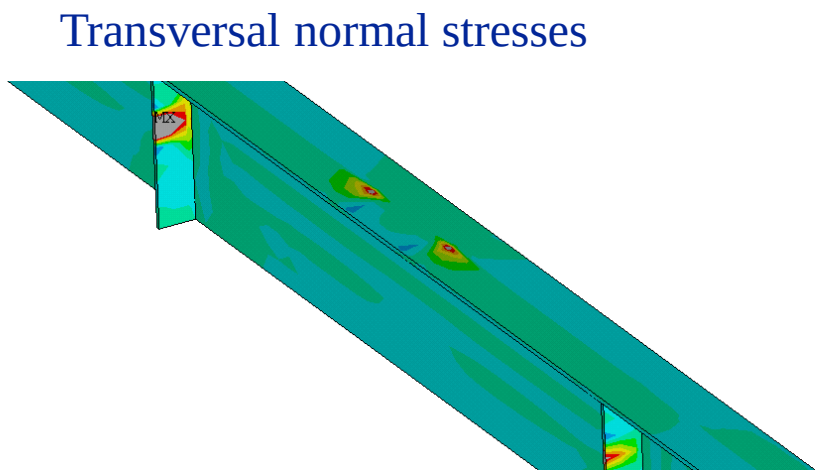
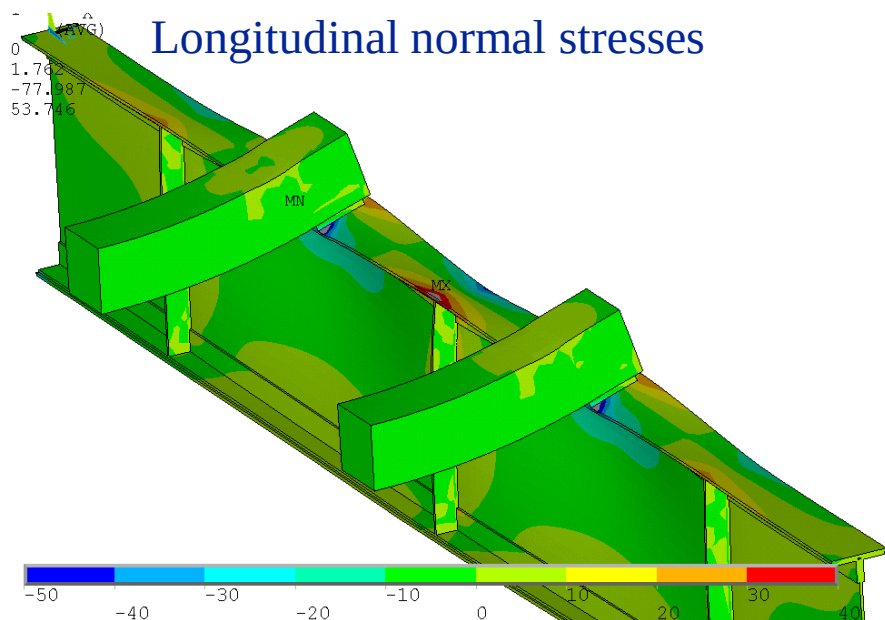
S-N curve for old riveted bridges (corrosion covered)



- S-N curve 71 (international literature)

Based on large test database

Analysis of stress concentration



Real crack pattern



Result of the fatigue check

Főtartó - alsó övrúd 18-19 csp. között

$\Delta\sigma_{\text{brutto,max}} = 83$ MPa	fáradási osztály $\Delta\sigma_c$	γ_{mf}	károsodás mértéke	
			bruttó km.	nettó km. + korrózió
$A_{\text{brutto}} = 589\text{cm}^2$	71	1,35	0,27	0,48
$A_{\text{netto}} = 512\text{cm}^2$		1,15	0,16	0,29

Főtartó - felső övrúd 19-20 csp. között

$\Delta\sigma_{\text{brutto,max}} = 76$ MPa	fáradási osztály $\Delta\sigma_c$	γ_{mf}	károsodás mértéke	
			bruttó km.	nettó km. + korrózió
$A_{\text{brutto}} = 578\text{cm}^2$	71	1,35	0,21	0,37
$A_{\text{netto}} = 489\text{cm}^2$		1,15	0,12	0,22

Keresztartó - alsó övlemez hosszartó bekötésnél

$\Delta\sigma_{\text{brutto,max}} = 70$ MPa	fáradási osztály $\Delta\sigma_c$	γ_{mf}	károsodás mértéke	
			bruttó km.	nettó km. + korrózió
Bruttó/nettó km inercia aránya: 1,25	71	1,15	0,28	0,68
		1,00	0,21	0,42

$\Delta\sigma_{\text{brutto,max}} = 140$ MPa	fáradási osztály $\Delta\sigma_c$	γ_{mf}	mértéke valós forgalom alapján	
			bruttó km.	nettó km. + korrózió
Bruttó/nettó km inercia aránya: 1,25	71	1,15	1,64	
		1,00	0,71	

Hosszartó - alsó öv

$\Delta\sigma_{\text{brutto,max}} = 69$ MPa	fáradási osztály $\Delta\sigma_c$	γ_{mf}	károsodás mértéke	
			bruttó km.	nettó km. + korrózió
Bruttó/nettó km inercia aránya: 1,23	71	1,15	0,36	1,03
		1,00	0,18	0,53

Hosszartó - felső öv

$\Delta\sigma_{\text{glob,brutto,max}} = 31$ MPa; $\Delta\sigma_{\text{loc,brutto,max}} = 0-32$ MPa	fáradási osztály $\Delta\sigma_c$	γ_{mf}	károsodás mértéke	
			bruttó km.	nettó km. + korrózió
Bruttó/nettó km inercia aránya: 1,23	71	1,15	14,6-0,21	29,9-0,72
		1,00	6,1-0,09	19,9-0,32



Thank you for your attention!