Steel structures, selected chapters

Fatigue: resistance, constructive details

(ref. TGC 10 sections 13.1 and 13.6)

Part 2

RESSLab
Resilient Steel Structures Laboratory - Prof. A. Nussbaumer

Content

- **Fatigue normalized curves**
- **Types of details and diff. resistance curves**
- Bolted, riveted connections
- Welded Connections
- Hot-spot method
- Execution of welds

Reminder: fatigue check format (constant amplitude)

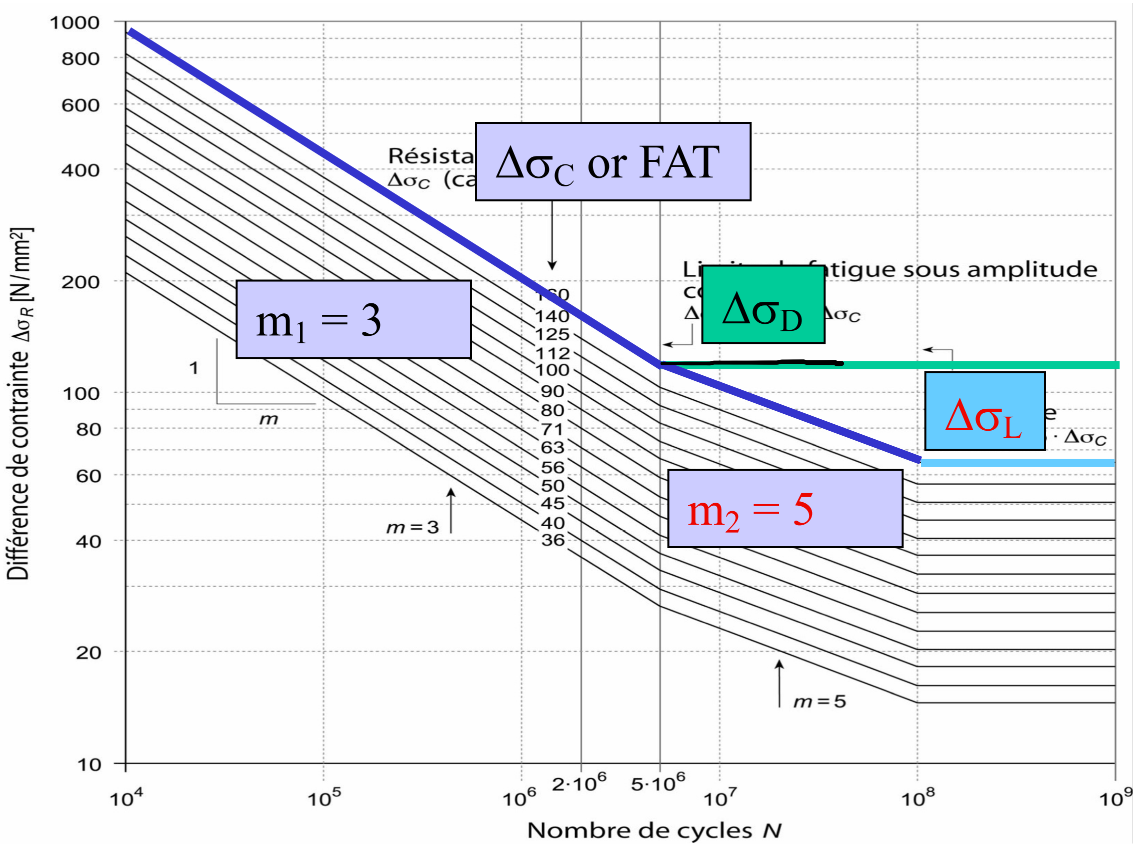
$$E_D \leq R_D \qquad \gamma_{Ff}\Delta\sigma_{E2} \leq \Delta\sigma_C/\gamma_{Mf}$$

- Basis of comparison 2 millions cycles (FAT)
- Action load effects adjusted to 2 millions cycles

$$\Delta\sigma_{E2} = \left(\frac{N}{2\cdot 10^6}\right)^{1/m} \cdot \Delta\sigma_N$$

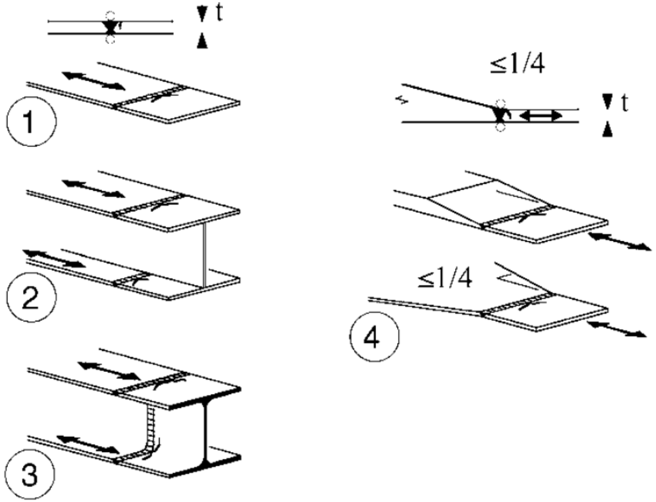
- Fatigue loading factor $\gamma_{Ff} = 1.0$
- Fatigue Resistance factor $\gamma_{Mf} \geq 1.0$

Fatigue resistance curves (SIA, Eurocode 3)



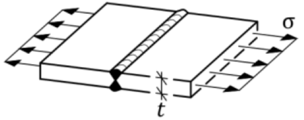
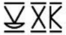
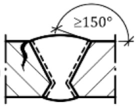
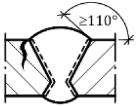
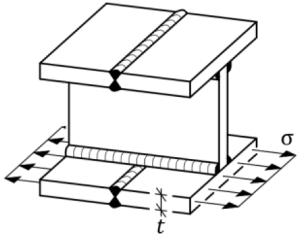
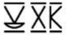
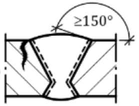
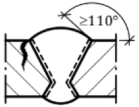
VA Model

EN 1993-1-9: Table of Categories of Detail (extract)

Detail category	Constructional detail		Description	Requirements
FAT $\Delta\sigma_C$ 112	Size effect for t > 25 mm: $\boldsymbol{k_s} = (25/t)^{0,2}$		Without backing bar: 1) Transverse splices in plates and flats. 2) Flange and web splices in plate girders before assembly. 3) Full cross-section butt welds of rolled sections without cope holes. 4) Transverse splices in plates or flats tapered in width or in thickness, with a slope ≤ ¼.	- 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. Detail 3): Applies only to joints of rolled sections, cut and rewelded.
			5) Transverse splices in plates or … …	- The height of the weld convexity … …

Size effect consideration: $\Delta\sigma_{C,red} = \boldsymbol{k_s} \cdot \Delta\sigma_C$

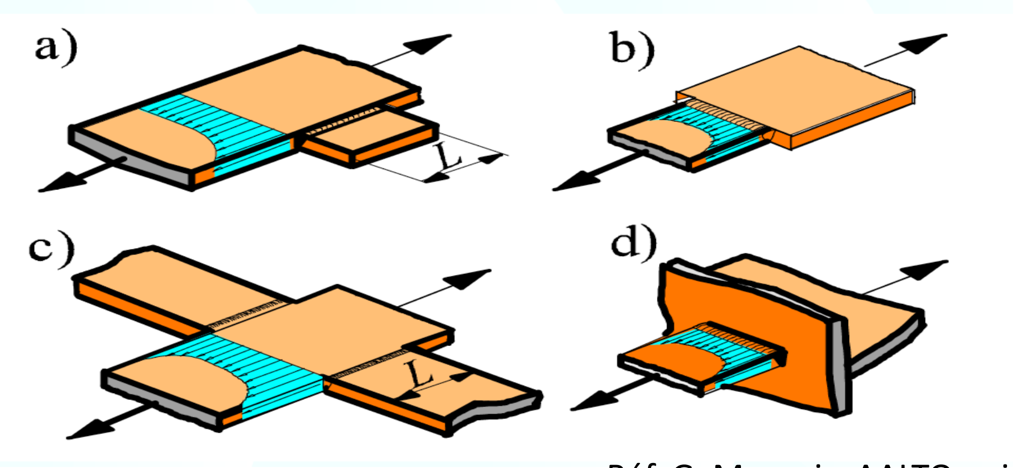
New EN (draft), improved tables of detail categories

Detail category	Constructional detail		Symbol	Description	Supplementary Requirements
112	 See NOTE 1 for size effect	① 		① Splices in plates and flats of same thickness, welded from both sides, ground flush	Weld all-around ground flush with plate surface in direction of stress. Misalignment ≤ 5% of plate thickness, see NOTE 2.
90		② 		② as aforementioned, but as-welded with flank angle ≥ 150°	②: Welded in welding position PA acc. to EN ISO 6947. ②③: Weld ground flush at plate edges in direction of stress, where relevant, after removing weld run-off pieces. Misalignment ≤ 5% of plate thickness, see NOTE 2.
80		③ 		③ as aforementioned, but as-welded with flank angle ≥ 110°	
112	 See NOTE 1 for size effect	⑦ 		⑦ Flange and web splices in plate girders, welded from both sides, ground flush	⑦⑧⑨: No full cross-section joint. Splices welded before assembly of girder. Longitudinal weld should be checked using Table 10.3 ⑦: see ①. ⑧: see ② ⑨: see ③.
90		⑧ 		⑧ as aforementioned, but as-welded with flank angle ≥ 150°	
80		⑨ 		⑨ as aforementioned, but as-welded, with flank angle ≥ 110°	

- Better drawings
- Weld descriptions, symbols
- Adding of details
- Review of detail categories wrt to state-of-art

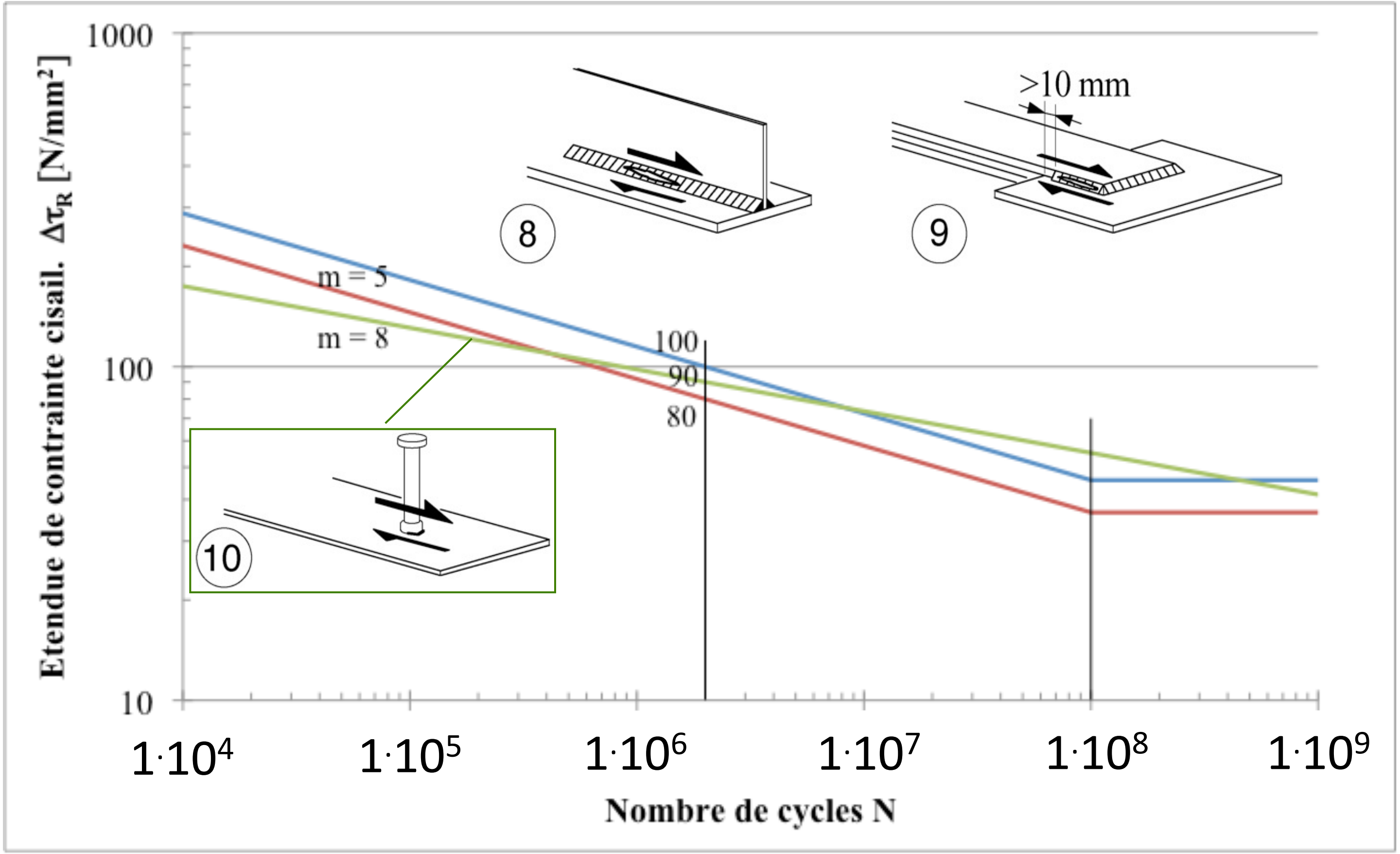
Types of Constructive Details

- Stress Concentration Rating (SCF)
- The higher it is, the worse the detail
- Influence of geometric parameters: width, length, thickness on the SCF, as well as type of weld, forces

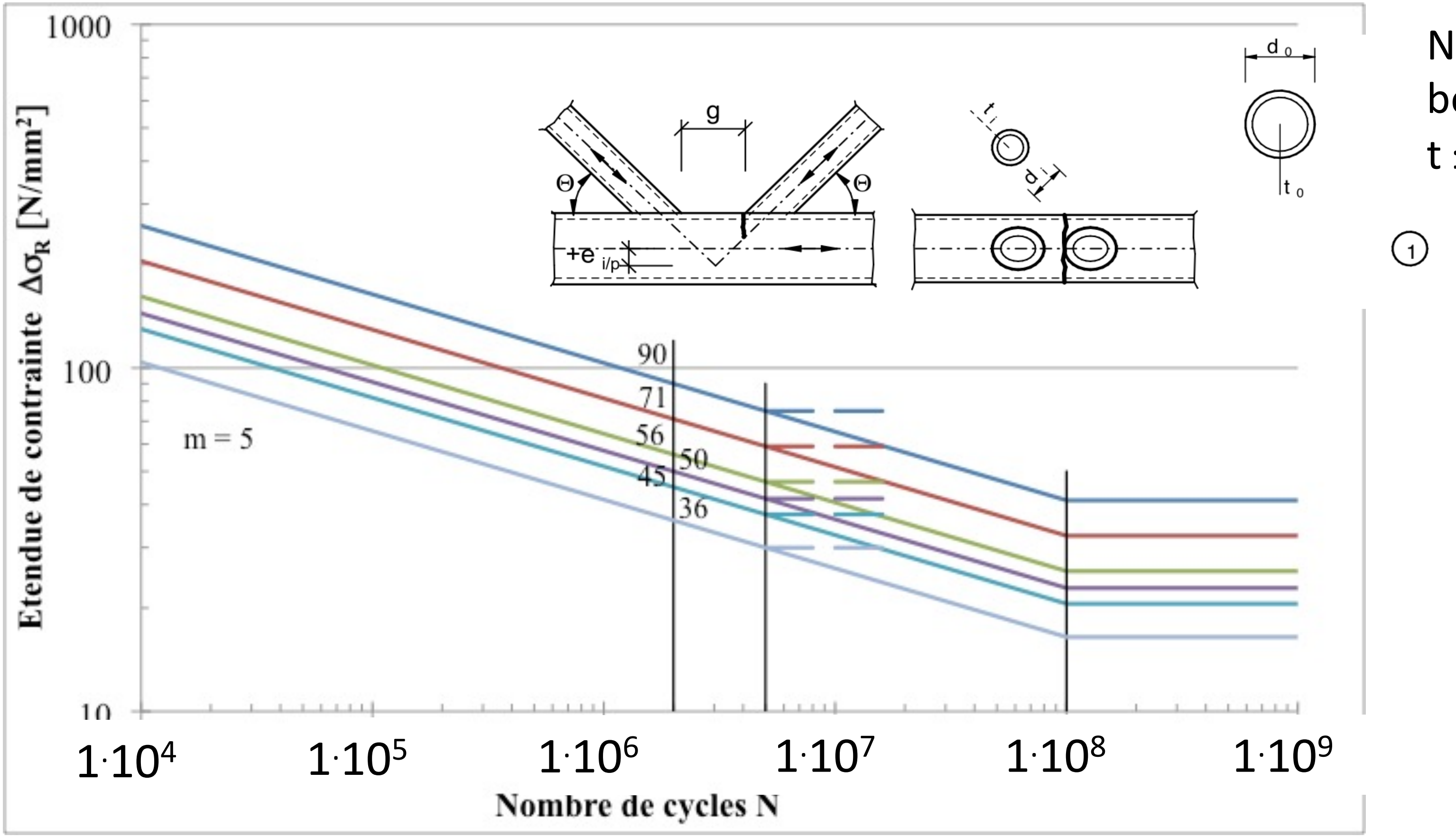


Réf. G. Marquis, AALTO univ.

Other resistance curves: shear stress cases



Other curves: tubular lattice girder node cases (t ≤ 8 mm)



New EN, will be raised to t ≤ 12.5 mm

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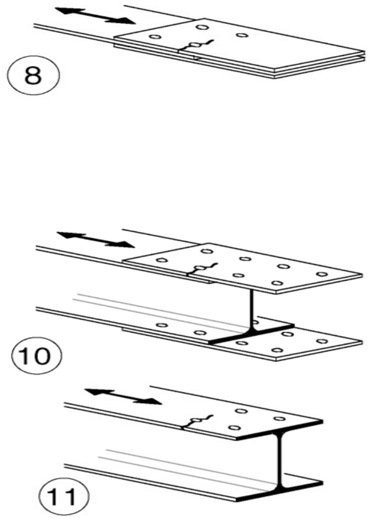
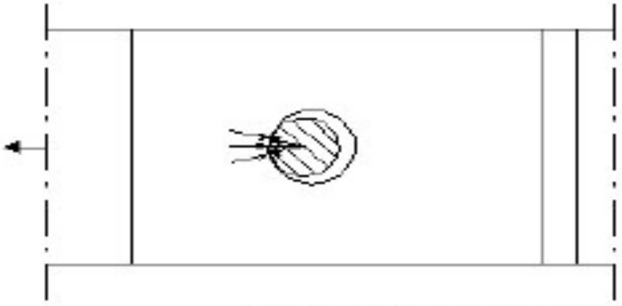
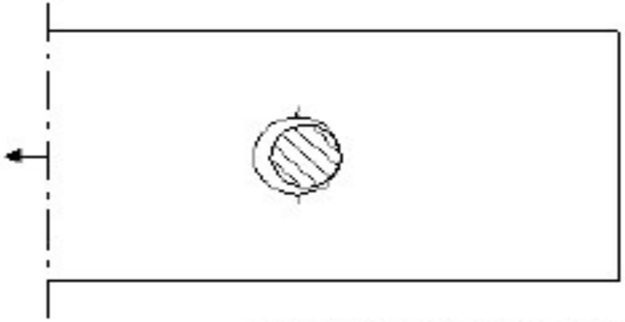
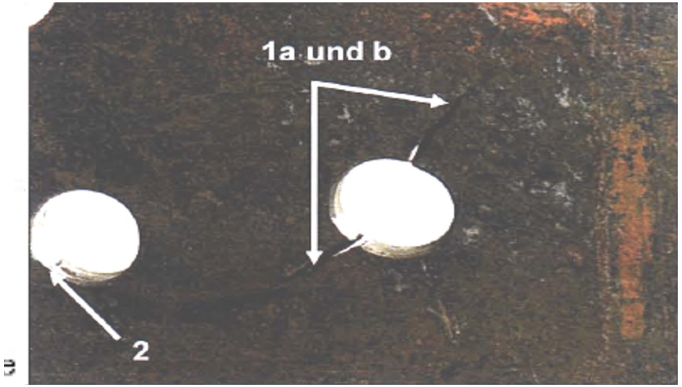
Shear bolted joints





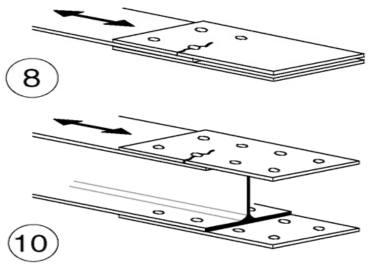


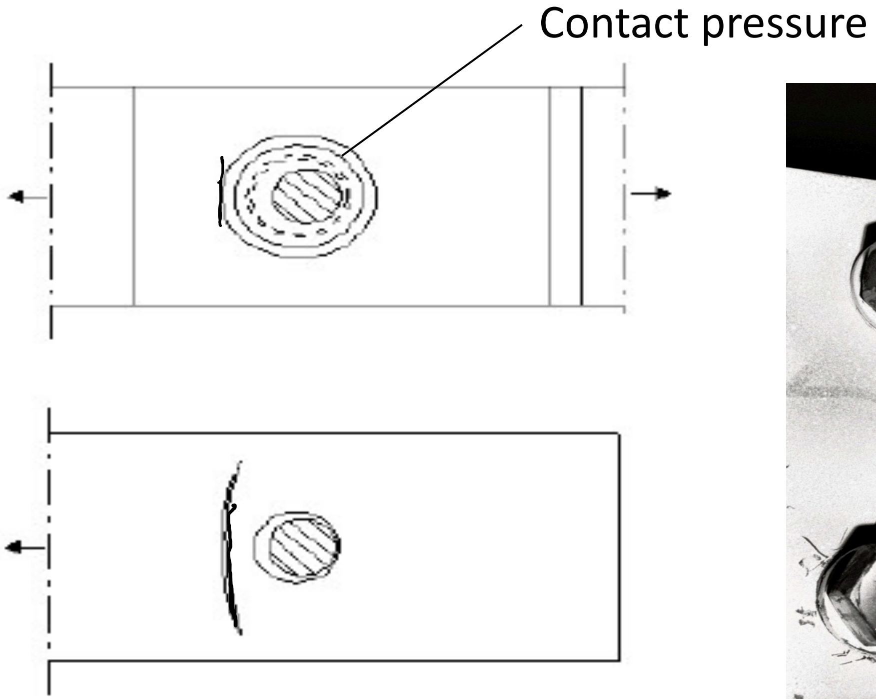


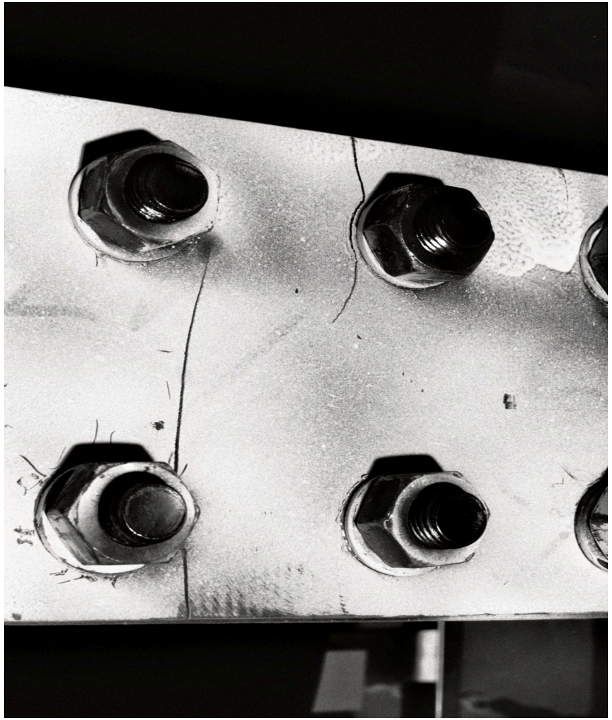
FAT between 50 and 90

(Δσ on the net cross-section)

Shear Prestressed Bolted Connections





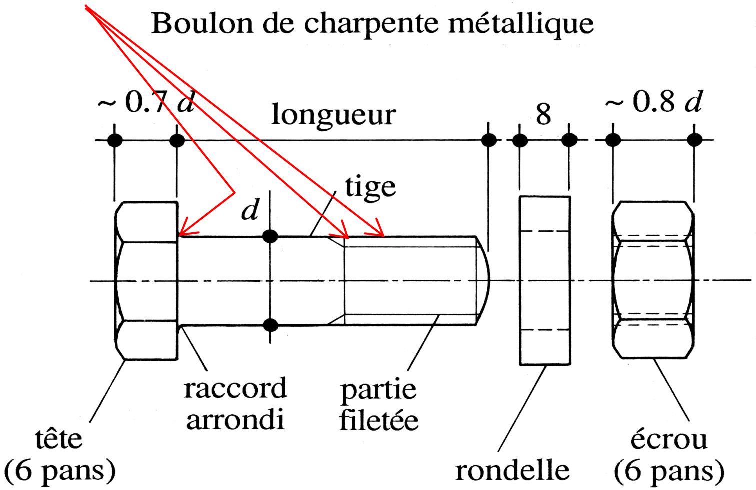


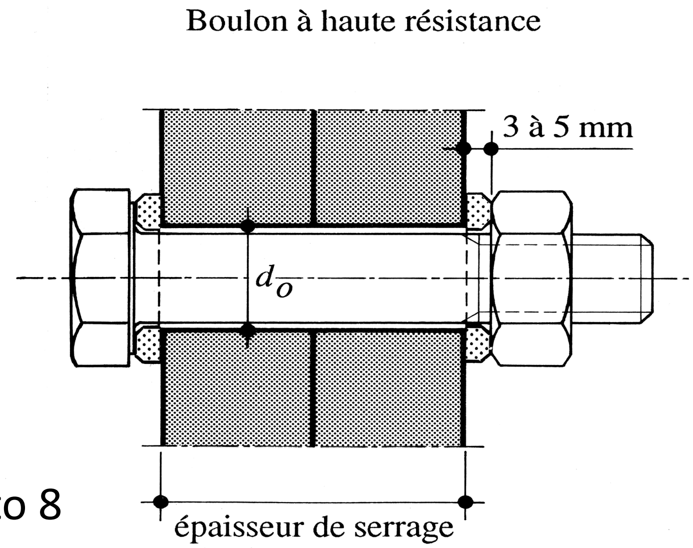
FAT between 90 and 112
(Δσ on gross cross-section)

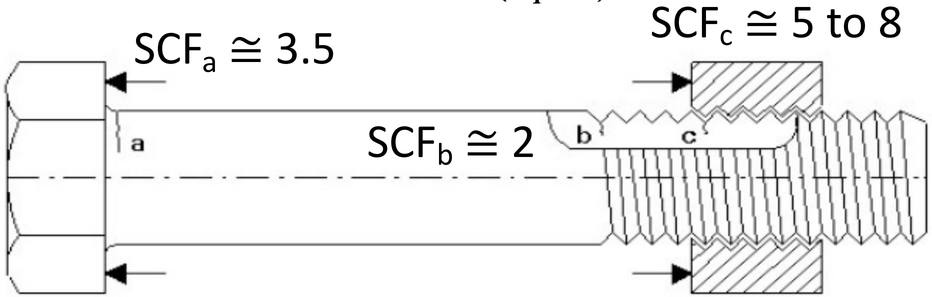
Tensile bolted joints (FAT 50)

Critical areas for fatigue:

Small rays, intro. Strength = High Stress Concentration

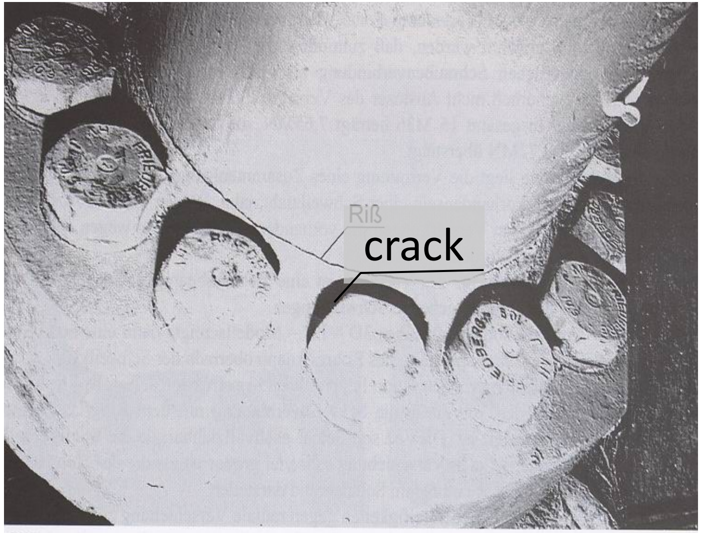






Tensile bolted connections

Case a, crack in weld



Case b, crack in bolt (FAT 50)

Tensile bolted joints (FAT 50)

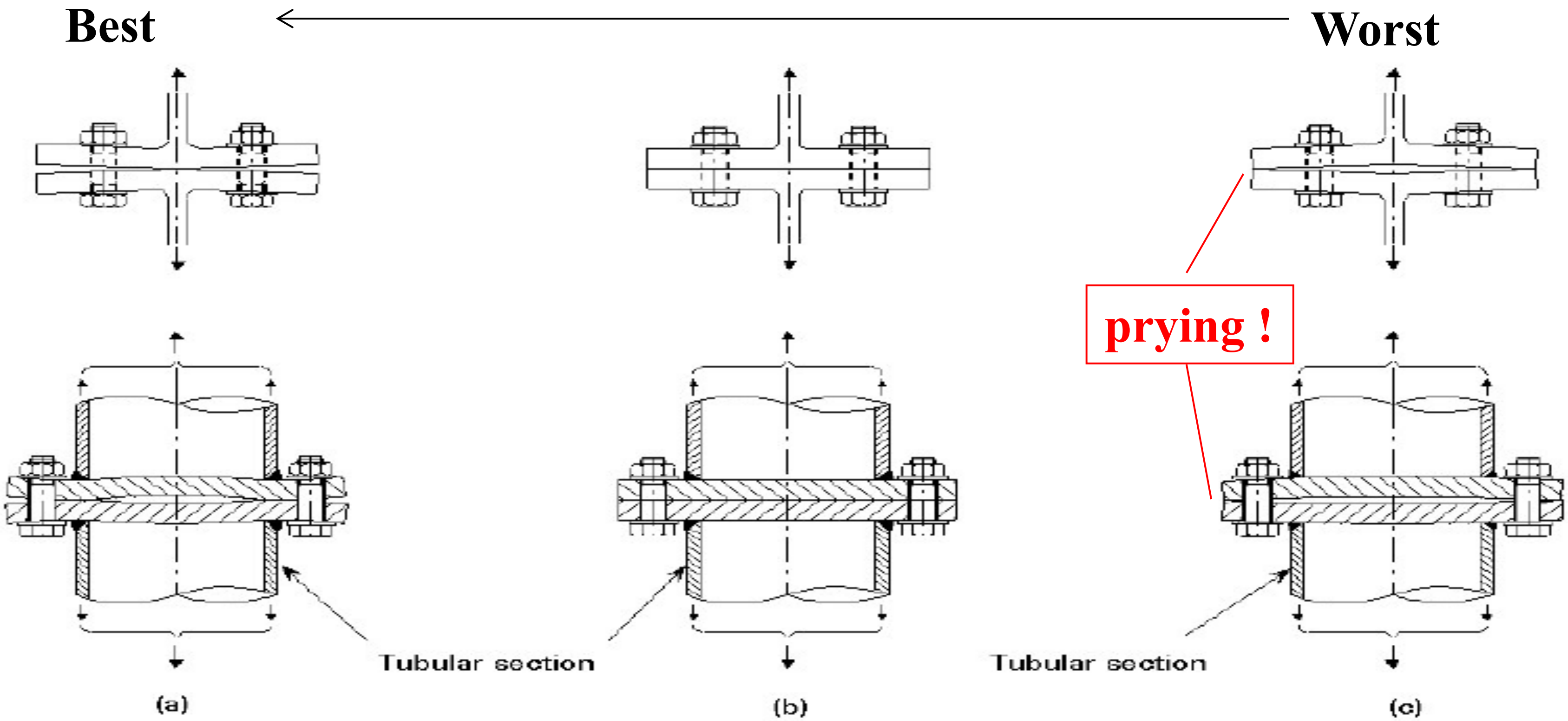


Fig. 8.28: Evolution of tension under external force

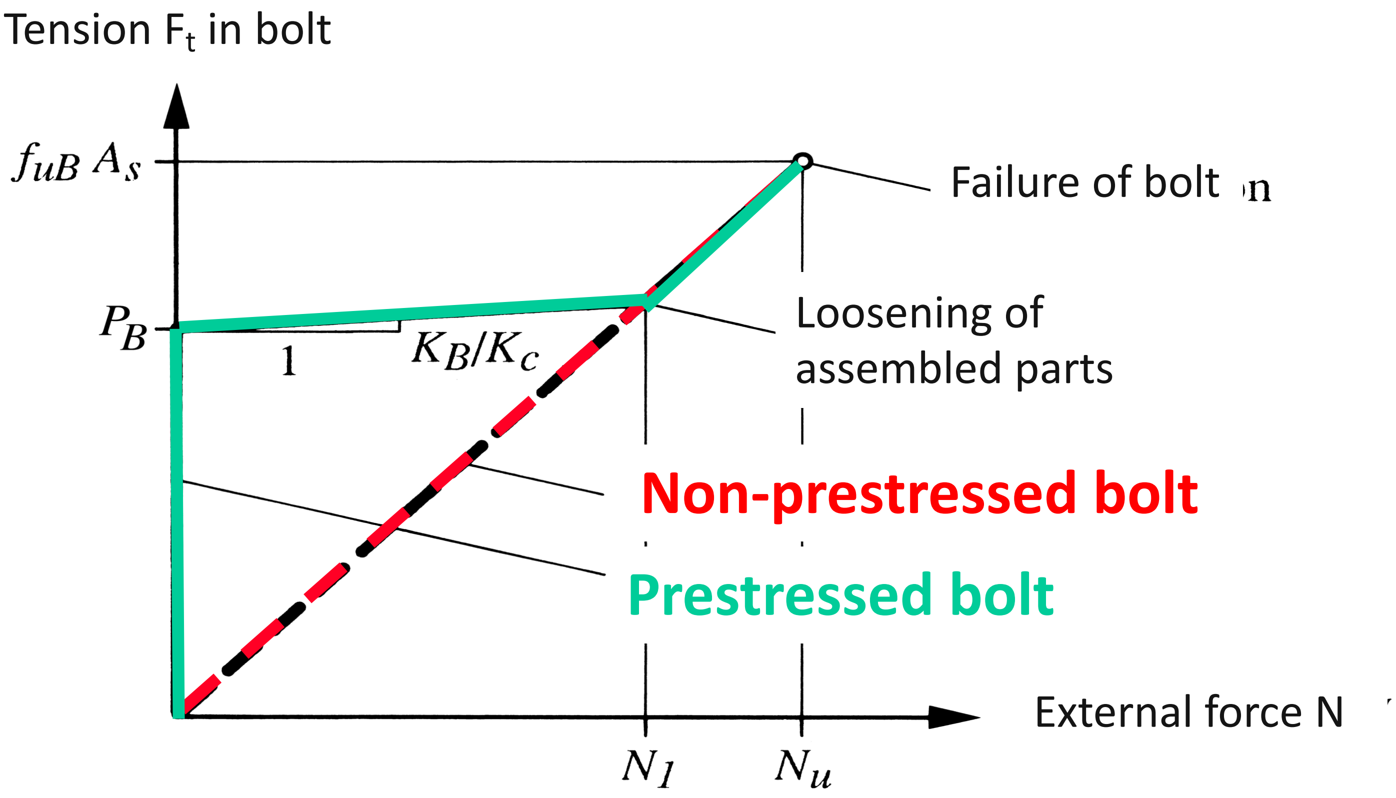
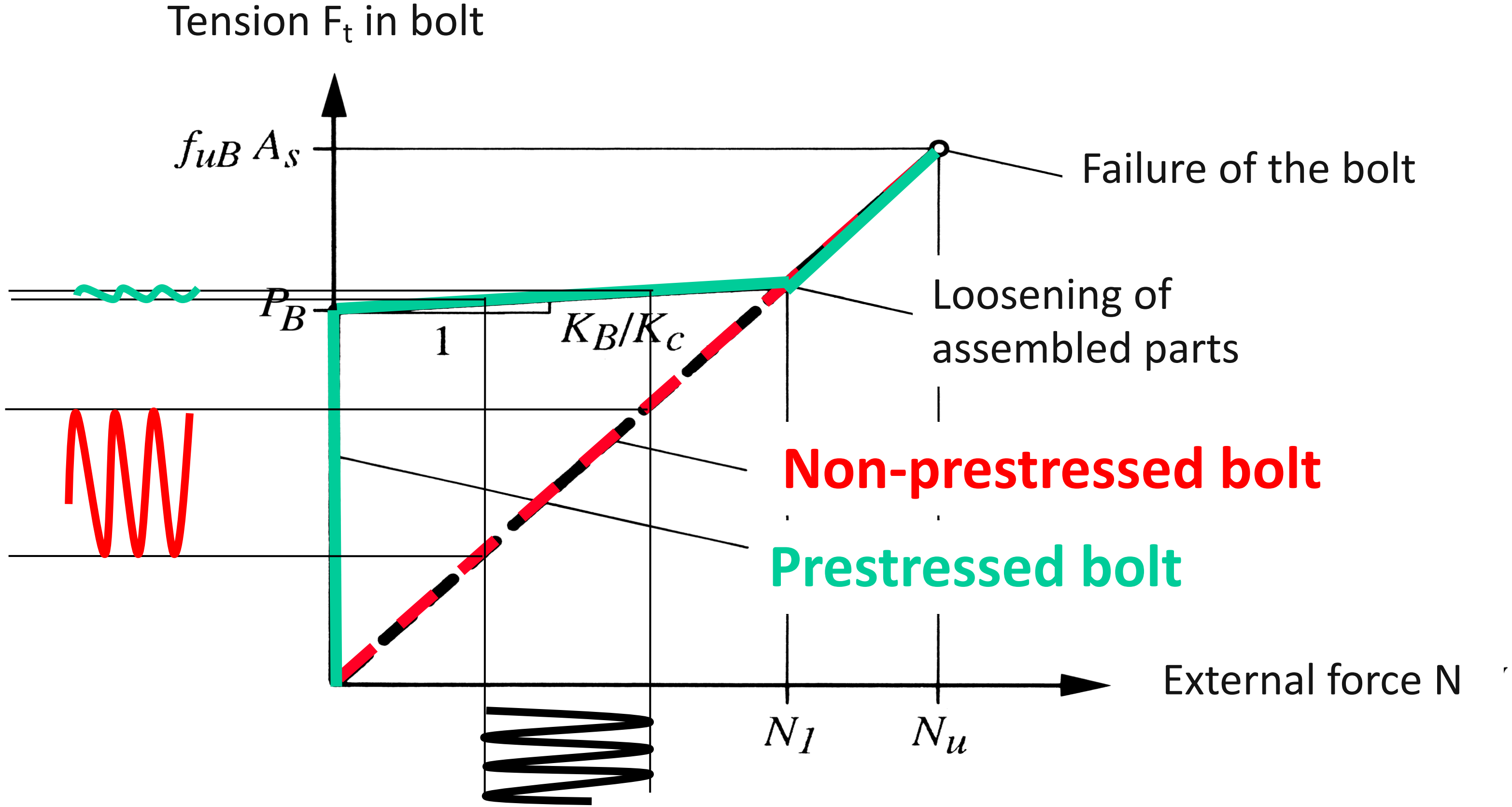
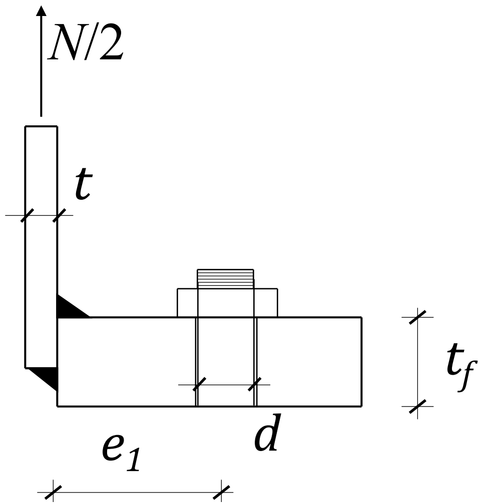
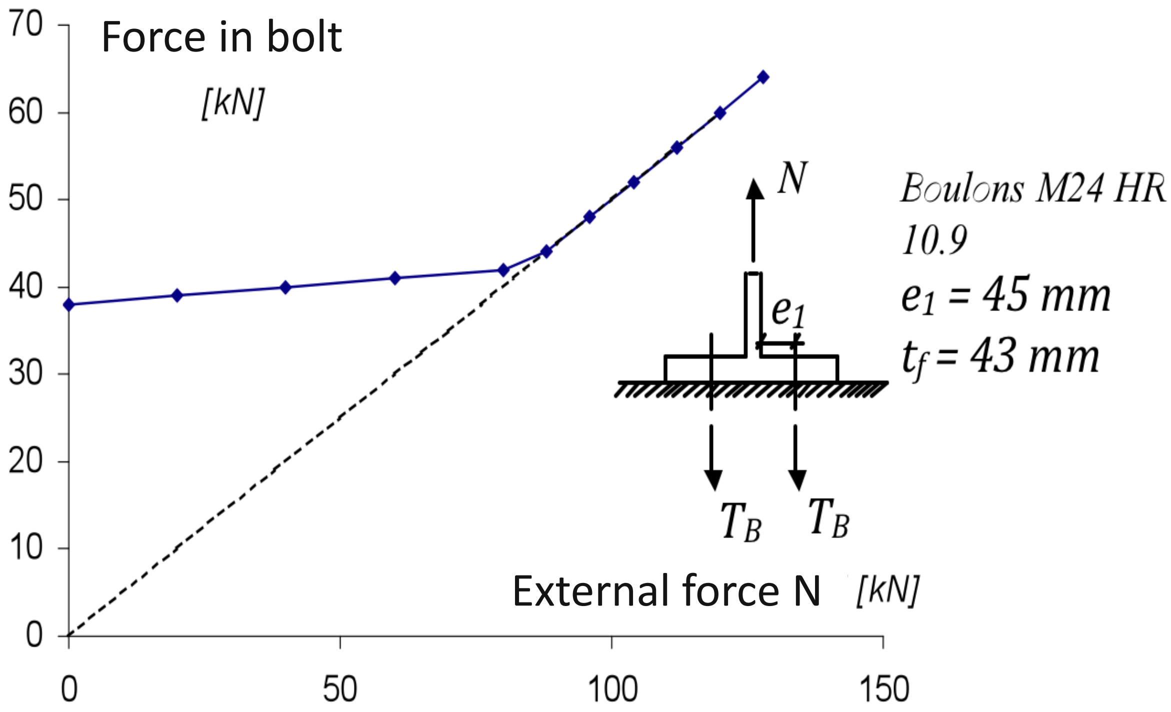


Fig. 8.28: Evolution of tension under external force

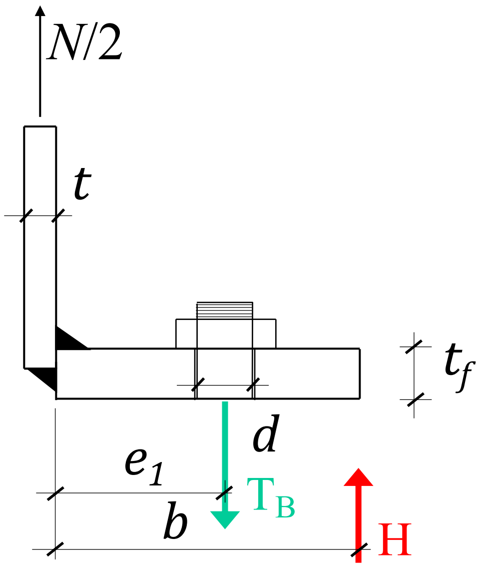


Bolted joints in tension, test with a rigid base plate





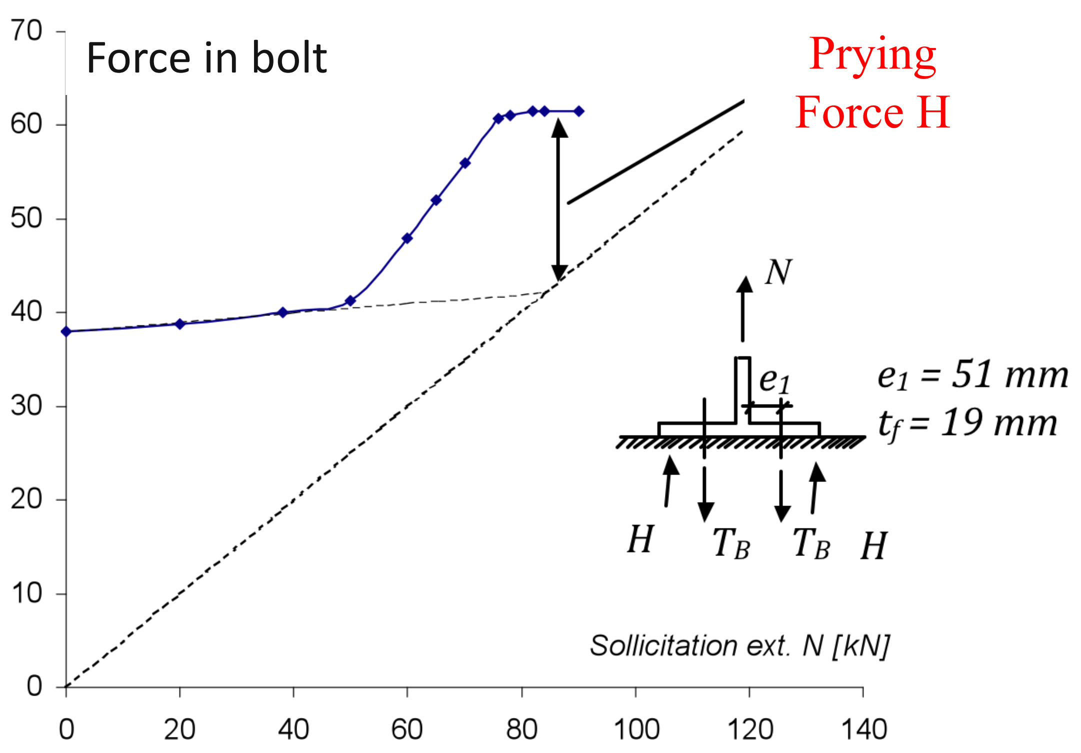
Bolted joints in tension, test with a flexible base plate



$$N/2 + H = T_B$$

$$(t/2 + e_1)\cdot N/2 = (b - e_1)\cdot H$$

$$H = \frac{\left(t/2 + e_1\right)}{\left(b - e_1\right)} \cdot N/2$$



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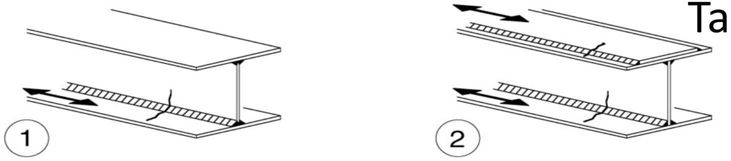
Families of welded joints, influence of:

- Shape, Stress Concentration (SCF)
- Length of attachment
- Thicknesses of plates
- Type of weld (fillets or full-penetration)

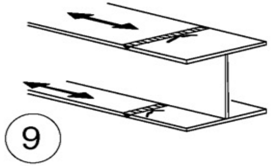
(Length of attachment and Thicknesses of plates:) Via FAT or k_s

EN 1993-1-9

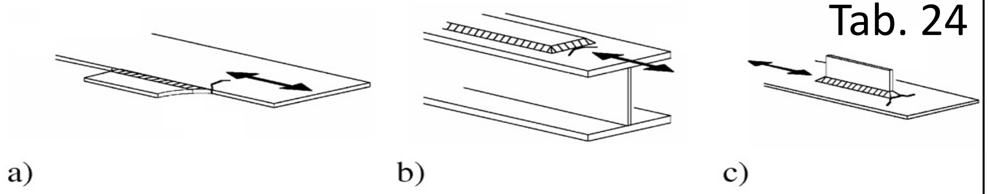
Longitudinal welds — 8.2 — Tab. 22



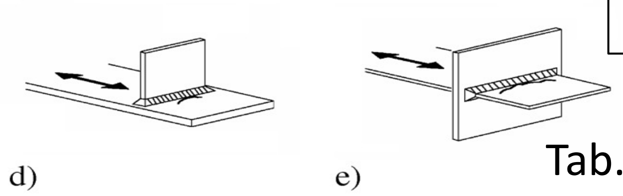
Transversal welds — 8.3 — SIA 263 Tab. 23



Longitudinal attachment — 8.4 — Tab. 24



Transversal attachment — 8.4, 8.5 — Tab. 25



Families of welded joints, influence of:

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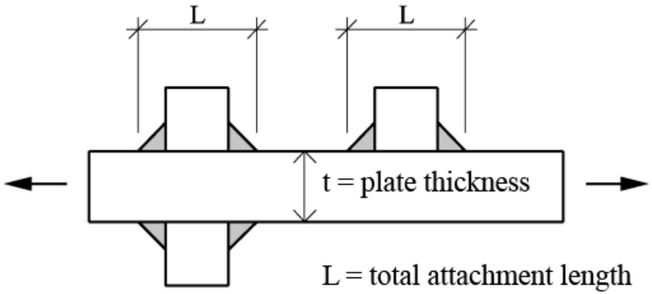
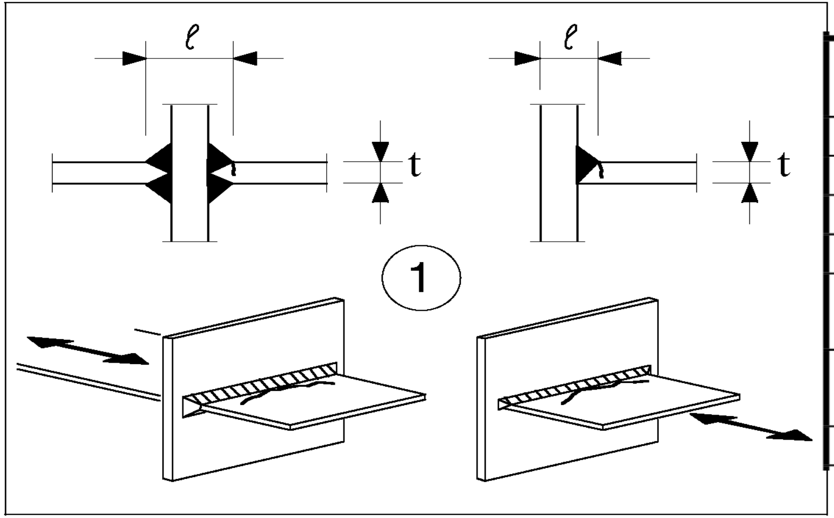
(Length of attachment and thicknesses of plates:) Via FAT or k_s



Transversal attachment



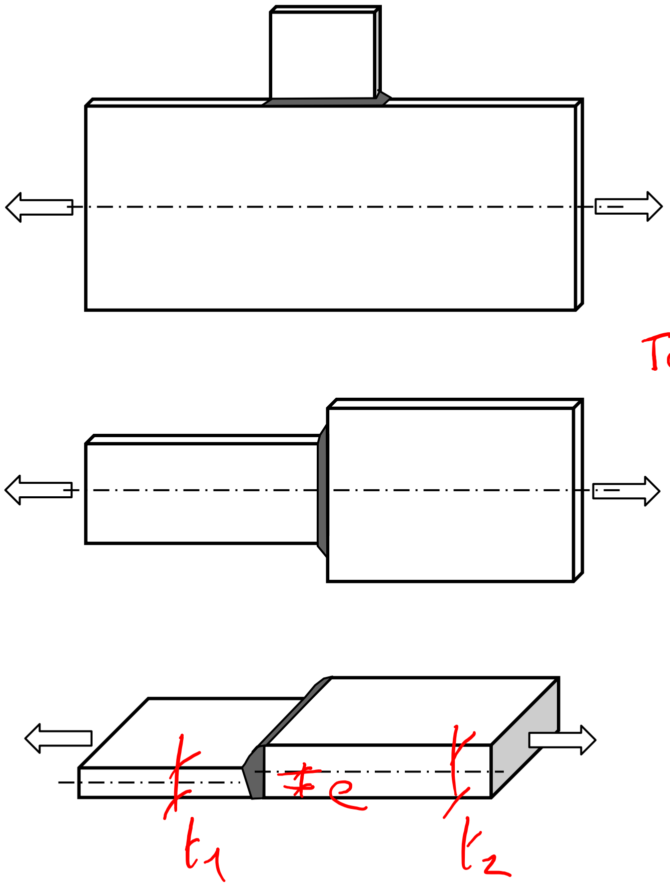
FAT		
80	ℓ<50 mm	all t [mm]
71	50<ℓ≤80	all t
63	80<ℓ≤100	all t
56	100<ℓ≤120	all t
56	ℓ>120	t≤20
50	120<ℓ≤200 ℓ>200	t>20 20<t≤30
45	200<ℓ≤300 ℓ>300	t>30 30<t≤50
40	ℓ>300	t>50

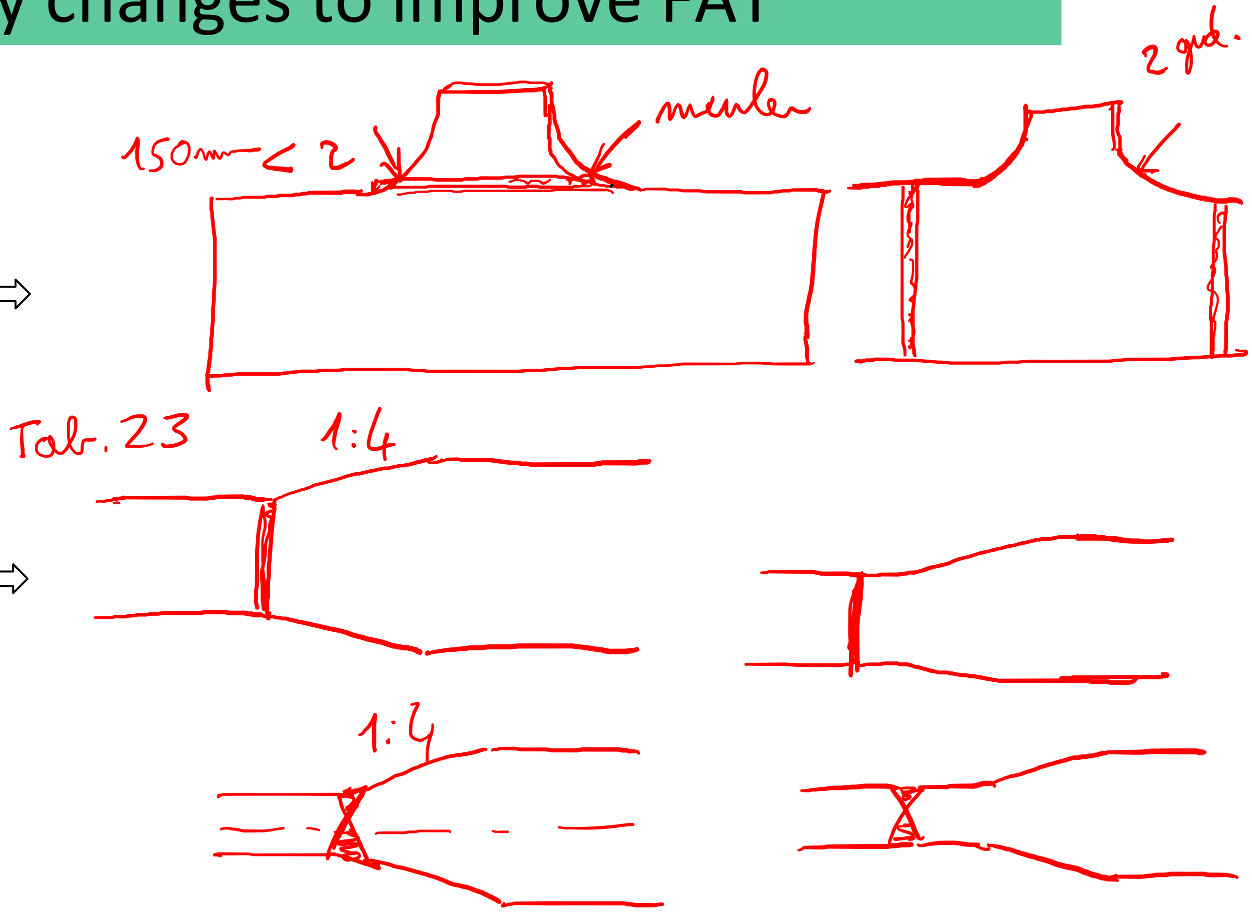
$$\Delta\sigma_{C,red} = k_s \cdot \Delta\sigma_C$$

$$k_s = \left(\frac{t_{ref}}{t_{eff}}\right)^n$$

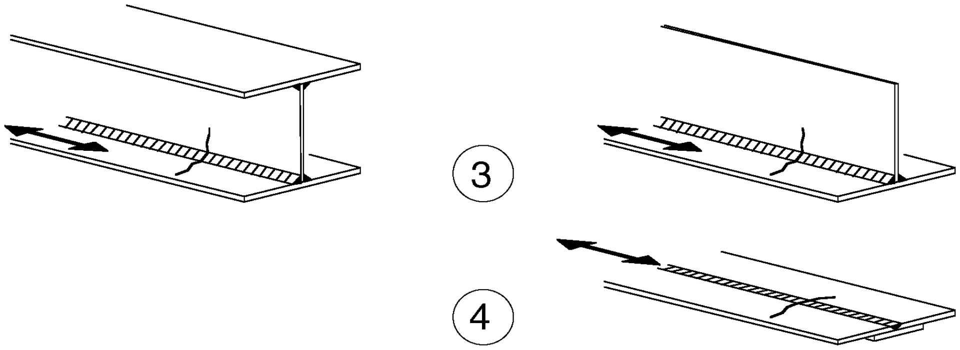
- $L/t < 2$ so $t_{eff} = t$
- Otherwise $t_{eff} = 0.5 \cdot L$ or $t_{eff} = t$

Examples of geometry changes to improve FAT

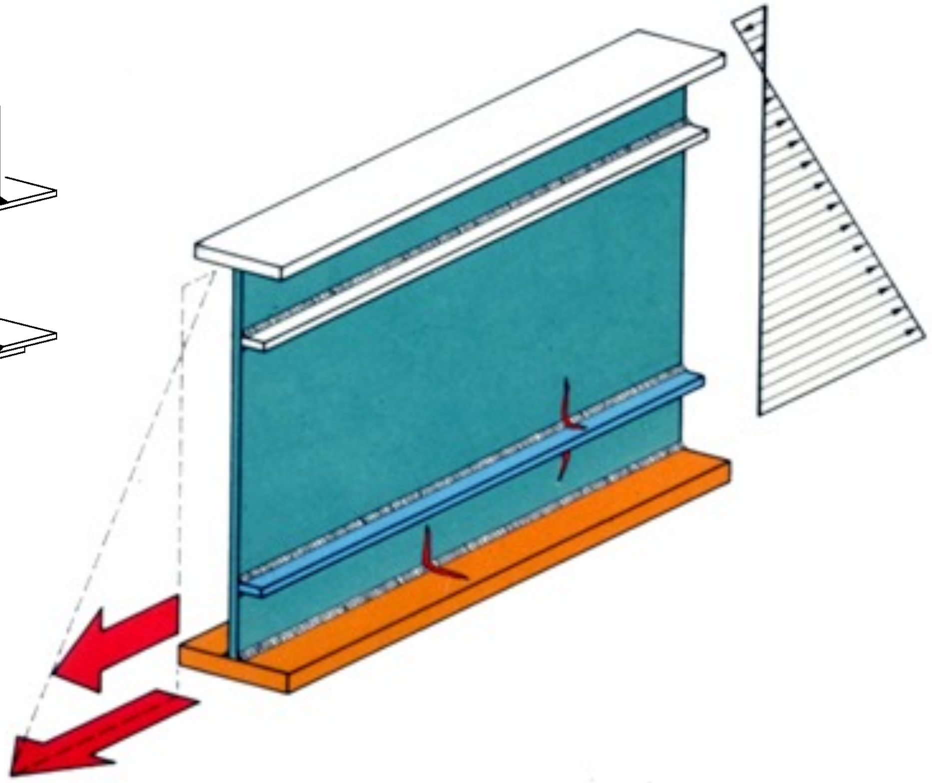




Longitudinal welds, propagation from internal imperfection

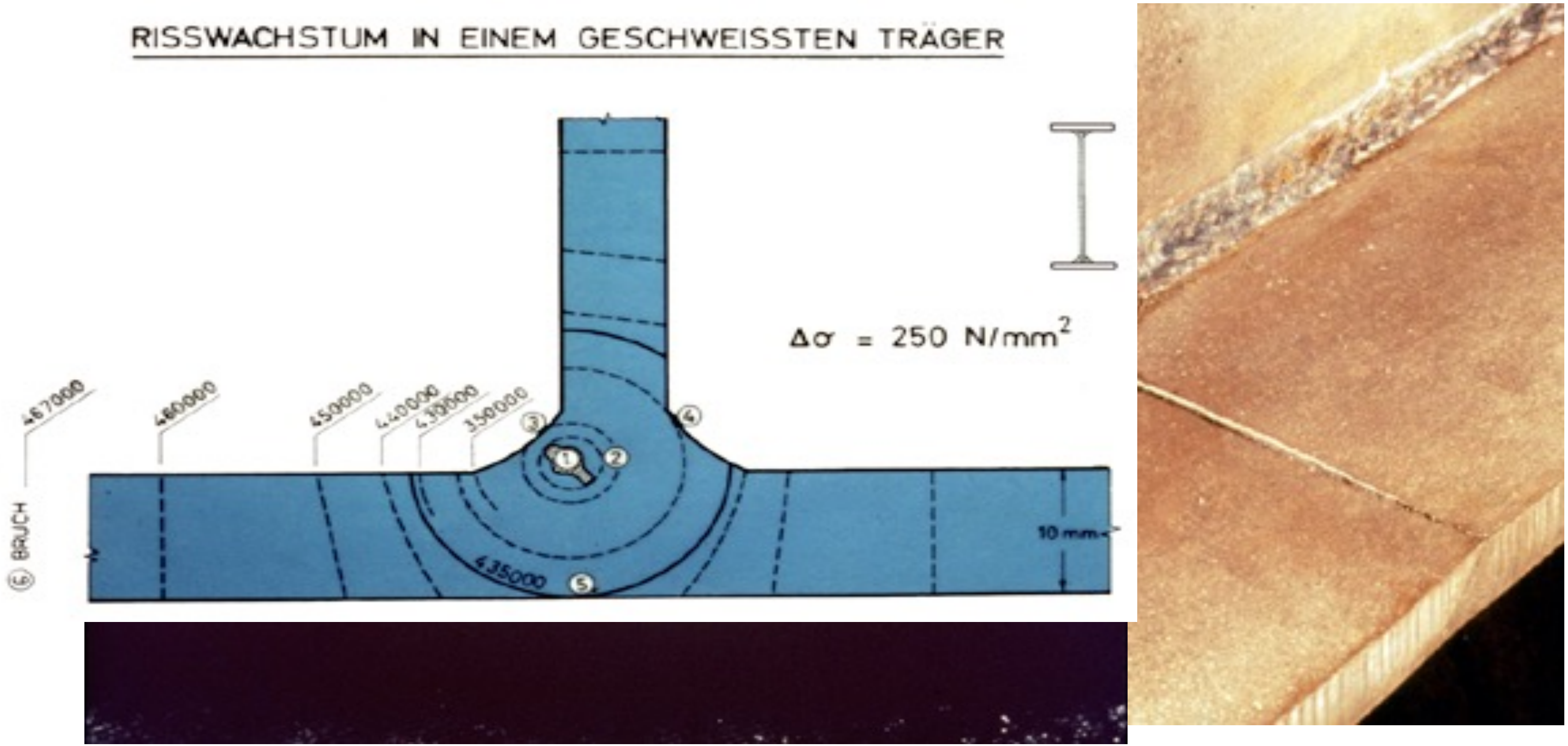


Detail categories
FAT 100 - 125



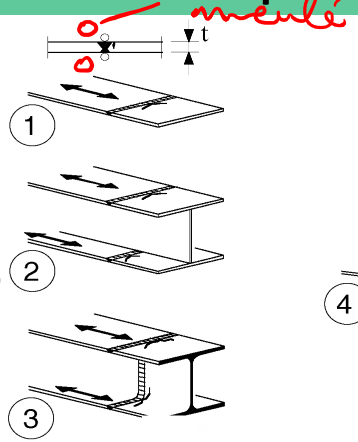
Longitudinal welds, propagation from internal imperfection

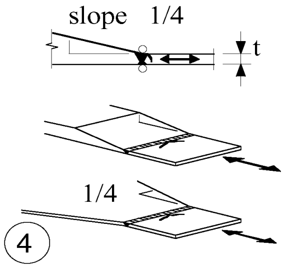
Longitudinal welds, propagation from internal imperfection



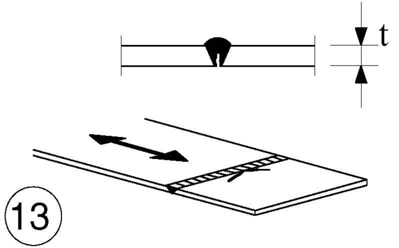
Transverse butt welds, propagation from imperfections

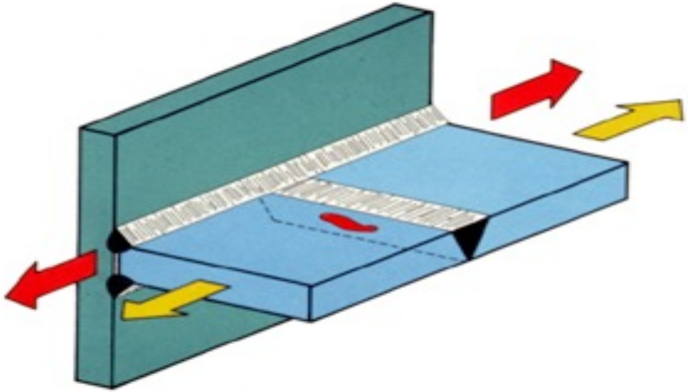
FAT 112 (ground, NDT checked)





FAT 36 !



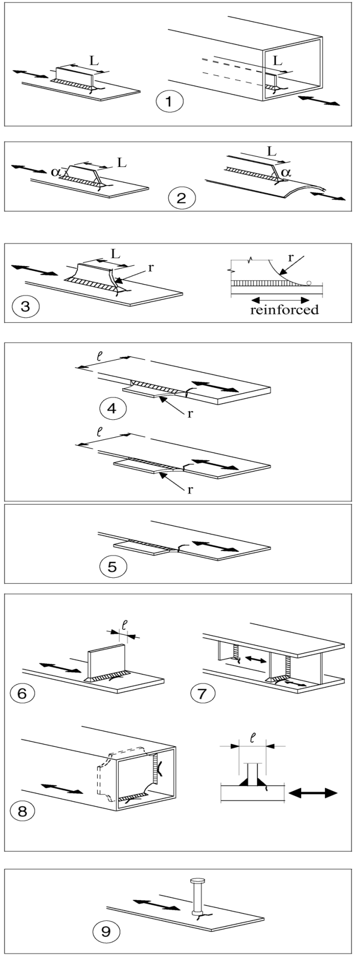


Propagation from end of longitudinal attachment

FAT 56 - 80

FAT 50 - 90

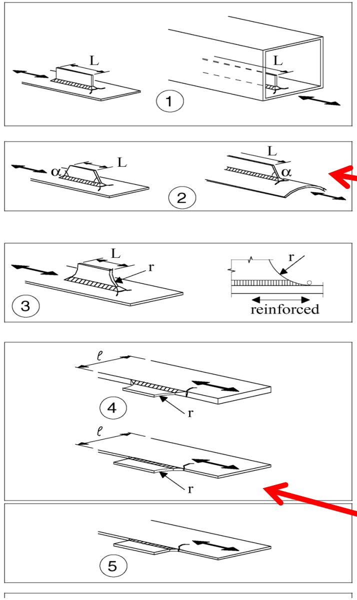
FAT 71 - 80

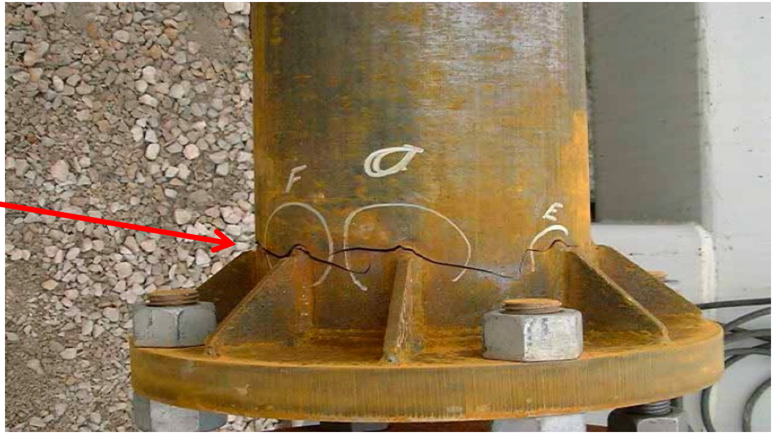


Propagation from end of longitudinal attachment

FAT 56 - 80

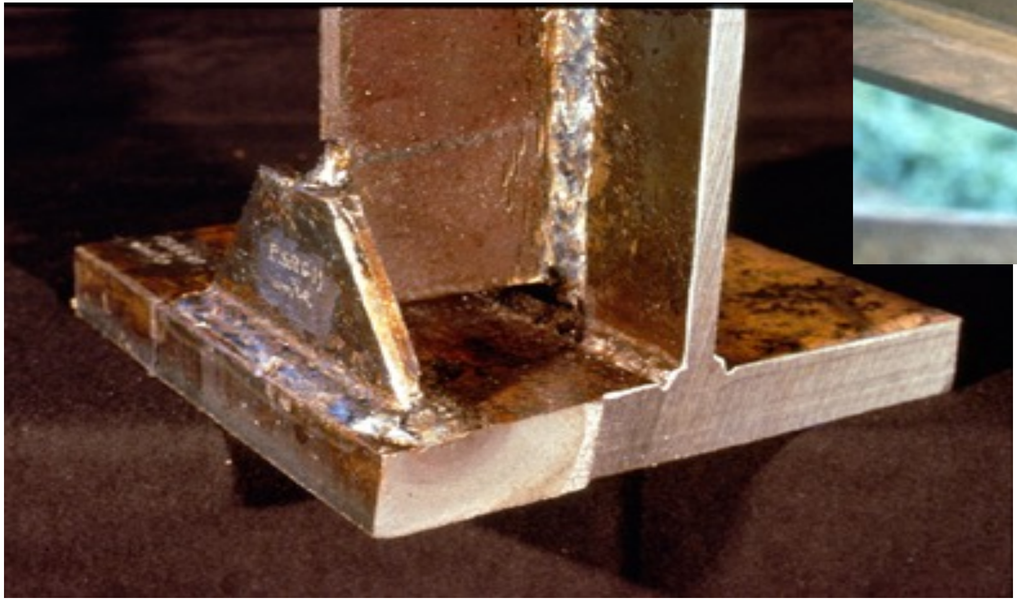
FAT 50 - 90



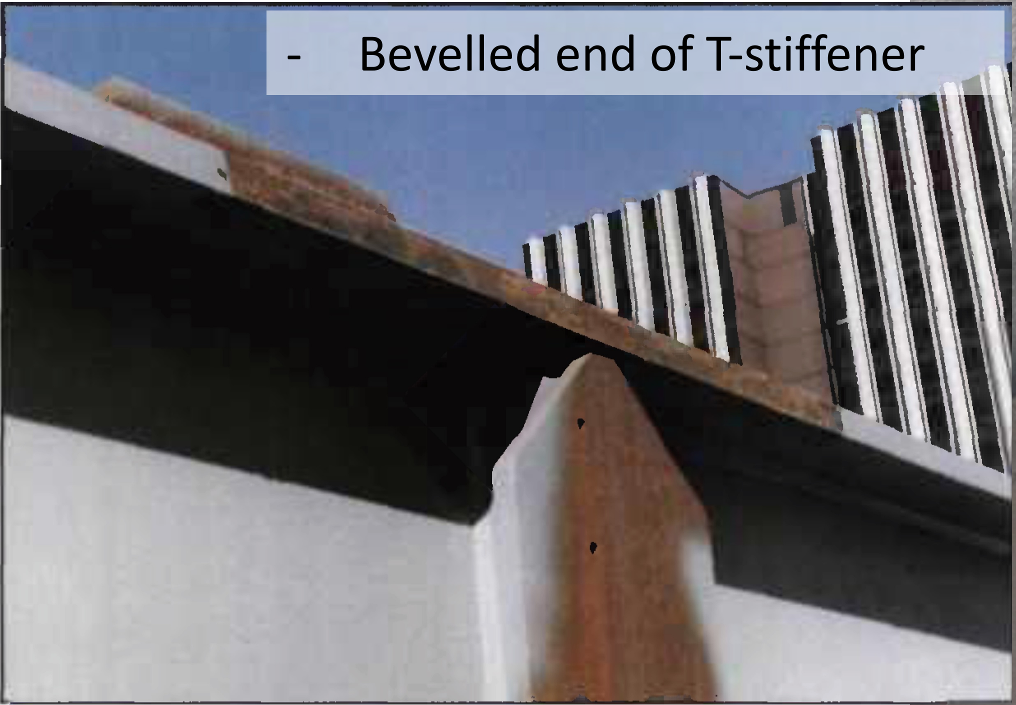


Propagation from end of longitudinal attachment

- Vertical stiffeners (transv. attachments) ⇔ "bad detail"
- Detailing error (ca. 1970), add long. attachment on flange !



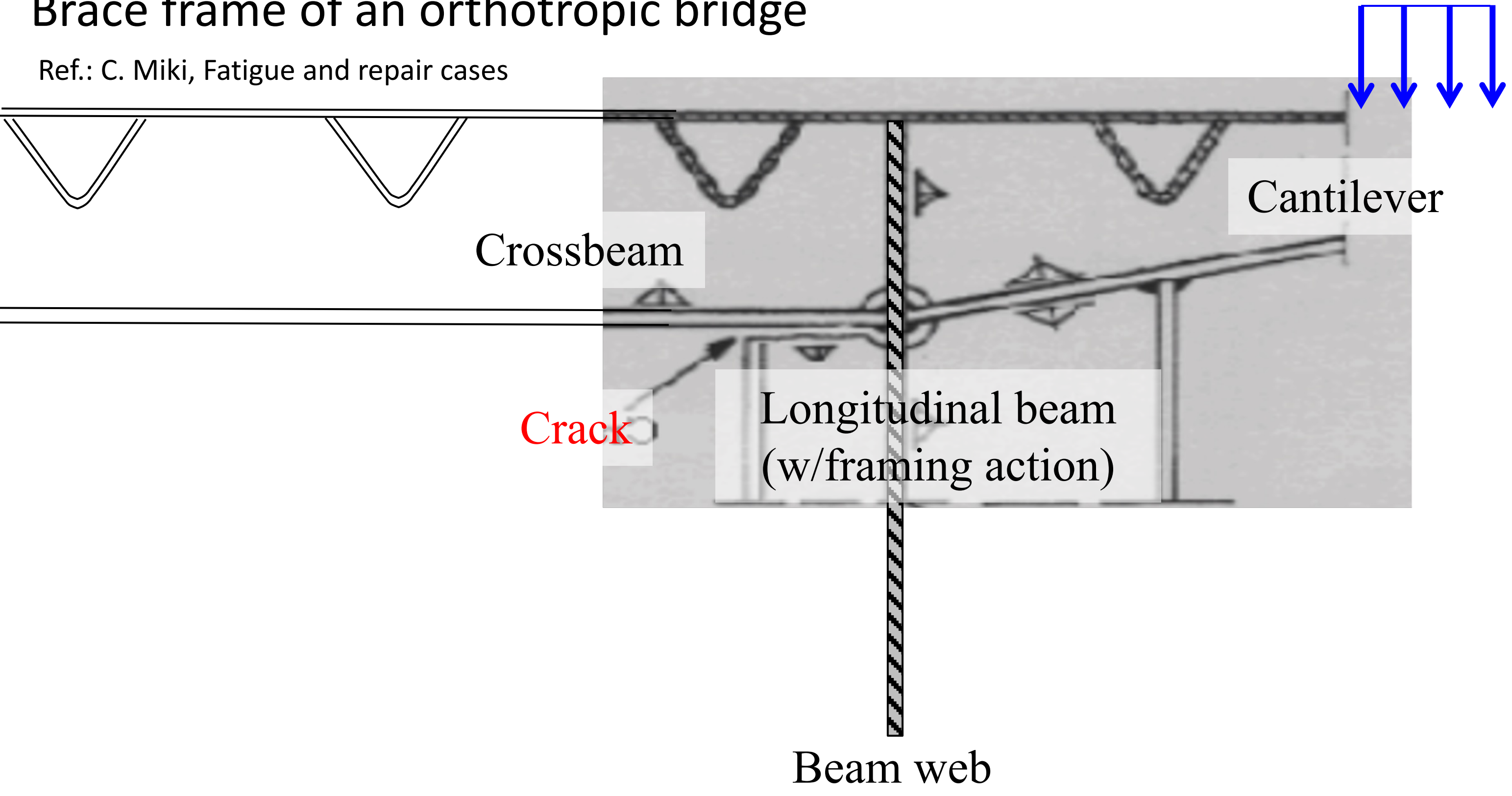
Enhanced detailing possibilities



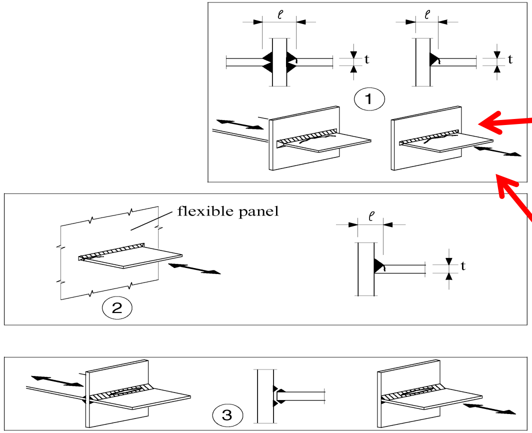
Propagation from loaded attachments

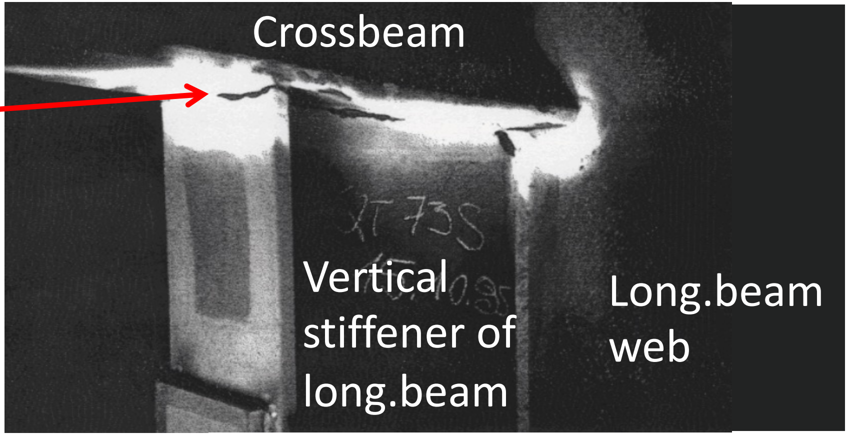
Brace frame of an orthotropic bridge

Ref.: C. Miki, Fatigue and repair cases



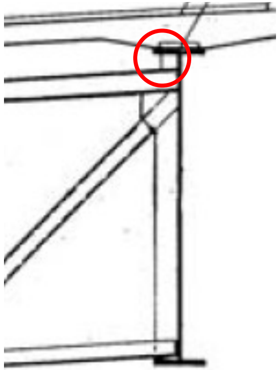
Propagation from loaded attachments





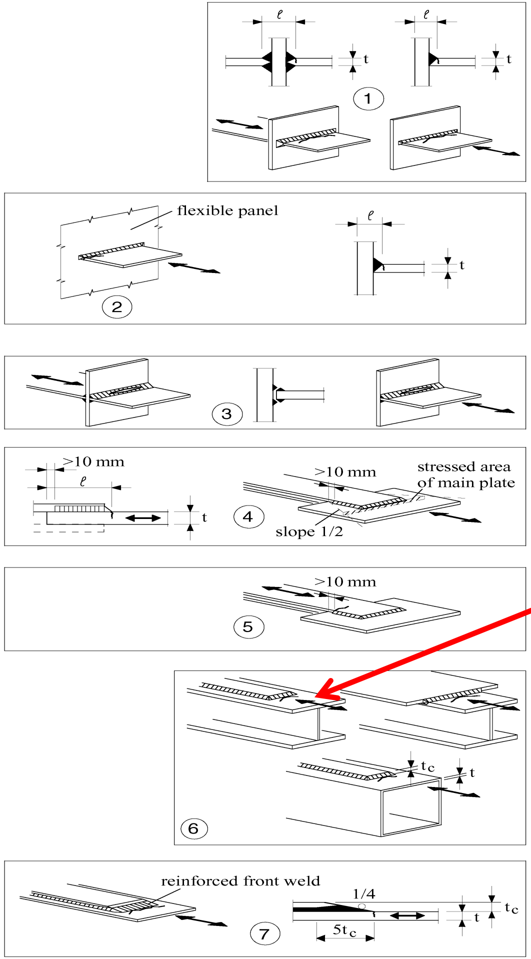
Ref.: C. Miki, Fatigue and repair cases

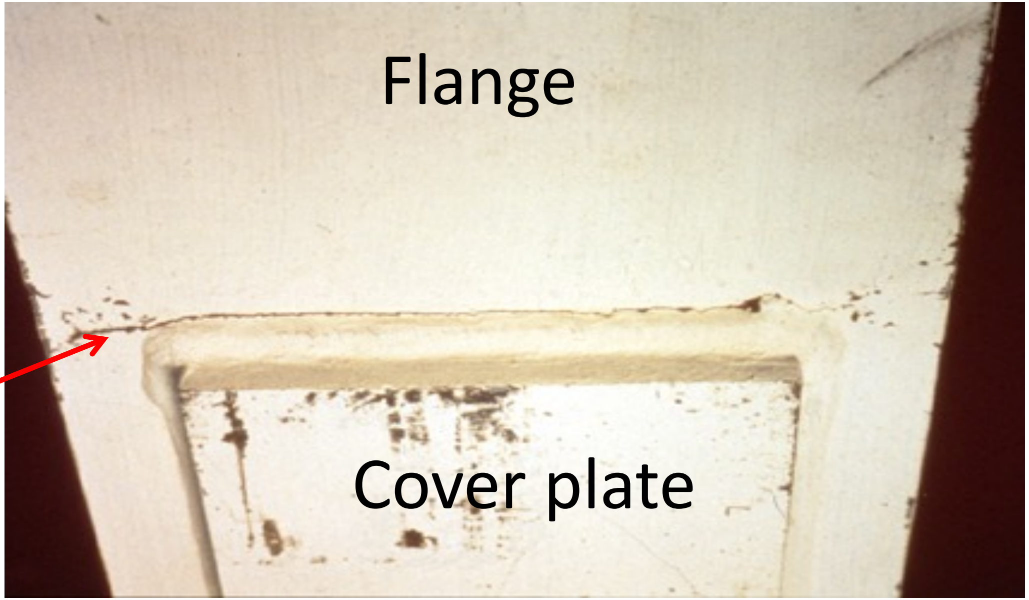
Motorway bridge (Austria) 2008



Source: Greiner, R., Taras, A., ECCS_TC6_24.2.2010, Damage cases

Propagation from loaded attachments

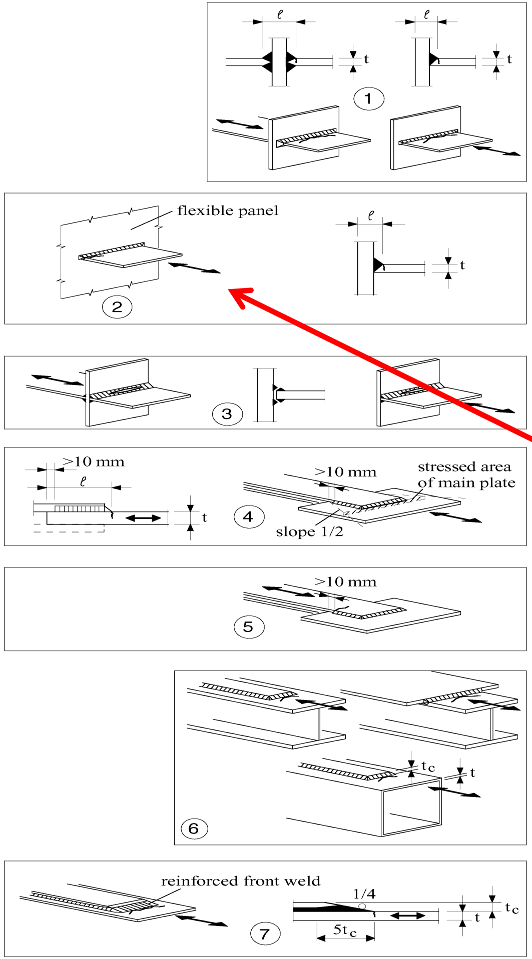




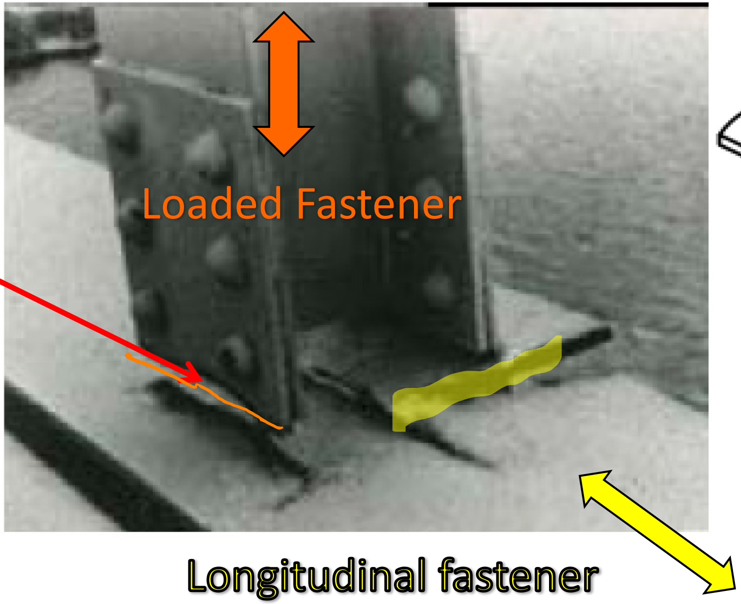
Ref.: C. Miki, Fatigue and repair cases

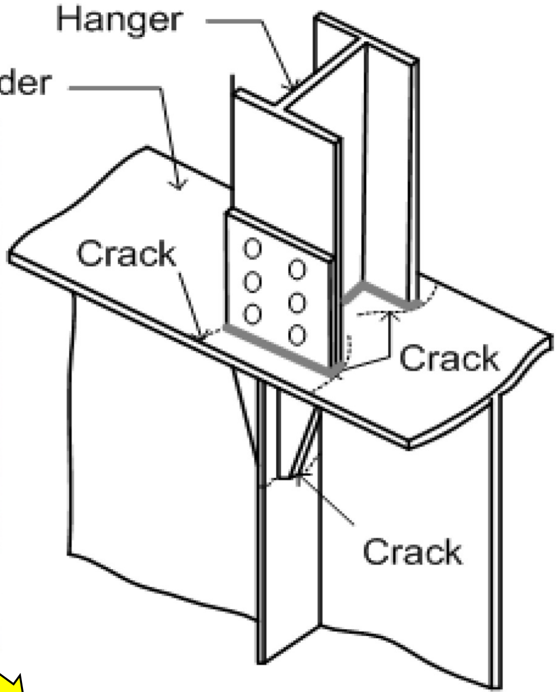
Propagation from loaded attachments

Propagation from loaded attachments



Hanger

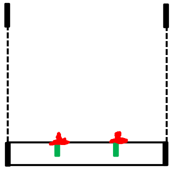


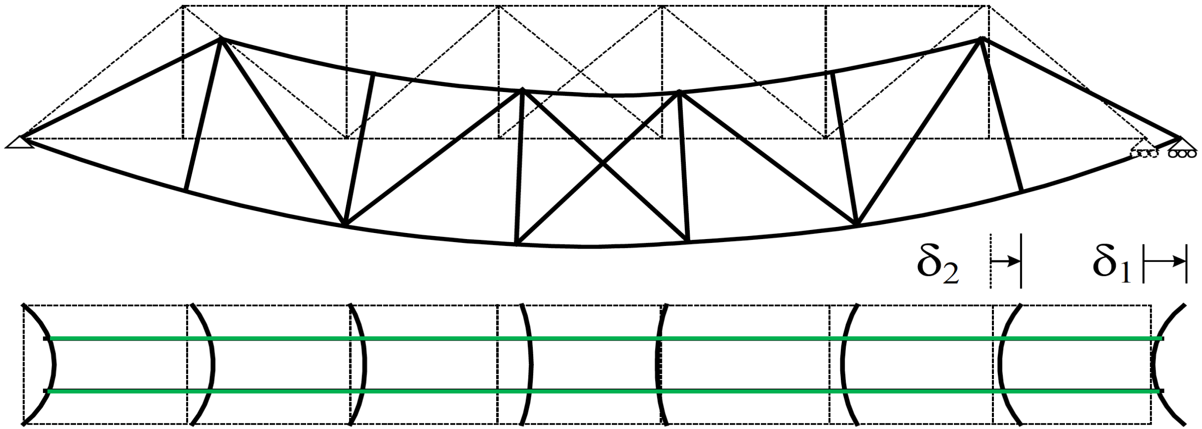


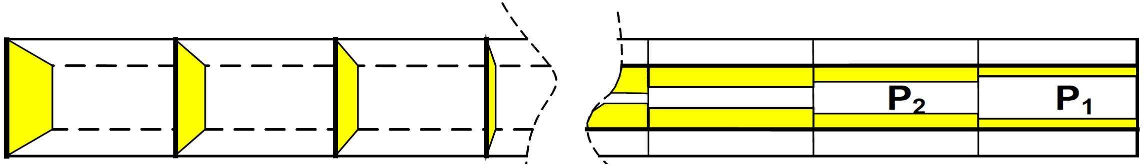
Ref.: C. Miki, Fatigue and repair cases

3D effects and out-of-plane distortions: Responsible for many cracks !!

Example: Shear drag effect between primary and secondary truss beams







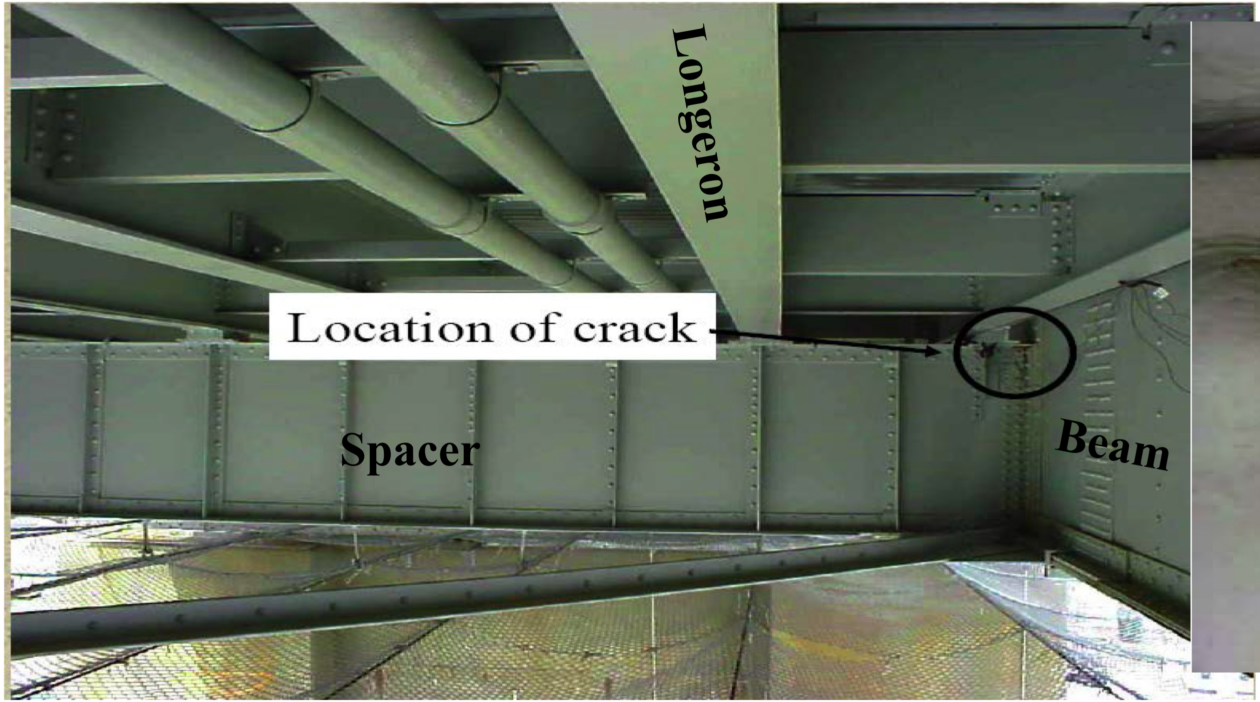
Transverse bending of the struts

Axial forces in the spars

Solution? Understand the fct of the structures you are studying

3D effects and out-of-plane distortions: Responsible for many cracks !!

Example, Chesapeake City Bridge (arch bridge)

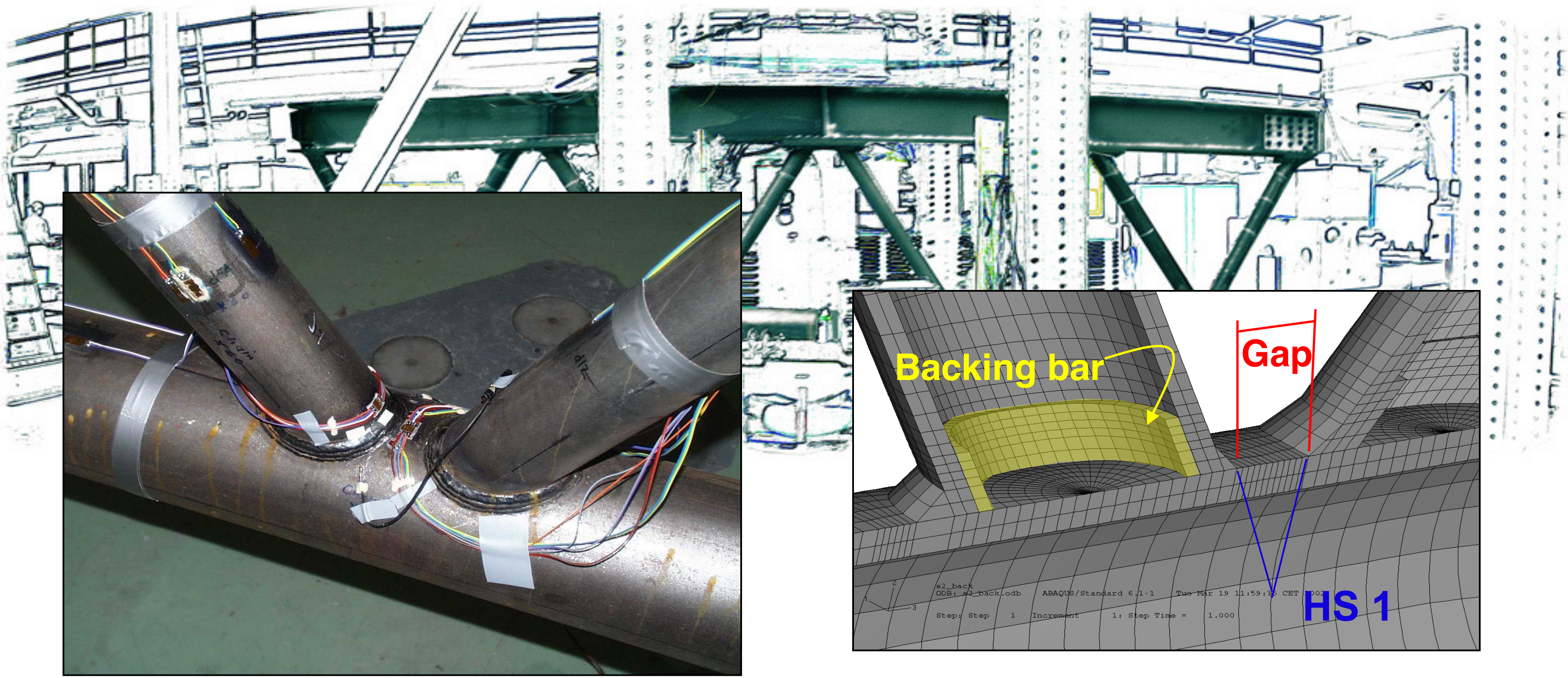


Ref.: Shenton III, H.W., Chajes, M.J., Finch, W.W., Rzucidlo, M.C., Carrigan-Laning, J., Chasten, C.P. (2003). "Field Test of a Fatigue Prone Steel Tied Arch," Proceedings of the 2003 ASCE Structures Congress.

Content

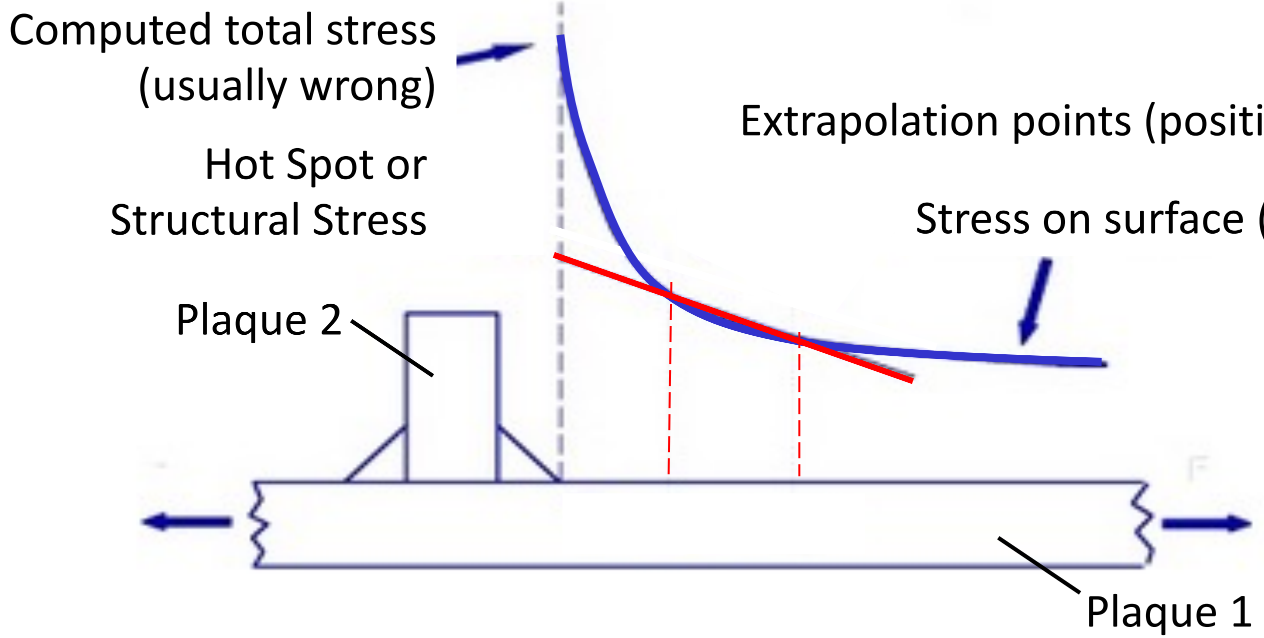
- Fatigue normalized curves
- Types of details and diff. resistance curves
- Bolted, riveted connections
- Welded Connections
- **Hot-spot method**
- Execution of welds

Fatigue of tubular structures, of tubular nodes



Fatigue of tubular structures, of tubular nodes

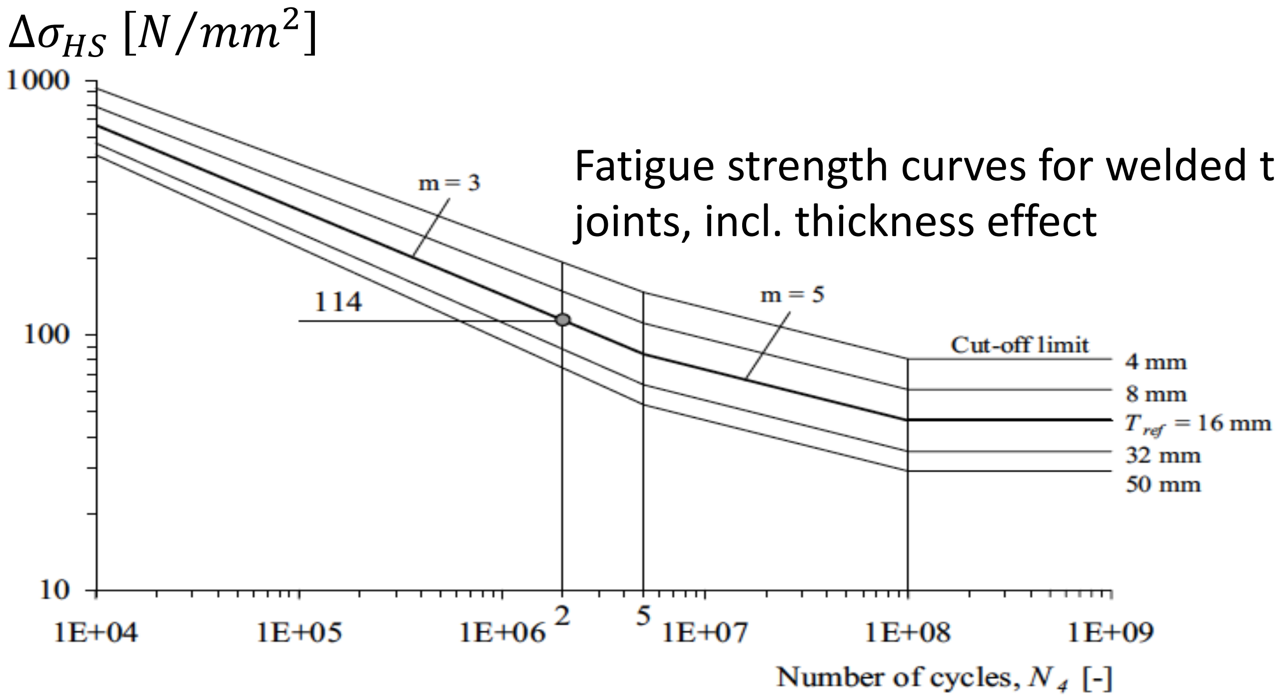
- Hot-Spot Method, from stress to hot spot, FEM calculations
- Eurocode EN 1993-1-9, Annex B
- Eurocode EN 1993-1-14 (new)
- CIDECT and IIW Guides



Getting started in SCF's FEM modeling:
IIW-doc. XIII-2650-16,
Round robin on local stress evaluation for fatigue by various FEM software (benchmark examples , with meshes given)

Fatigue of tubular structures, of tubular nodes

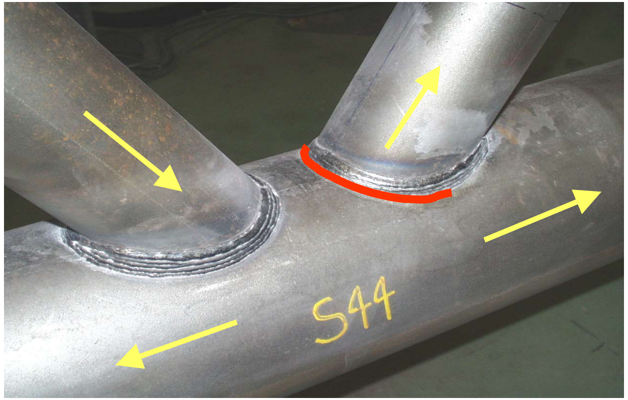
- Hot-Spot Method, from stress to hot spot, FEM calculations
- Eurocode EN 1993-1-9, Annex B
- Eurocode EN 1993-1-14 (new) => Determination of $\Delta\sigma_{Ed,HS}$
- CIDECT and IIW Guides



Fatigue strength curves for welded tubular joints, incl. thickness effect

Tubular nodes:
Examples of design/strength improvement studies

- Fatigue always at the foot of the chord



1) Put the weld out of the stressed area

Conventional butt welds

2) Use finishing methods to introduce residual compressive stresses

Content

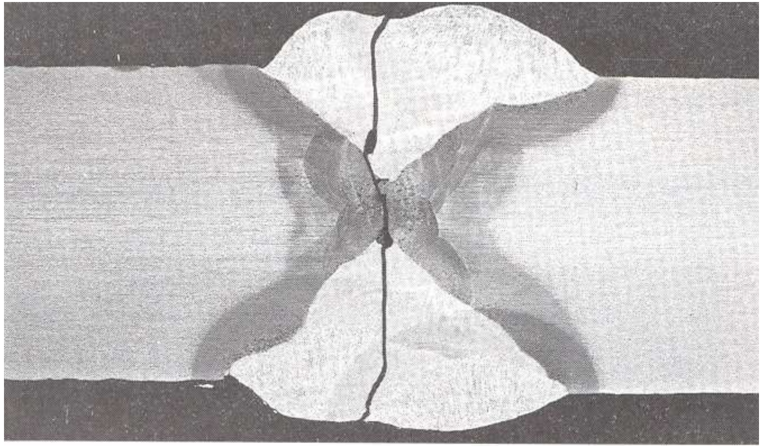
- Fatigue normalized curves
- Types of details and diff. resistance curves
- Bolted, riveted connections
- Welded Connections
- Hot-spot method
- **Execution of welds**

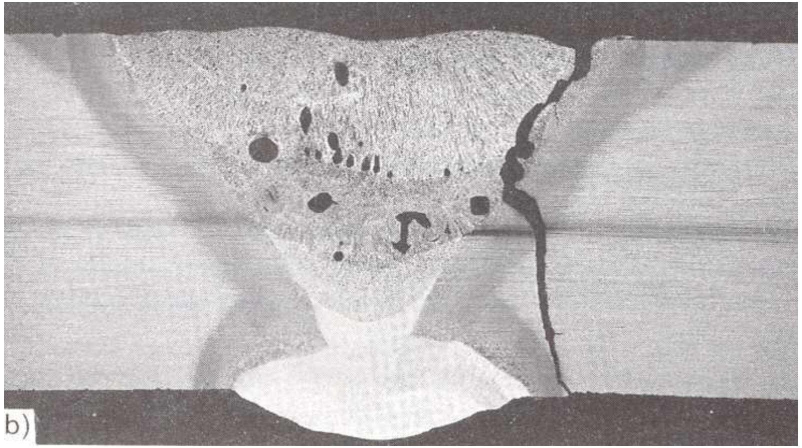
Execution of welds

Have a great influence on fatigue resistance:

- quality of the work
- Weld specifications (type, controls)

Example, butt welding:





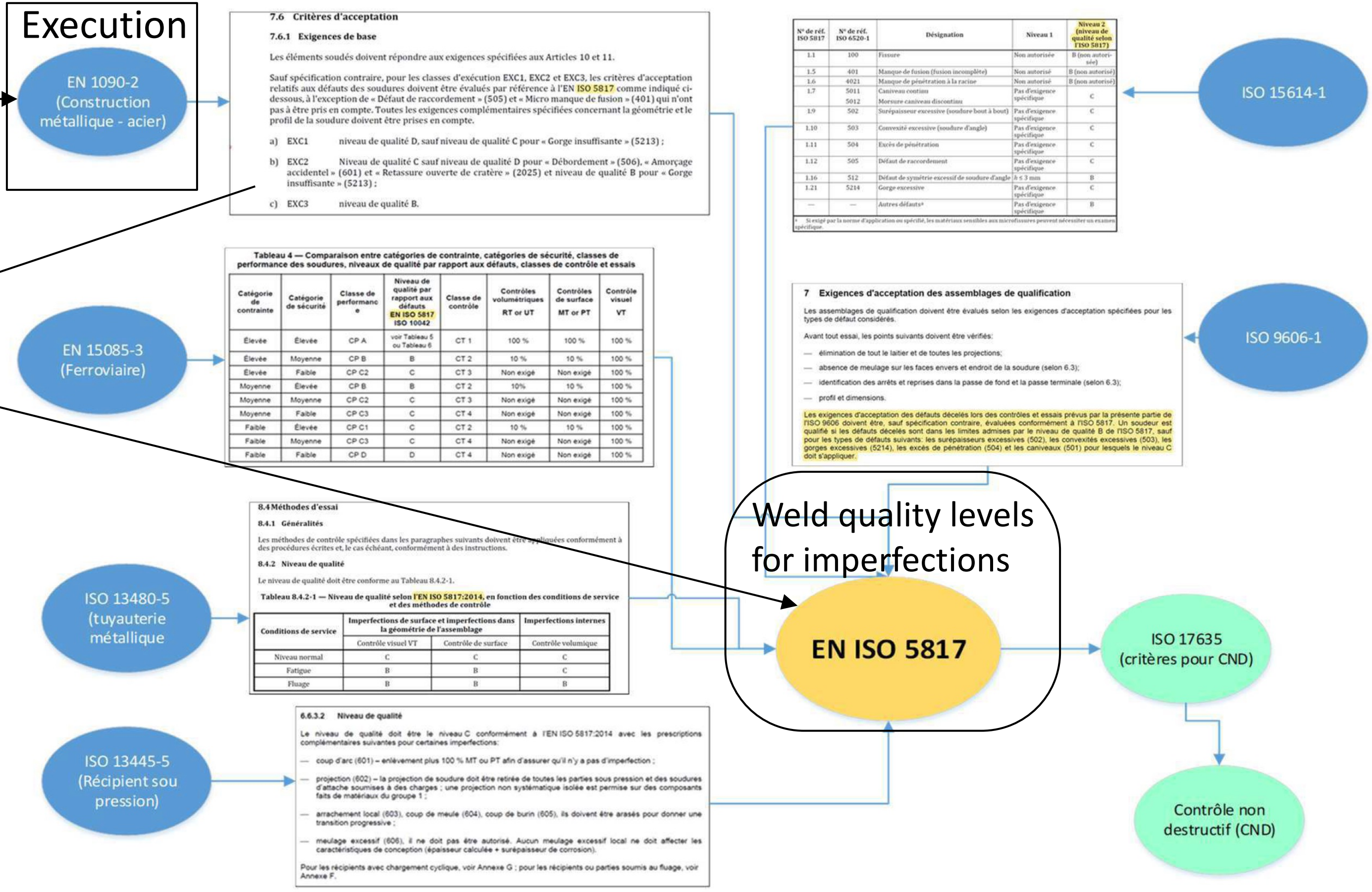
Réf.: J. Maljaars, TNO

Quality control <=> guaranteed FAT classes

Design:
SIA 263
EN 1993-1-1

EXC 2 ⇔ C
EXC 3 ⇔ B

In fatigue, by default require B



Source:

SWISS WELDING INSTITUTE

END

of part 2

Appendices of Part 2

EN 1994-1-1: When is fatigue verification required ?

- Given in § 8.1
- Shall be verified where the structures are subjected to repeated fluctuations of stresses
- In bridges, in crane runways, masts, always required
- In buildings : only required where
  - Structural steel, shear connection, EN 1993-1-1 § 4(4) applies
  - Concrete, reinforcement, EN 1992-1-1 § 6.8.1 does not apply
- In other types of structures, silos, piling, … see relevant code parts

EN 1994-1-1: When is fatigue verification required ?

EN 1993-1-1 § 4(4):

For building structures no fatigue assessment is normally required except as follows:

a) Members supporting lifting appliances or rolling loads

b) Members subject to repeated stress cycles from vibrating machinery

c) Members subject to wind-induced vibrations

d) Members subject to crowd-induced oscillations.

EN 1992-1-1 § 6.8.1:

Verification conditions

- The resistance of structures to fatigue shall be verified in special cases. This verification shall be performed separately for concrete and steel
- A fatigue verification should be carried out for structures and structural components which are subjected to regular load cycles (e.g. crane-rails, bridges exposed to high traffic loads).

Annex: Implementation, quality control

- According to EN 1090-2 since 2014 (replaces SIA 263/1)

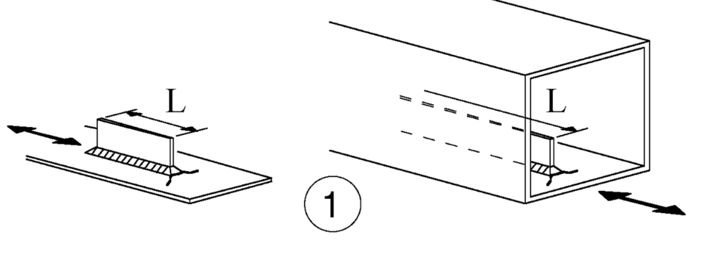
- For welding in particular:

- Requirements according to class of execution:
    - EXC1: EN ISO 3834-4 «Basic Quality Requirements »
    - EXC2: EN ISO 3834-3 «Normal Quality Requirements »
    - EXC3 et EXC4: EN ISO 3834-2 «Higher Quality Requirements »
- Acceptance criteria, reference to ISO 5817:2014. EXC4 must meet, at a minimum, the EXC3 requirements. Additional requirements to be specified (on a case-by-case basis)
- Static loads, EXC2 ⇔ EN 1993-1-8
- New in 2024: Fatigue loads as a function of detail category (DC) ⇔ EN1993-1-9
- Note: fillet welds can only satisfy EXC2

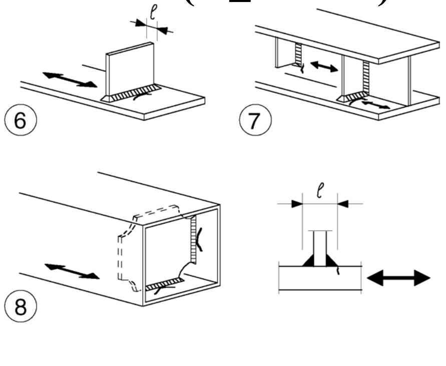
Fatigue requirements

- The Project shall specify relevant acceptance criteria in relation to DCs (FAT) for the location of welded assembly
- EXC2, EXC3 and EXC4, in addition to criteria specified (in EN ISO 5817):
    - DC not exceeding 63: quality level C63
    - DC greater than 63 and not exceeding 90: quality level B90
    - DC greater than 90 and not exceeding 125: quality level B125
- Must meet performance requirements in Tables EN1993-1-9, EN1993-2

DC 80 (L≤ 50 mm) à DC 56 (L > 100)



DC 80 (L ≤ 50 mm)



Weld controls and basic tests

- EXC1, EXC2 and EXC3, scope of testing according to EN1090-2, Table 24
- EXC4, range of additional controls to be specified for each identified weld
- Controls and testing: basic or project-specific

EN1090-2, Table 24: Scope of Type Controls

Type de soudure	Soudures d'atelier et de chantier		
	EXC1	EXC2	EXC3 [a]
Soudures transversales à pleine pénétration et soudures à pénétration partielle dans les assemblages en bout :	0 % [b]	10 %	20 %
Soudures transversales à pleine pénétration et soudures à pénétration partielle : — dans les assemblages en croix — dans les assemblages en T	 0 % [b] 0 %	 10 % 5 %	 20 % 10 %
Soudures d'angle transversales [c] : avec $a > 12$ mm ou $t > 30$ mm avec $a \leq 12$ mm et $t \leq 30$ mm	 0 % 0 %	 5 % 0 %	 10 % 5 %
Soudures longitudinales à pleine pénétration entre l'âme et la semelle supérieure des poutres de ponts roulants	0 %	10 %	20 %
Autres soudures longitudinales [d], soudures de raidisseurs et soudures spécifiées comme étant en compression dans le cahier des charges d'exécution	0 %	0 %	5 %

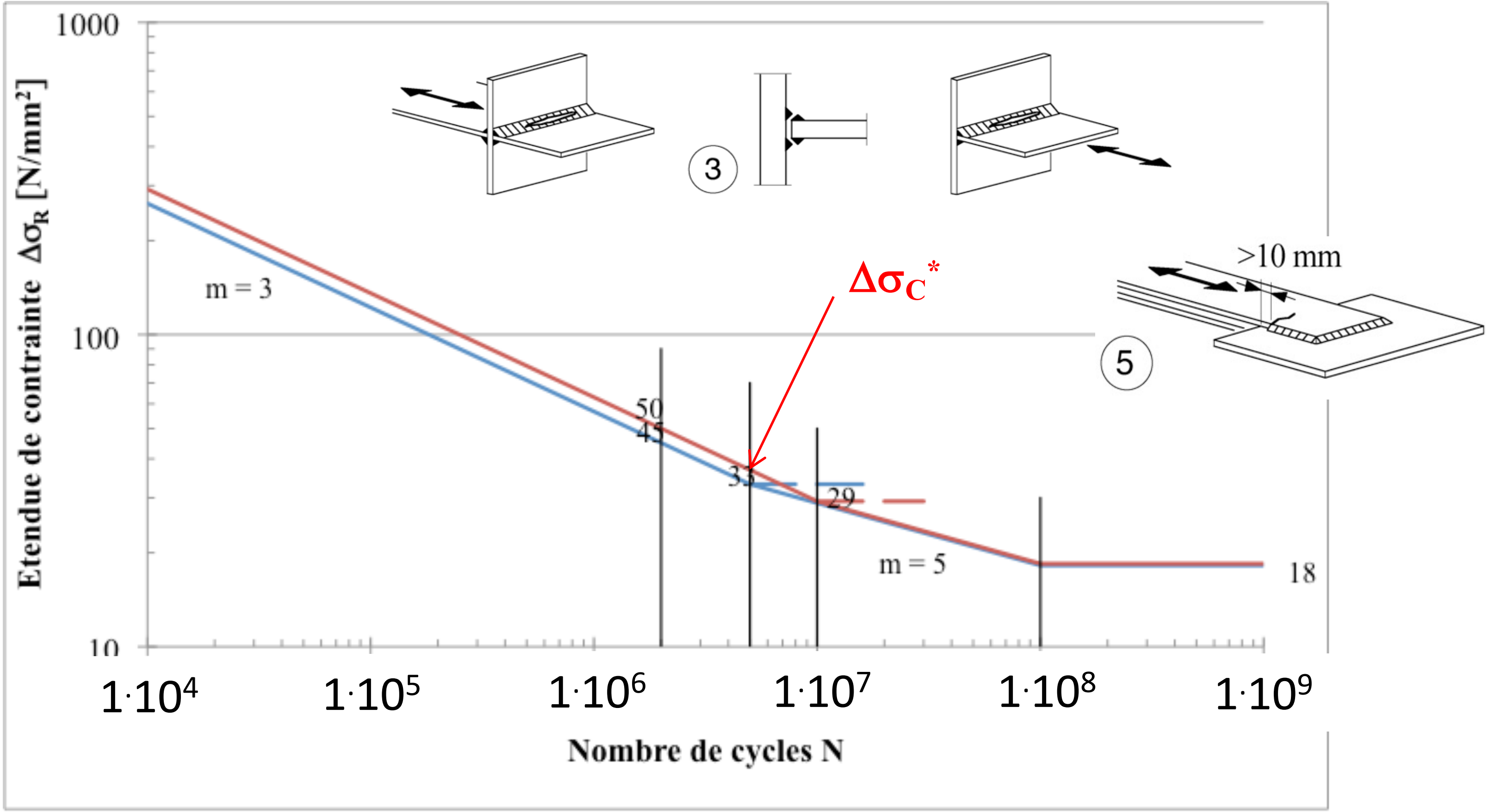
a Pour la classe EXC4, l'étendue des contrôles en pourcentage doit etre au moins celui donné pour la classe EXC3.

b 10 % pour de telles soudures exécutées en acier ≥ S420.

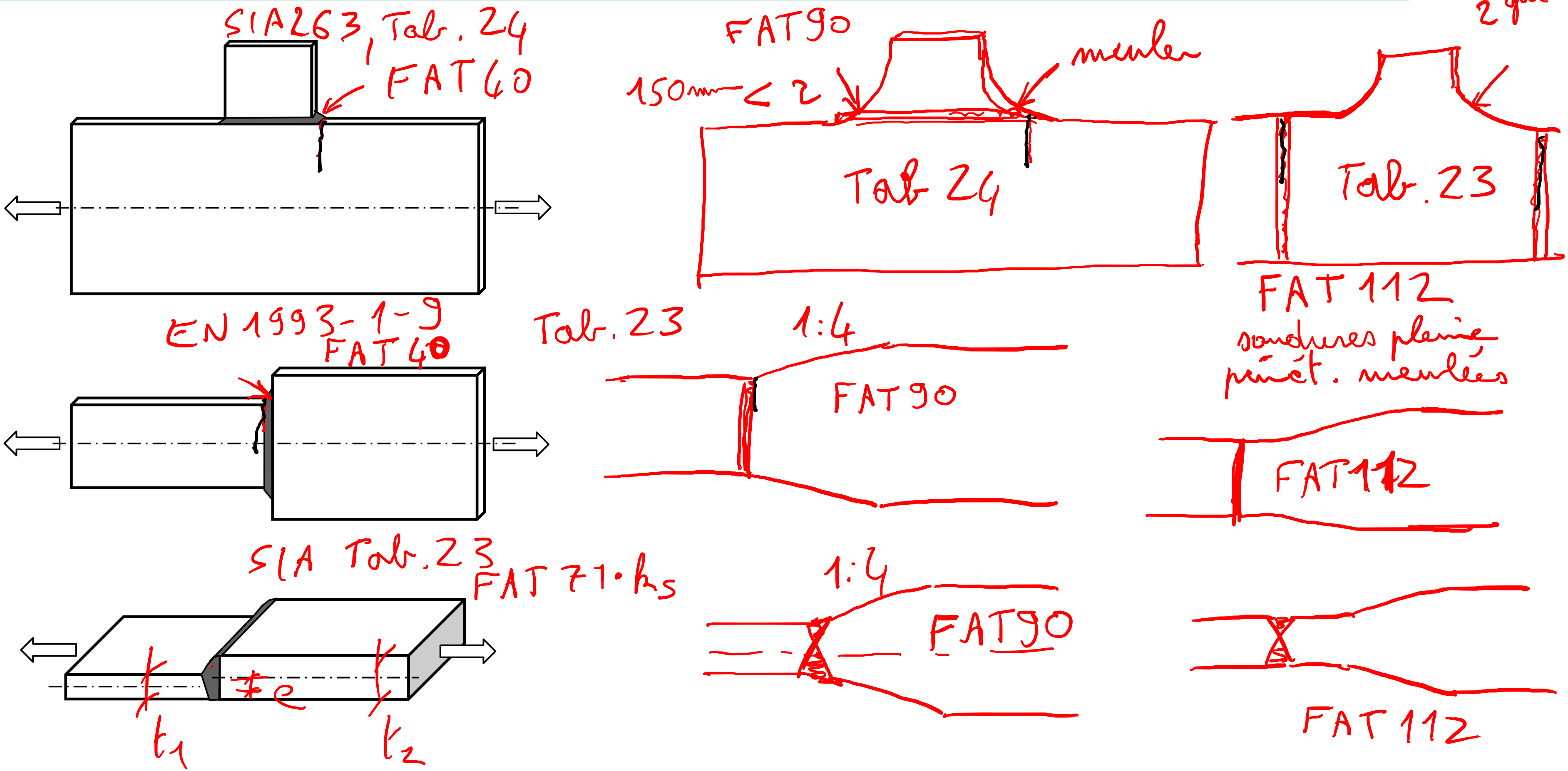
c Les termes a et t se rapportent respectivement à l'épaisseur de gorge et à l'épaisseur du matériau le plus épais devant être assemblé.

d Les soudures longitudinales sont celles réalisées parallèlement à l'axe de l'élément. Toutes les autres sont considérées comme des soudures transversales.

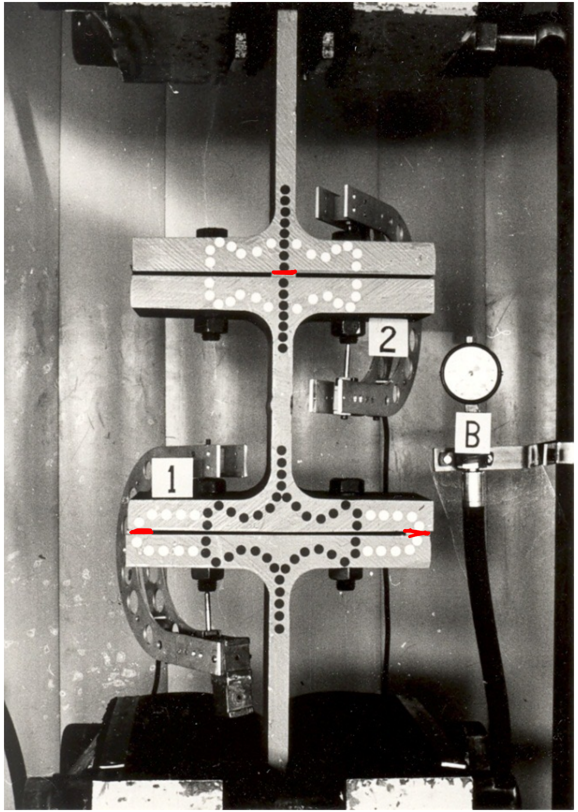
Annex: other curves, details classified as DsC*

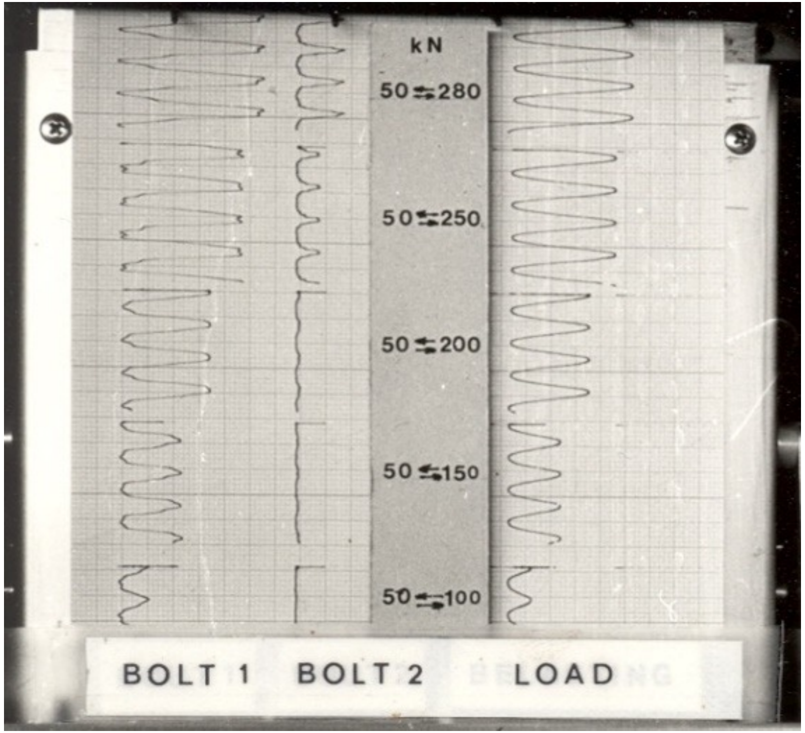


Examples of geometry changes to improve FAT



Bolted connections.
Relationship e.g. tensile force - external force

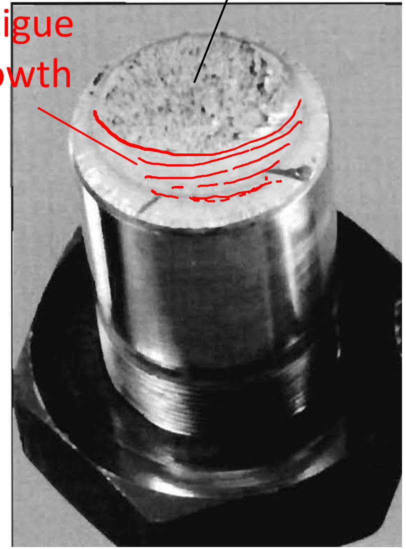




Réf.: J. Maljaars, TNO

Final fracture

Fatigue growth



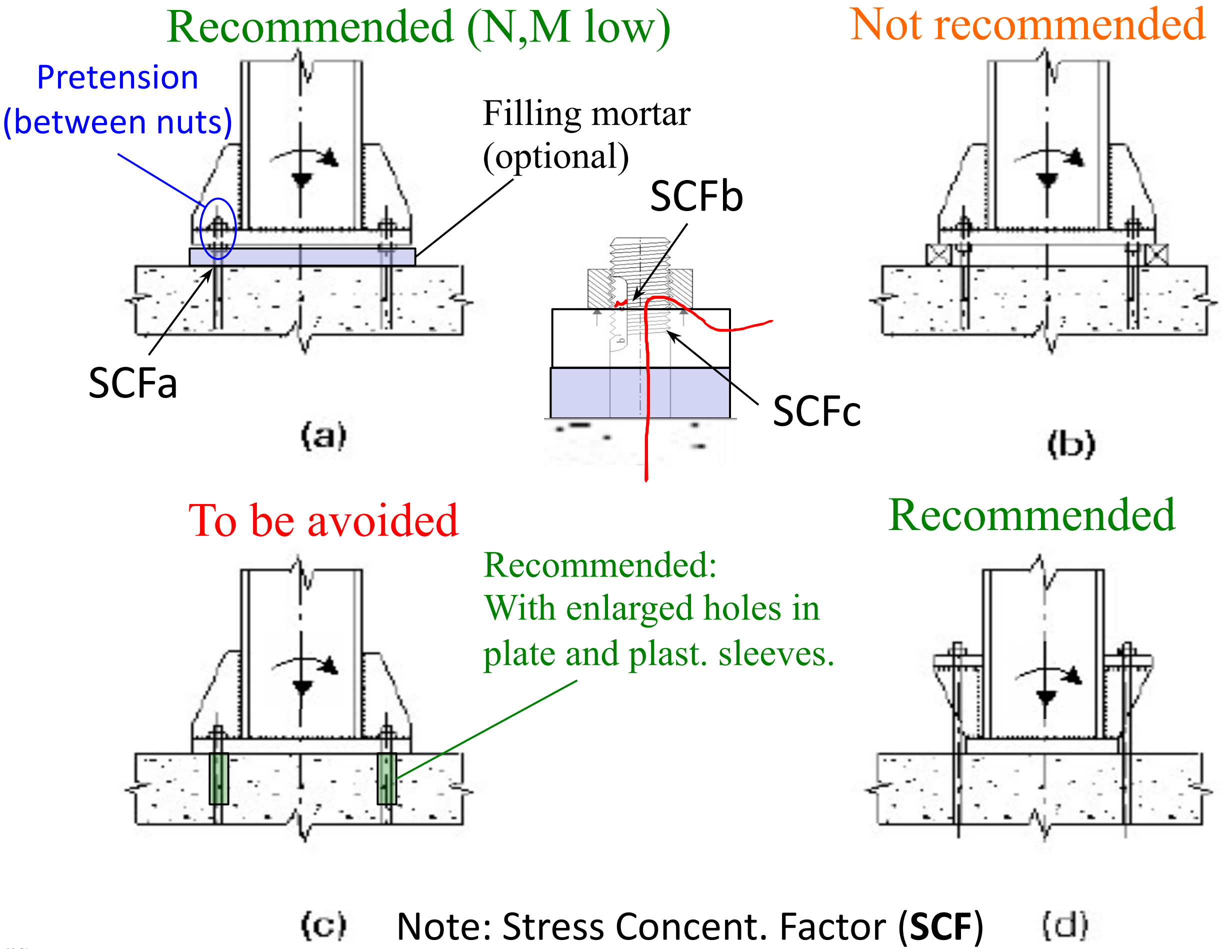
Réf.: Caterpillar, analyzing fractures part1

Platines: best solution for bolted assembly?

Supports de structures panneaux de signalisation

Platines: Best Solution for Bolted Assembly ?

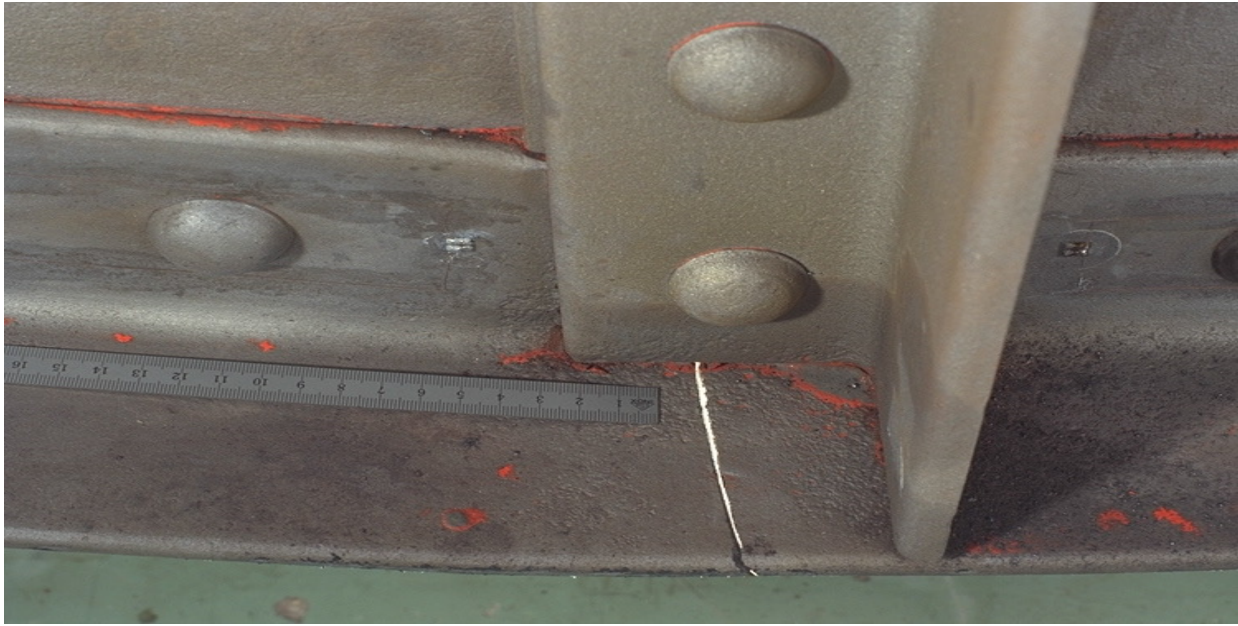
On the platform, Bern station



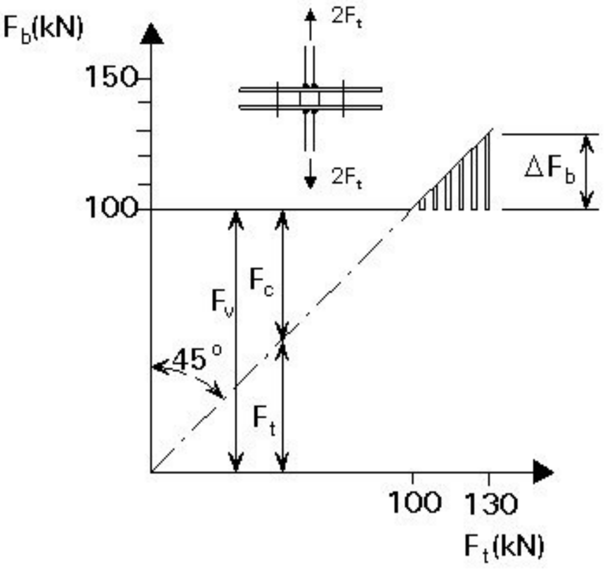
Note: Stress Concent. Factor (**SCF**)

Riveted connections, FAT 71 (not in SIA 263 or Eurocode 3)

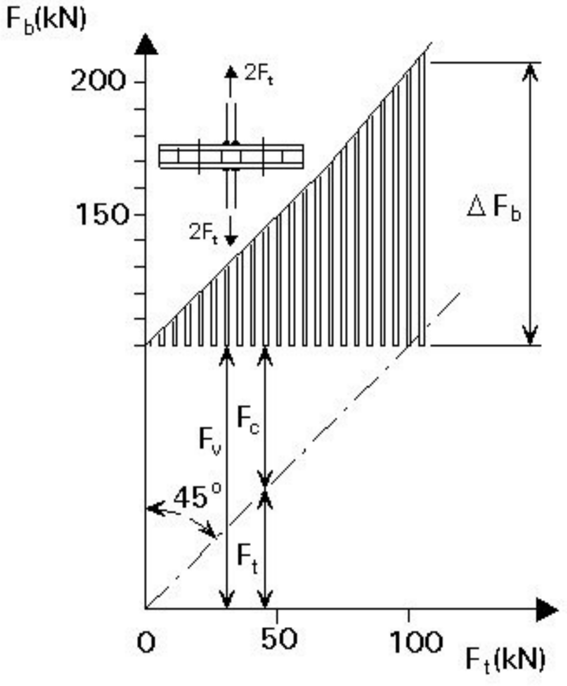
- In SIA 269/3 (existing structures)



- Prestressed
- Depending on contact position



(a) Contact force in centre

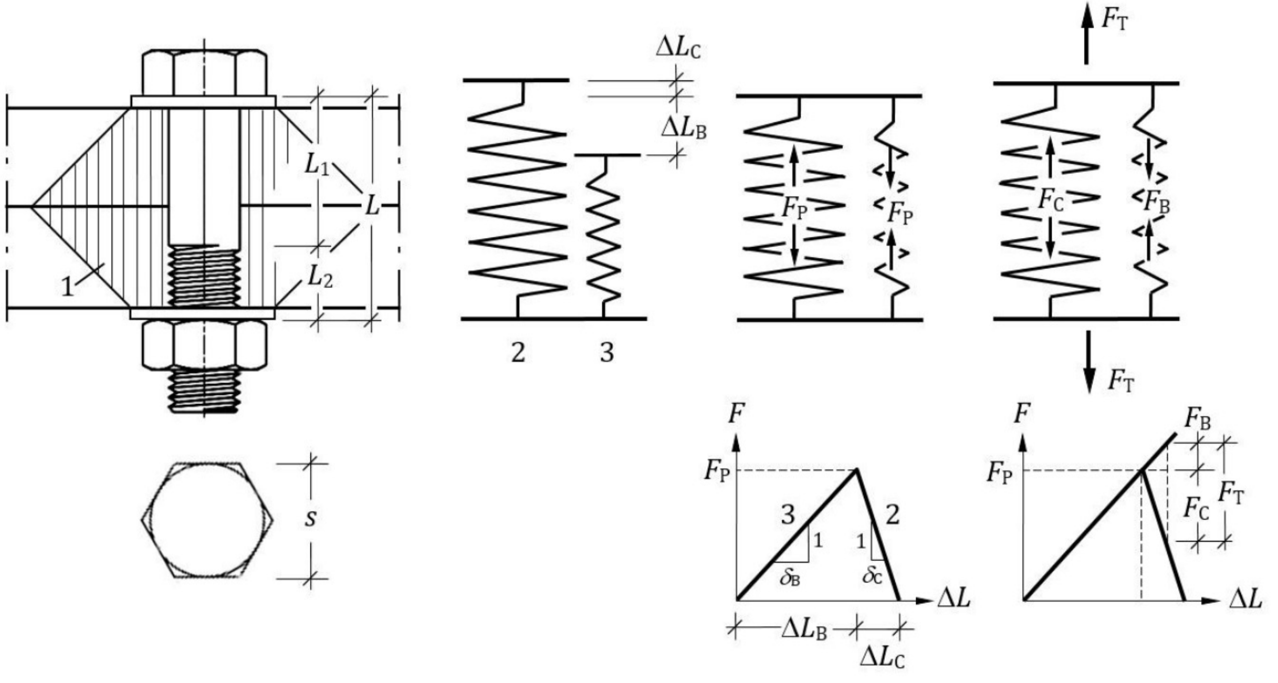


(b) Contact forces located at flange edges.

Réf.: cours Esdep

Prestressed bolted connections, computation of force range

- EN 1993-1-9 : draft 2022. Annex D



a) dimensions

b) spring model before preloading

c) spring model after preloading

d) spring model with forces due to external force

Additional tensile force F_B on bolt, reduction compressive force F_C

$$F_B = \frac{\delta_c}{\delta_b + \delta_c} F_T$$

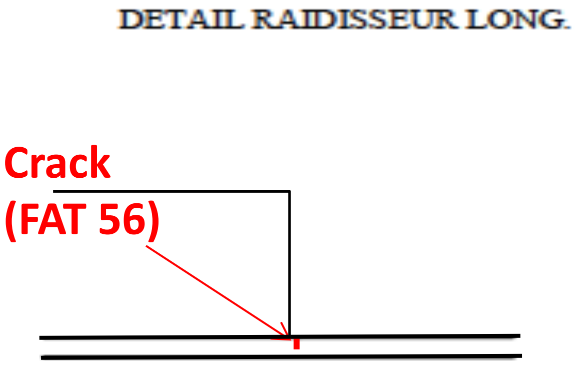
$$F_C = \frac{\delta_b}{\delta_b + \delta_c} F_T$$

Flexibility of bolt δ_b and of clamped components δ_c

$$\delta_b = \frac{L_1}{E\,(1{,}1\,A_S)} + \frac{L_2}{E\ A}$$

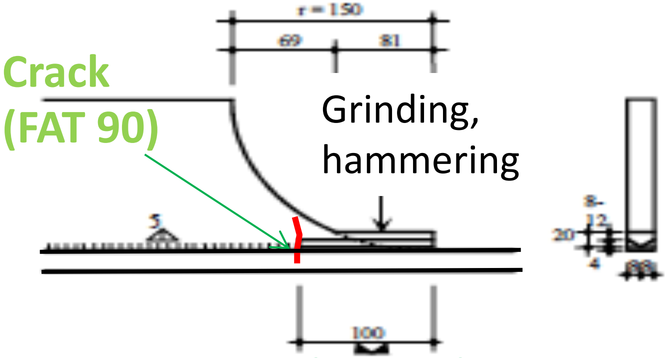
$$\delta_c = \frac{L}{A_p\ E}$$

Appendix: Example of a design improvement study: Longitudinal attachment ends (FAT 56)

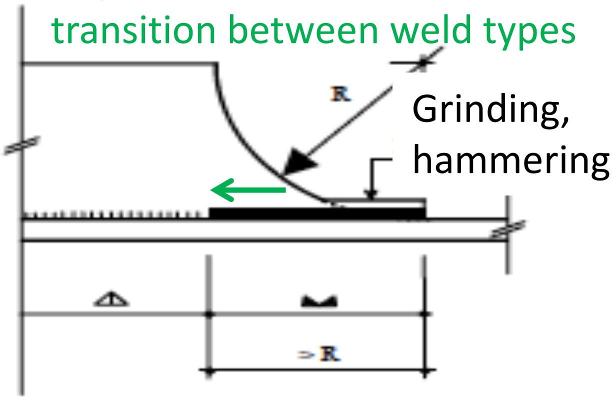


Appendix: Example of a design improvement study: Longitudinal attachment ends (FAT 56 **-> 80 -> 112**)

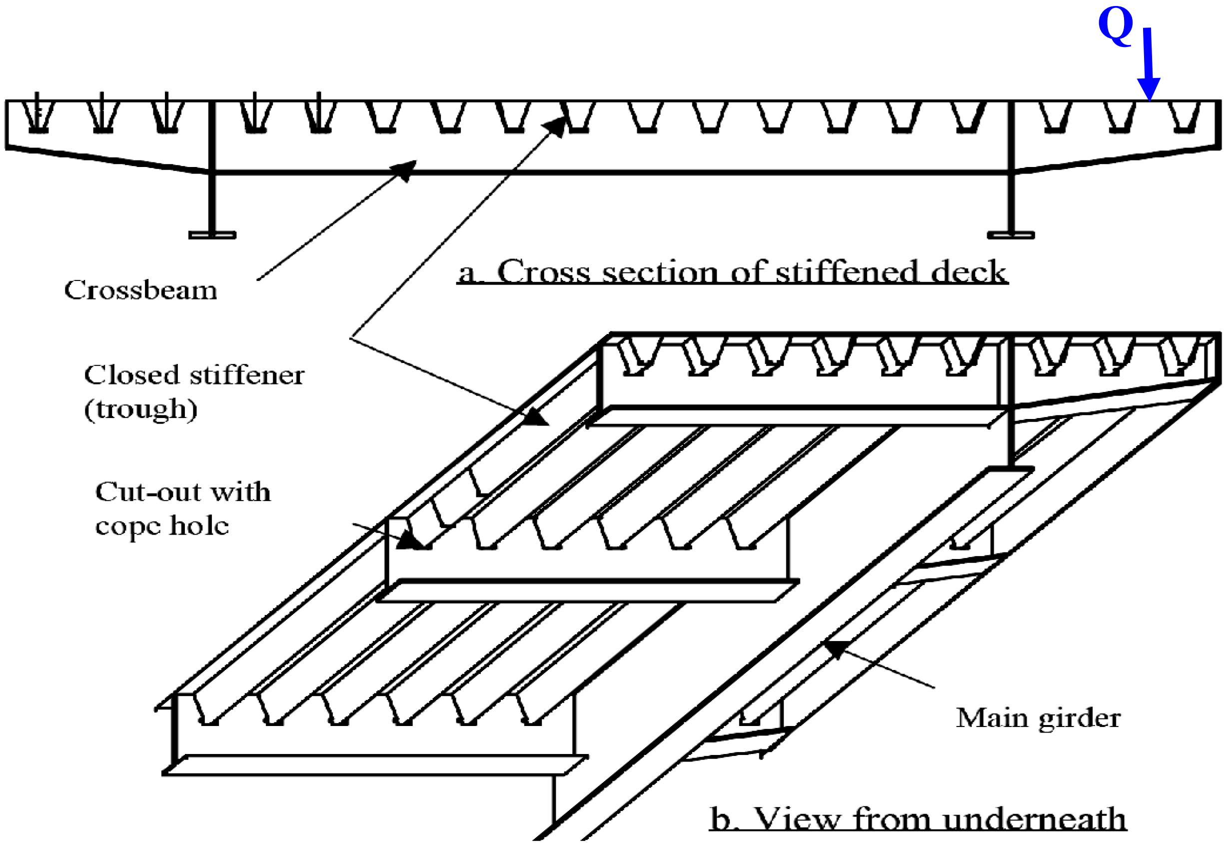
Improv. 1, rounded, chgt potential crack location



Improv. 2 (FAT 112) Setback of transition between weld types



Annex: orthotropic slabs, components and features, fct in 3D



Behavior:

1. Transv. flexion decking
2. Long flexion. bucket + decking, rotations at supports
3. Transv. bending, shear spacer + decking
4. Loads in main beams

=> Strut core subjected to stress in and out of its plane

Orthotropic slabs, 2 "optimal" design solutions

1. USA design: Low spacing between struts (2 to 3 m), therefore reduced height of the buckets and struts. Bucket height = width, spacing 300 to 600 mm. For good fatigue behavior, cuts as small as possible, addition of reinforcement plates in the buckets (improves spacer behavior in its plane, reduces shear deformations.) Rotations imposed by the buckets remain small (spans, height), limited out-of-plane deformations.
2. EU design: widely spaced spacers (3 to 5 m), therefore a minimum of high spacers. We need more buckets, higher too. The troughs are higher than they are wide, spaced 600 to 900 mm apart. Detailed recommendations in EN 1993-2, Annex C. For good fatigue behaviour, wide cut-outs to accommodate the large rotations imposed by the buckets (out-of-plane behaviour). Behavior in the spacer plane ok because of the great height, so limited shear deformations.

Orthotropic slabs, cracking areas to be checked