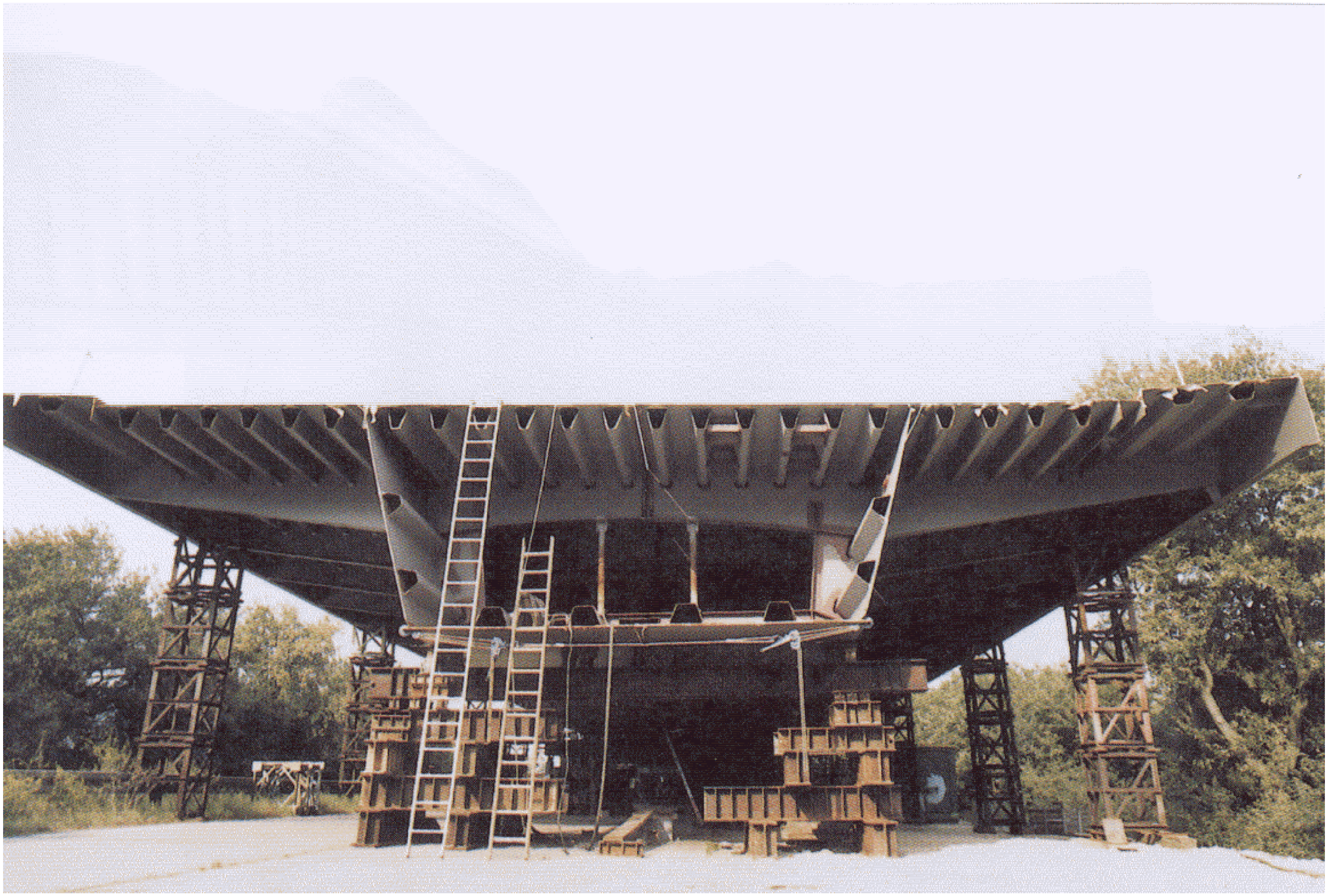
Design of steel-bridges

Overview of key content of EN 1993-Eurocode 3
Illustration of basic element design

G. Hanswille, W. Hensen, M. Feldmann, G. Sedlacek

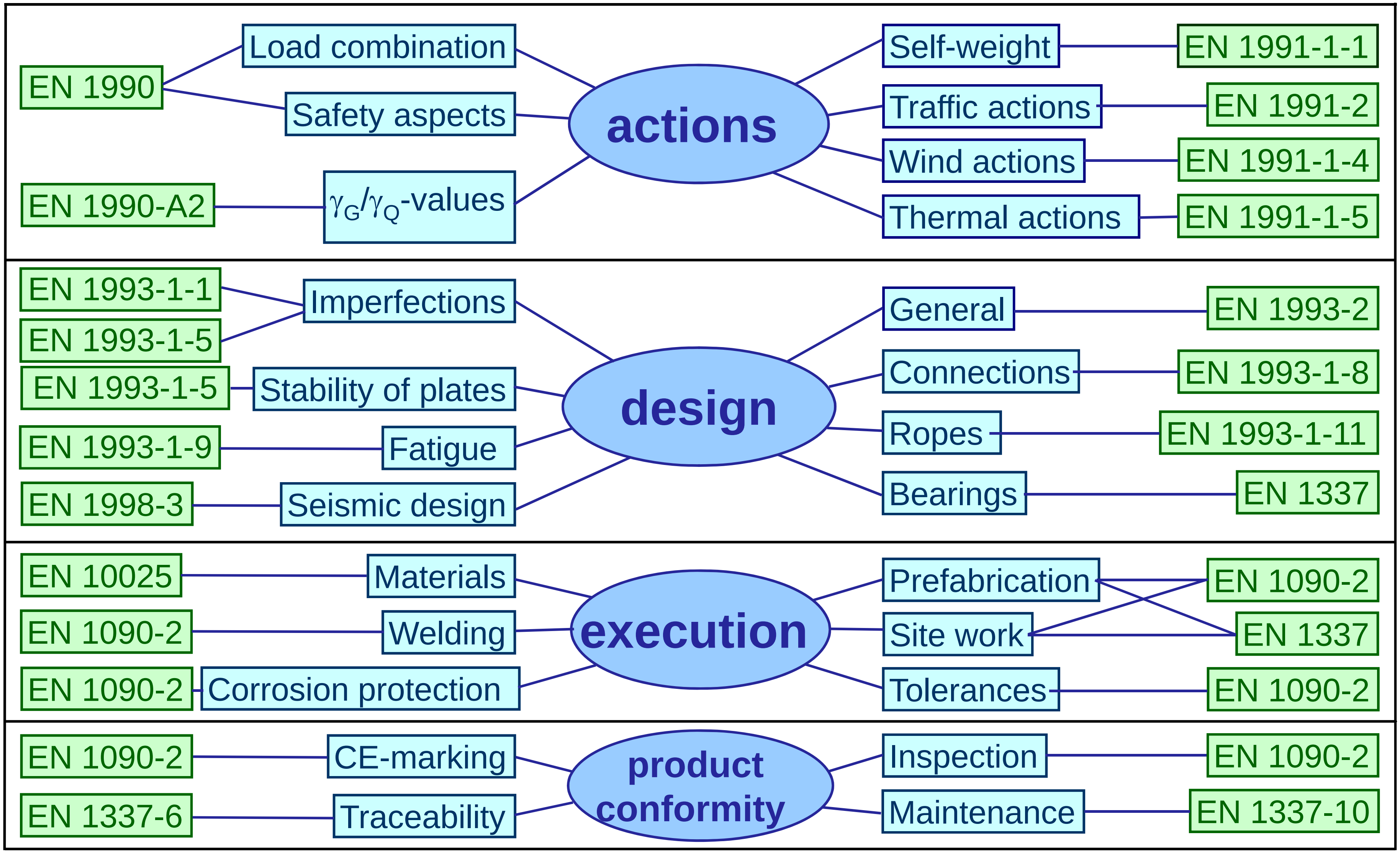
LIST OF CONTENTS

CROSS SECTION OF A BOX GIRDER BRIDGE WITH AN ORTHOTROPIC DECK



HASELTALBRÜCKE SUHL

NAVIGATION THROUGH STANDARDS



SURVEY OF THE EUROCODES

EN 1990
Eurocode: Basis of Design

EN 1991

Eurocode 1: Actions on Structures

- 1-1 Self weight
- 1-2 Fire Actions
- 1-3 Snow
- 1-4 Wind
- 1-5 Thermal Actions
- 1-6 Construction Loads
- 1-7 Accidential Actions
- 2 Traffic on bridges
- 3 Loads from cranes
- 4 Silo loads

EN 1992 to EN 1996

- Eurocode 2: Concrete structures
- Eurocode 3: Steel structures
- Eurocode 4: Composite structures
- Eurocode 5: Timber structure
- Eurocode 6: Masonry structures

EN 1997 and EN 1998

- Eurocode 7: Geotechnical Design
- Eurocode 8: Design in seismic areas

EN 1999

- Eurocode 9: Aluminium structures

1. THE EUROPEAN STANDARD FAMILY AND STEEL BRIDGES

EN 1090 – Part 1 „Delivery Conditions for prefabricated steel components“

hEN product standards for steel materials, semi- finished products etc.

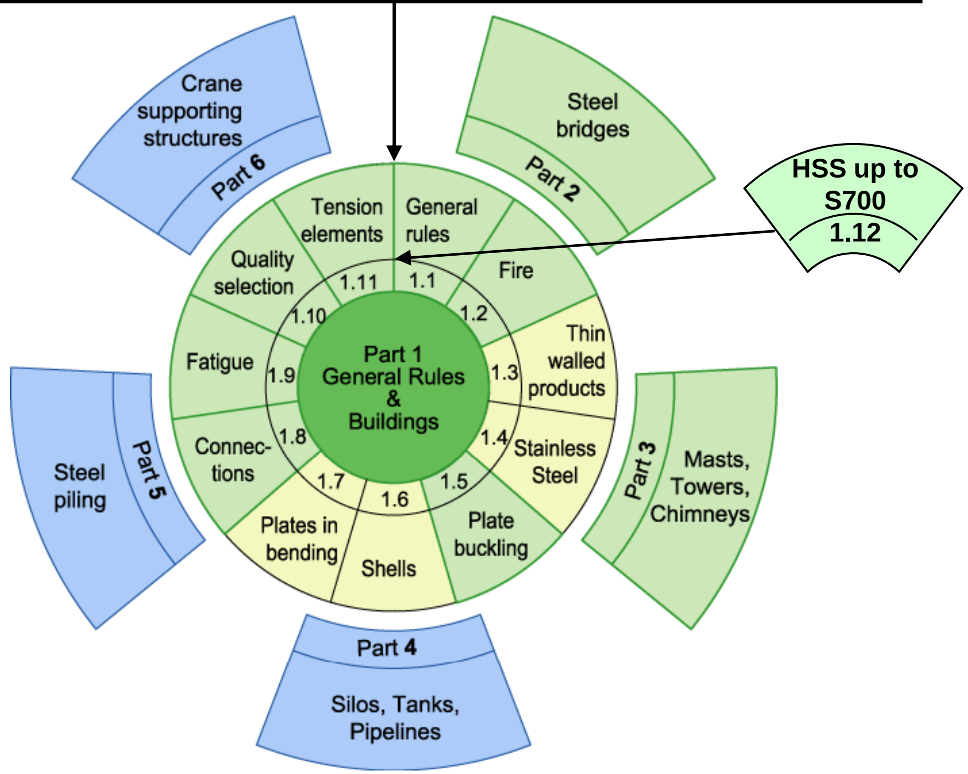
Eurocode: EN 1990 – „Basis of structural design“

Eurocode 1: EN 1991 – „Actions on structures“

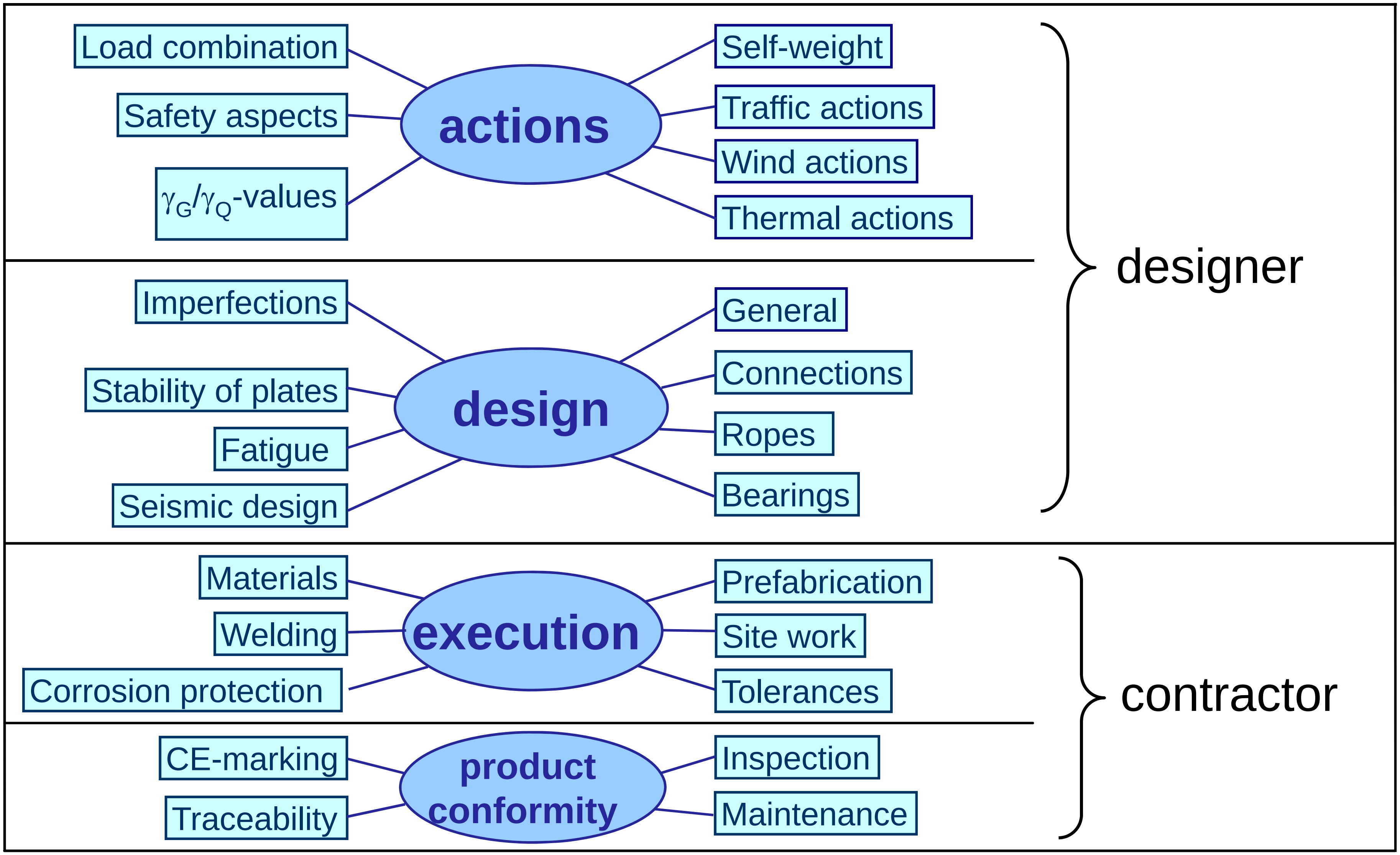
Eurocode 3: EN 1993 – „Design rules for steel structures“

EN 1090 – Part 2 „Execution of steel structures “

Standard system for steel structures



1. THE EUROPEAN STANDARD FAMILY AND STEEL BRIDGES



Tasks for designer and contractor

1. THE EUROPEAN STANDARD FAMILY AND STEEL BRIDGES

EN 1993-Part 1-1 General rules

1-5 Plate buckling

1-8 Connections

1-9 Fatigue

1-10 Choice of material

1-11 Rope structures

EN 1993-Part 2 Steel bridges

Annex A Requirements for bearings

Annex B Requirements for expansion joints

Annex C Recommendations for orthotropic plates

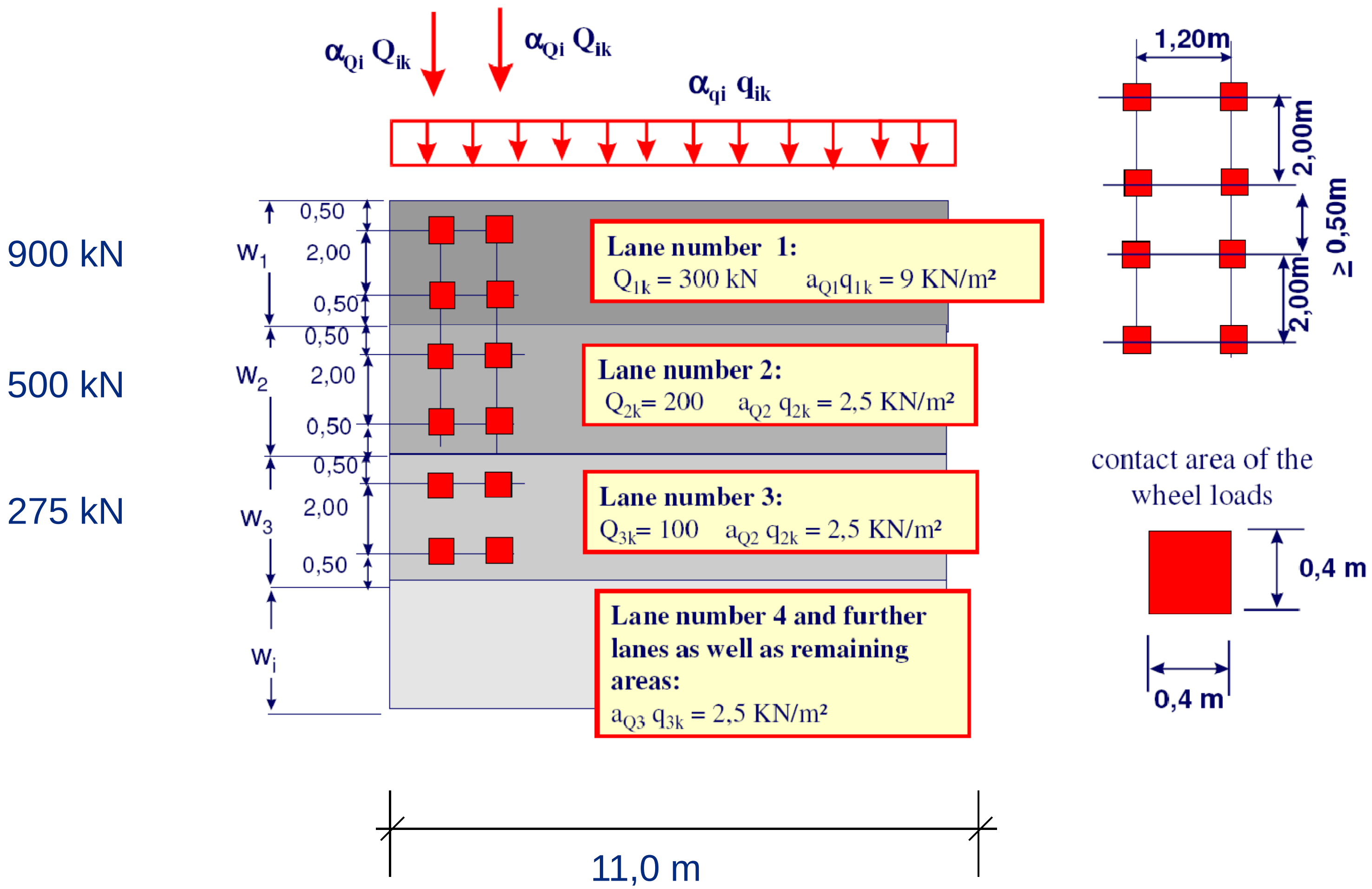
Design rules for steel bridges in Eurocode 3

1. THE EUROPEAN STANDARD FAMILY AND STEEL BRIDGES

Limit State Concept ULS $E_d \leq R_d$ SLS $E_d \leq C_d$ Fatigue $\Delta\sigma_E \leq \Delta\sigma_c$
Choice of material based on fracture mechanics (EN 1993-1-10)
Stability of members and plates Single λ-value for combined actions, FEM-methods (EN 1993-1-1) (EN 1993-1-5)
Fatigue assessments unless recommended details are used (EN 1993-2) (EN 1993-1-9)

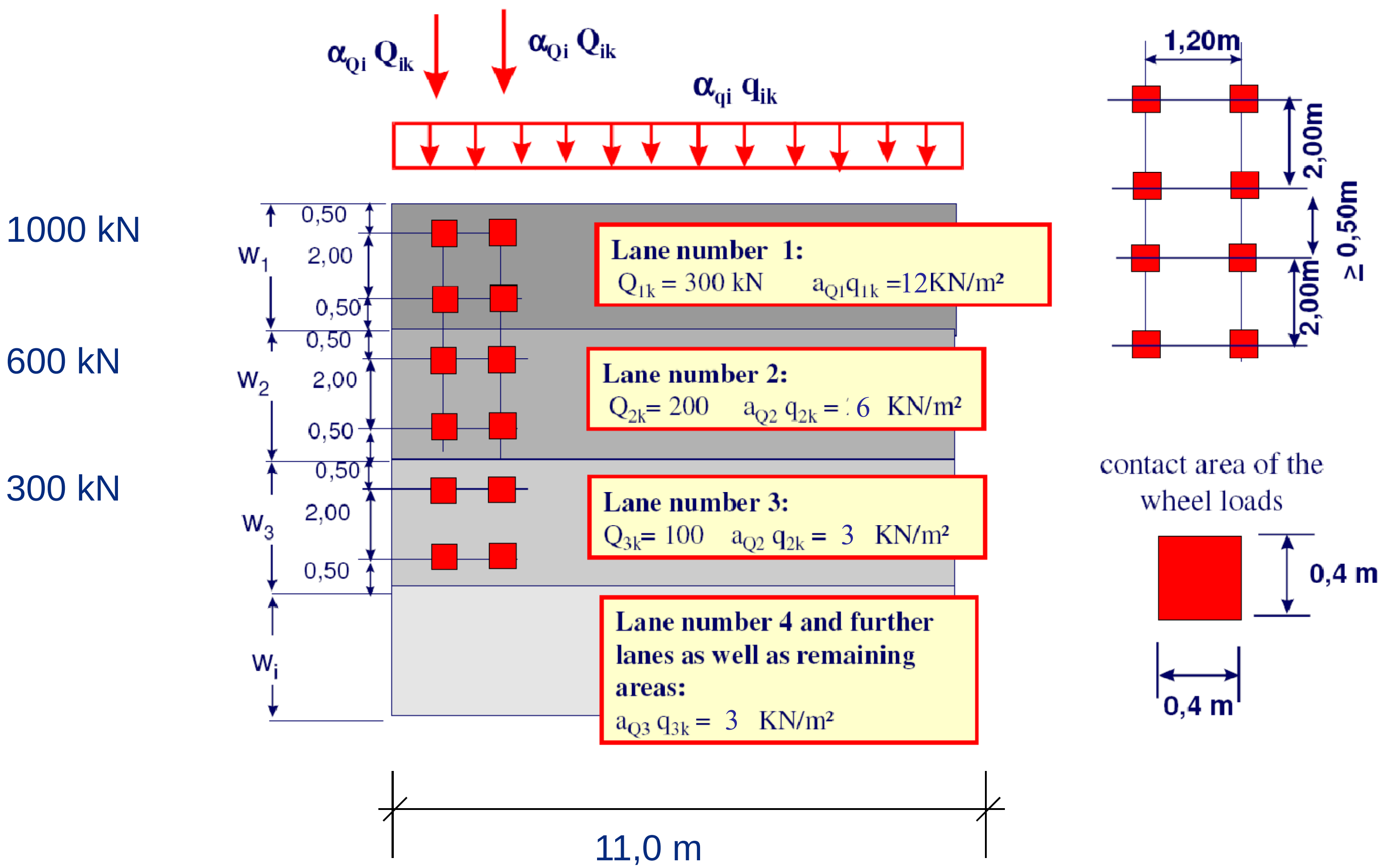
Basic features of design rules for bridges

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



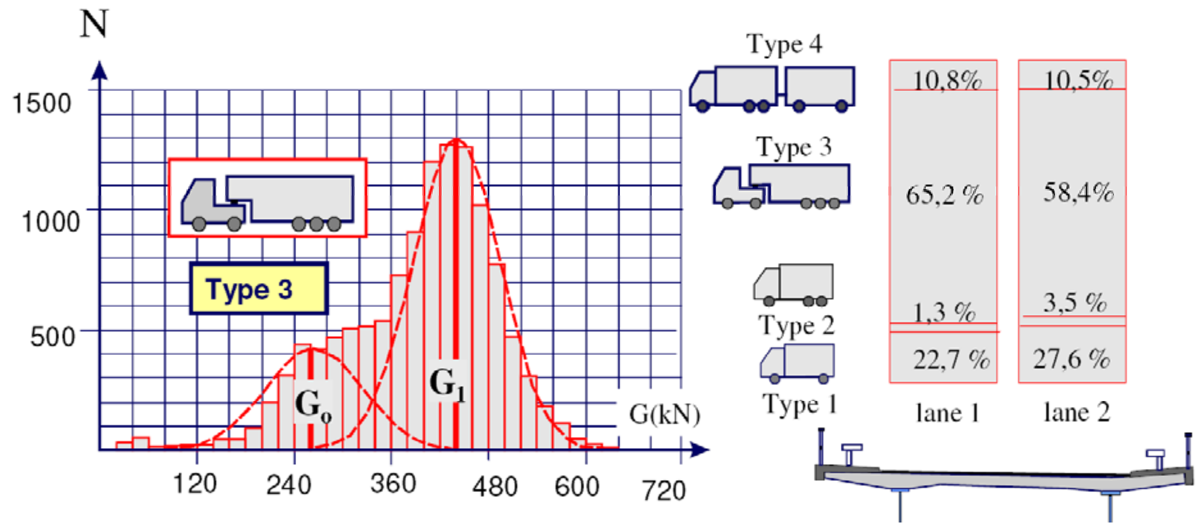
Load-model LM1

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



Load-model LM1 (draft German NA)

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

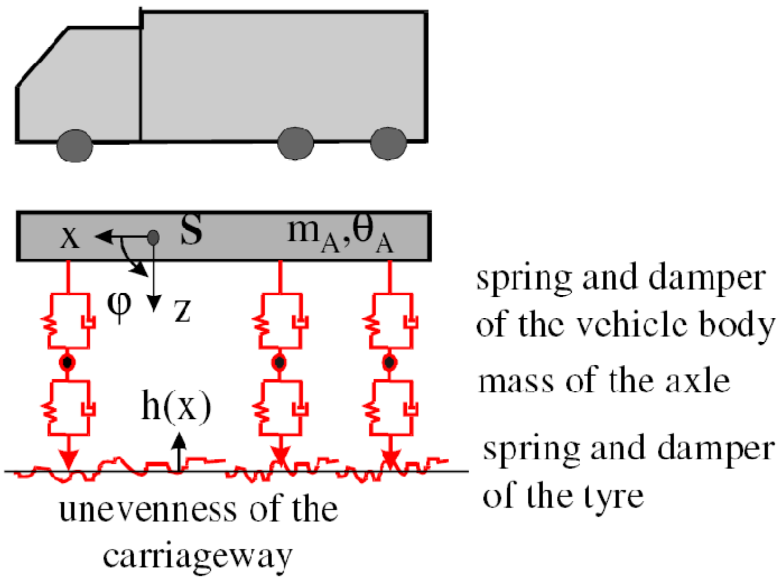


		mean value μ of the total vehicle weight kN		standard deviation σ kN		relative frequency %	
		Lane 1	Lane 2	Lane 1	Lane 2	Lane 1	Lane 2
Type 1	G_o	74	64	35	33	13,3	17,2
	G_l	183	195	28	34	9,4	10,4
Type 2	G_o	123	107	46	45	0,3	1,3
	G_l	251	257	38	43	1,0	2,2
Type 3	G_o	265	220	60	78	17,1	28,0
	G_l	440	463	54	79	48,1	30,4
Type 4	G_o	254	196	45	69	3,6	4,1
	G_l	429	443	68	78	7,2	6,4

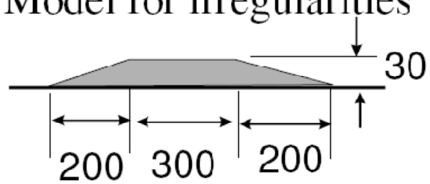
Statistical distribution of characteristics of vehicle

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

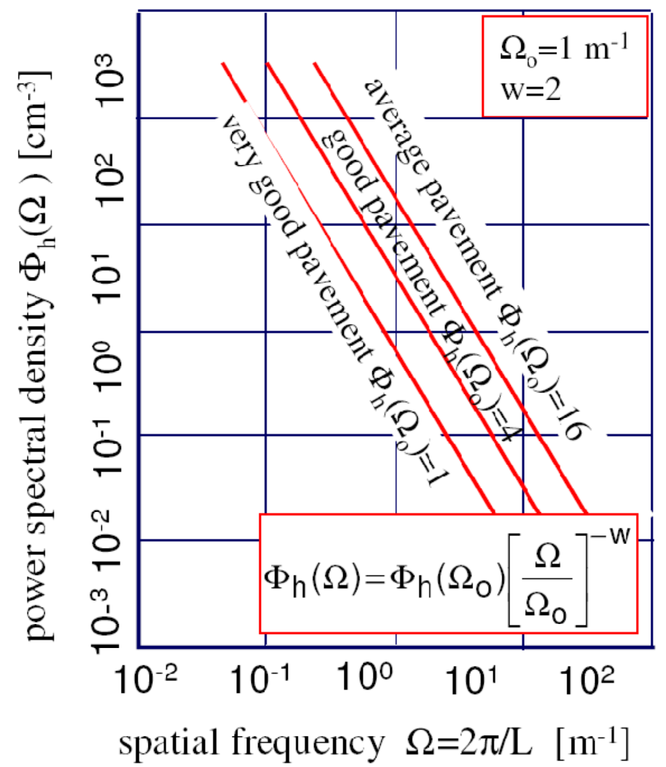
Modelling of the vehicles

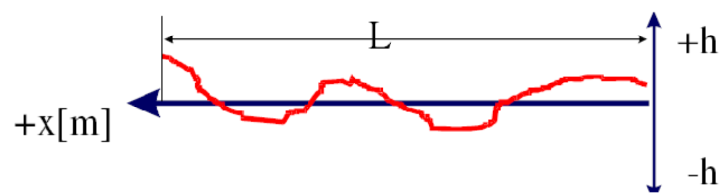


Model for irregularities



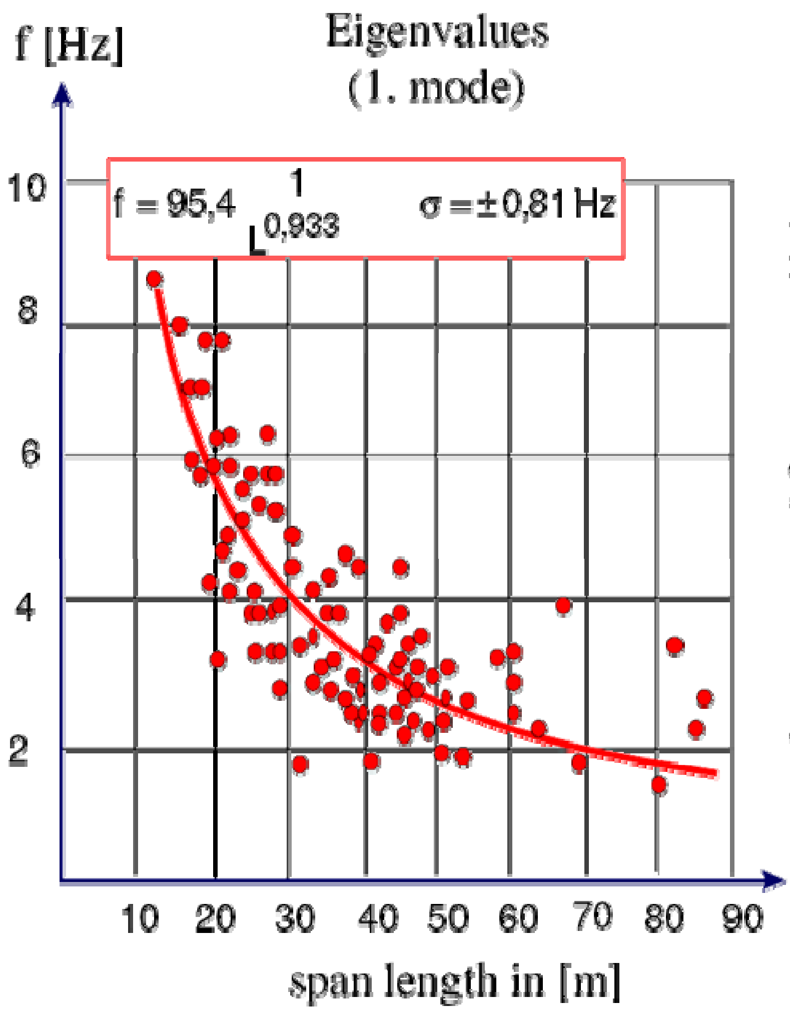
PSD- spectras acc. to ISO-TC 108

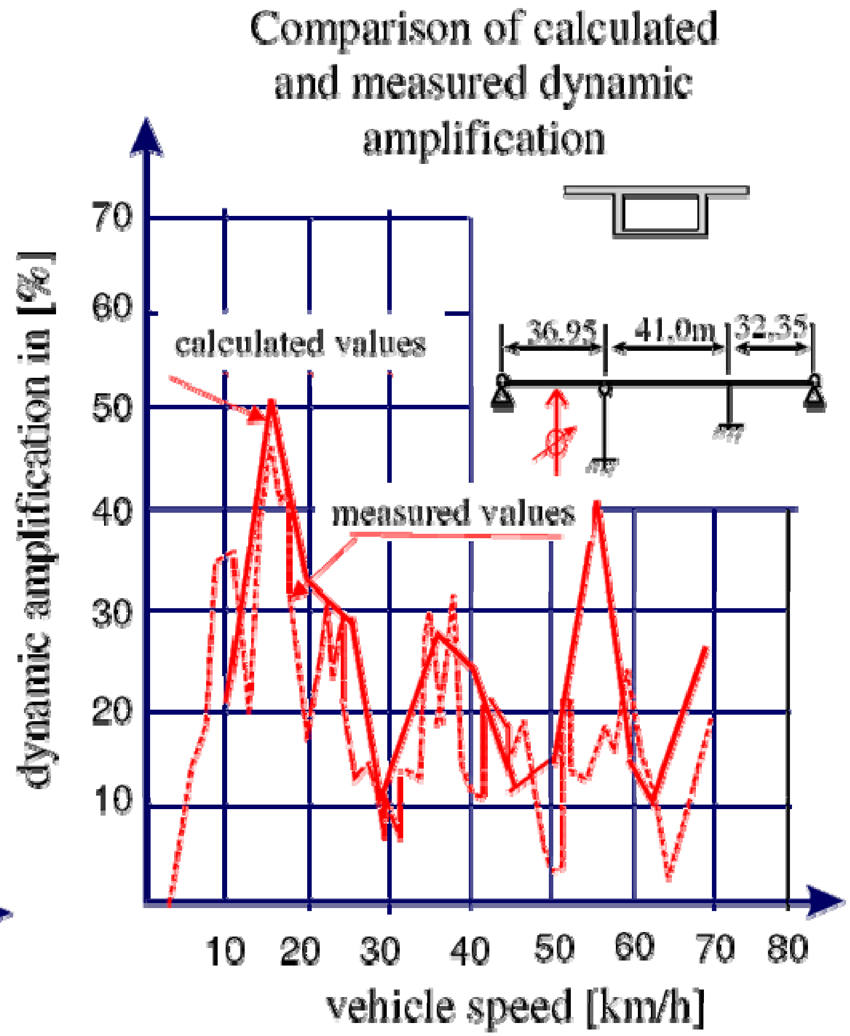




Modelling of vehicles and surfaces

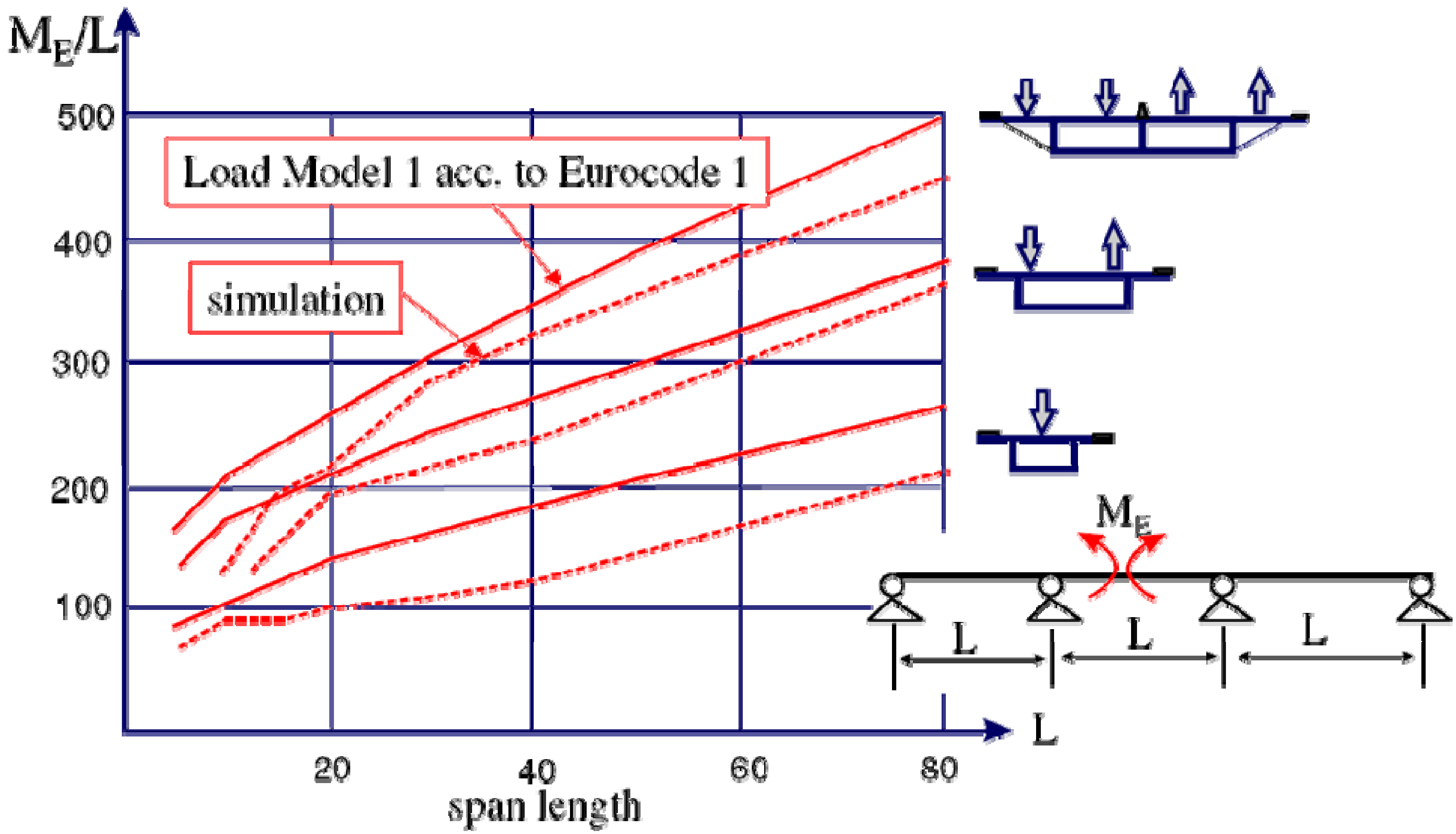
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES





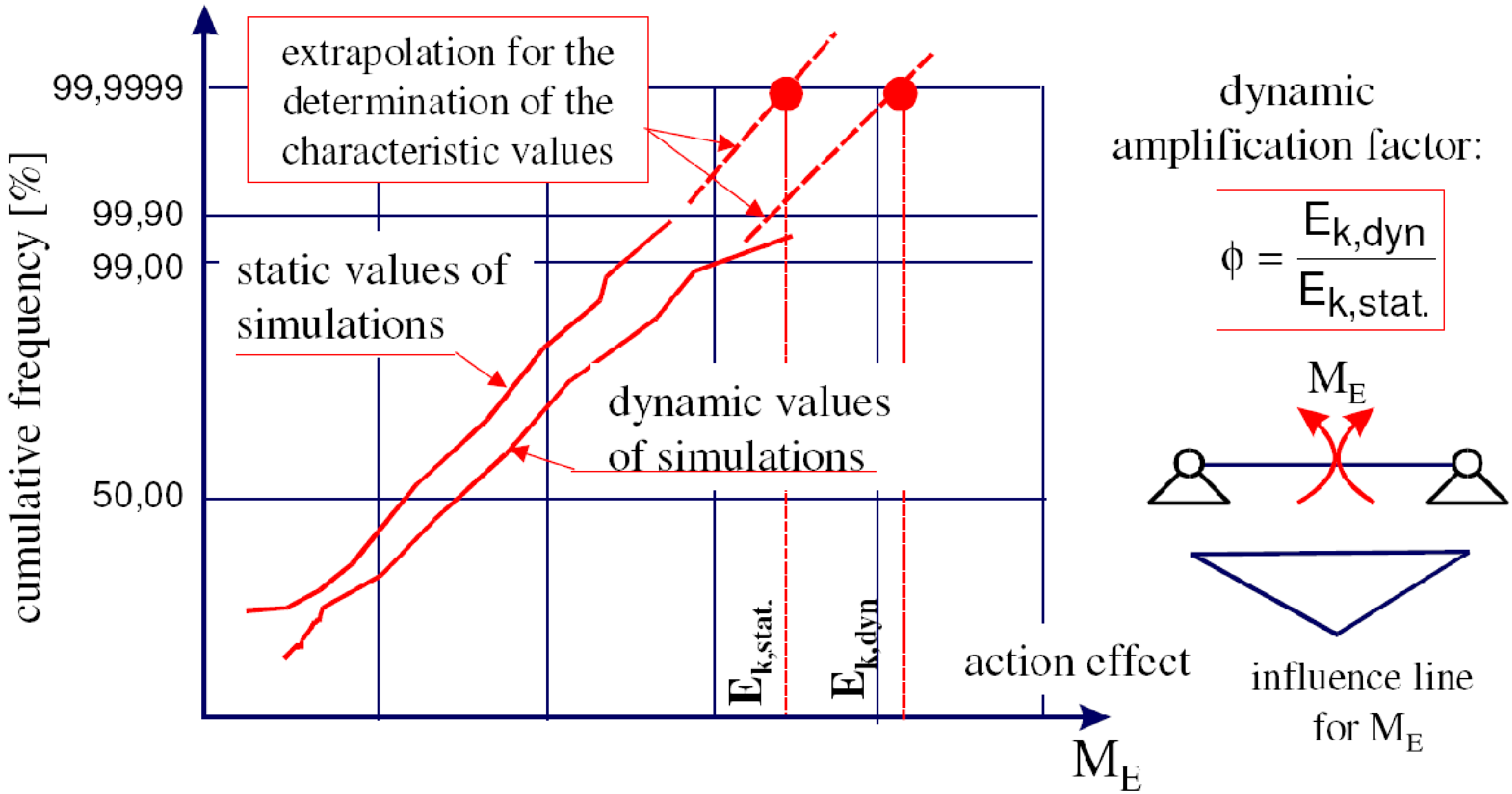
Modelling of bridges

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



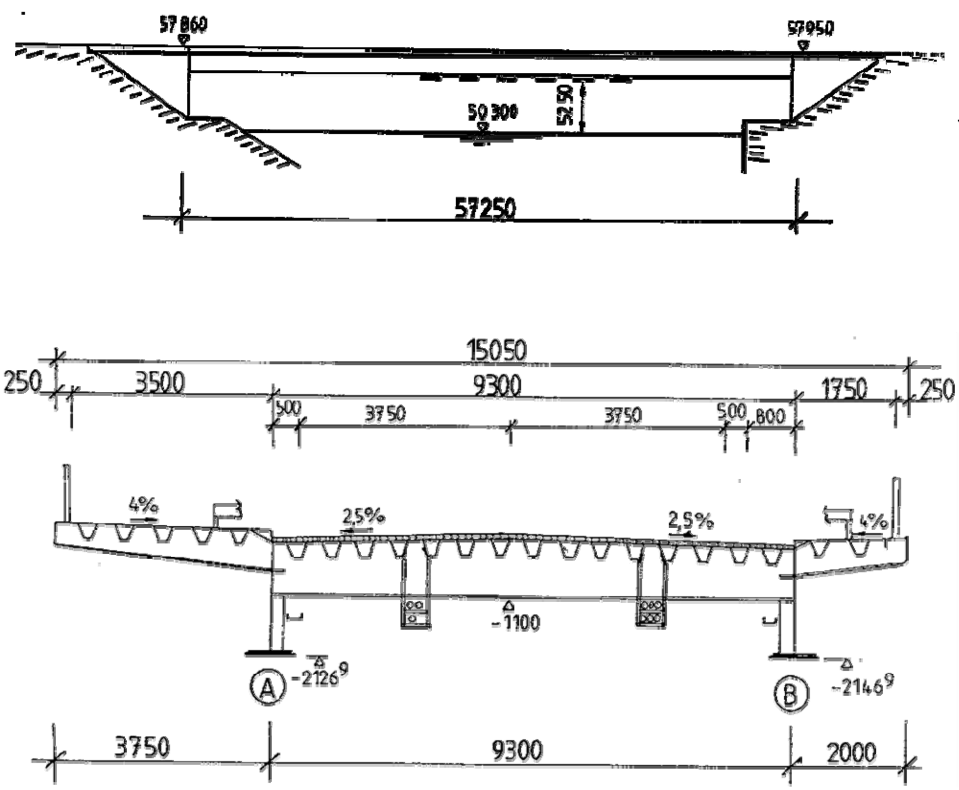
Load-model and simulations

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

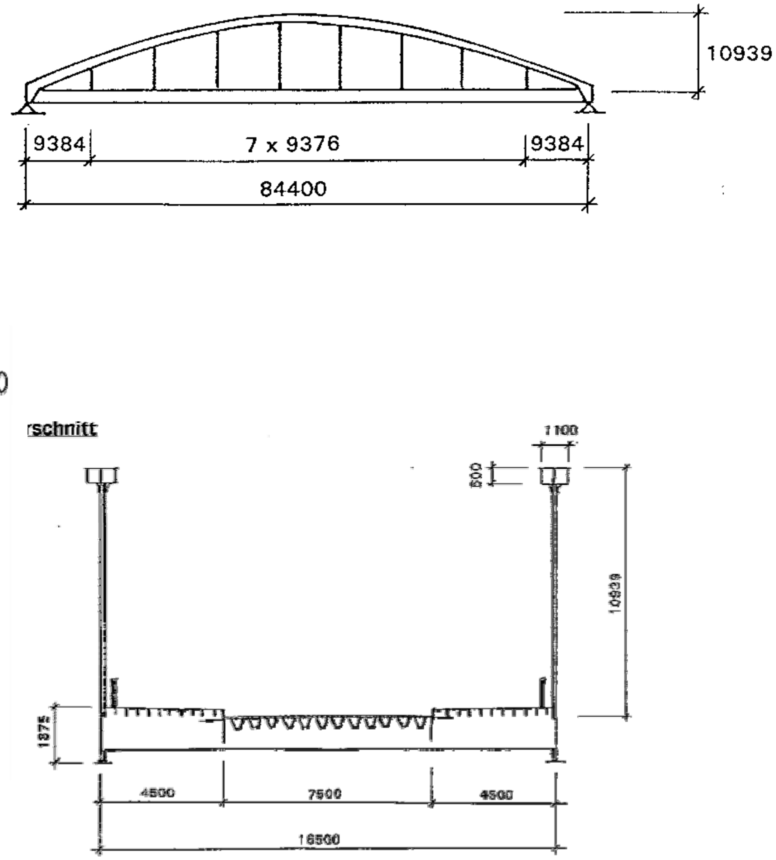


Dynamic effects

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



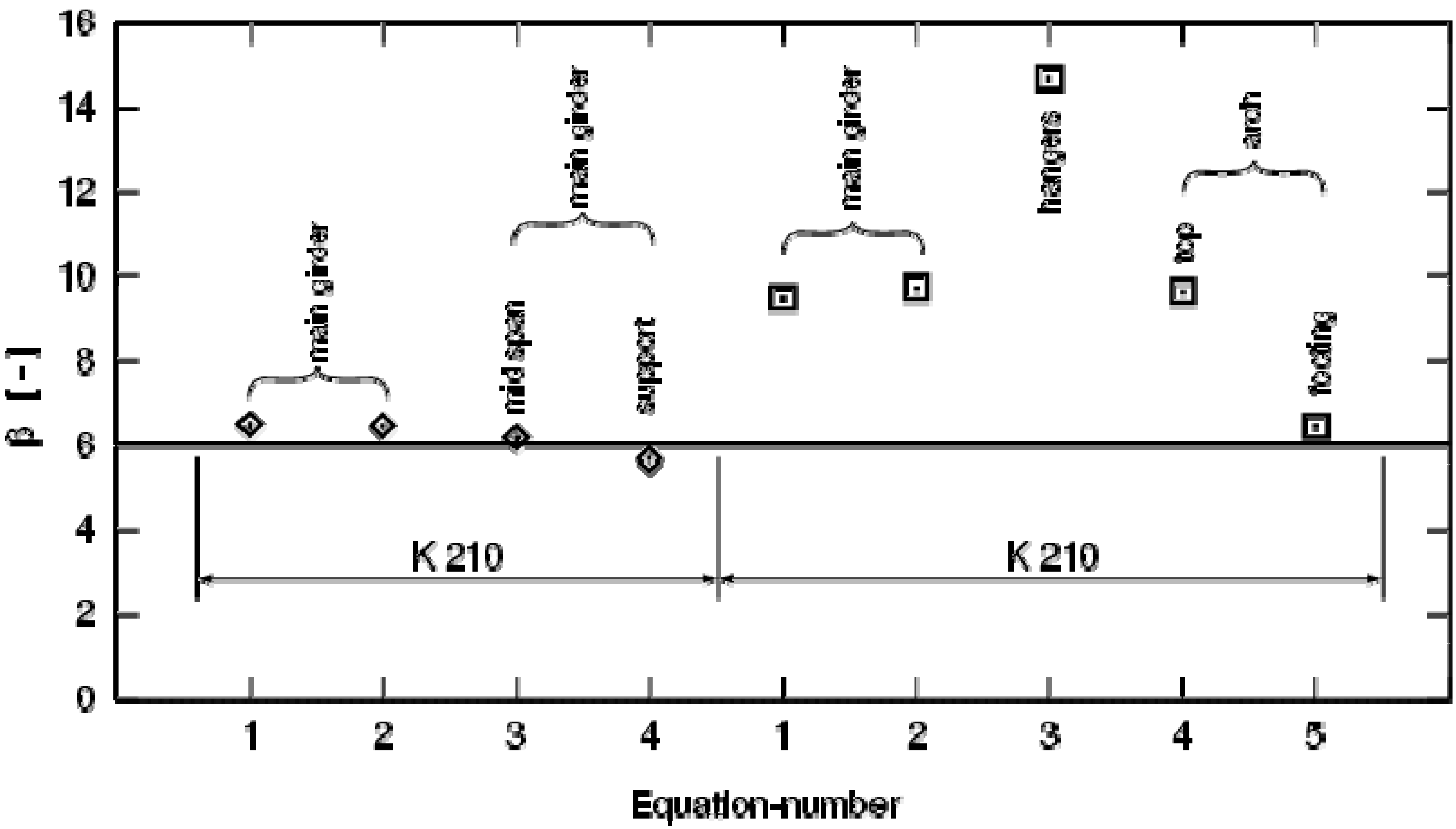
K 210



K 138

Reference bridges for reliability analysis

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



Definition of target β-value

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

Probabilistic design

$W_{required}$

$$M_{Qd} = \frac{f_y \cdot W_{requ}}{\gamma_M} - M_G \cdot \gamma_G$$

where

$$\gamma_M = 1{,}10$$

$$\gamma_G = 1{,}35$$

EC 1 - Part 2 Load Model

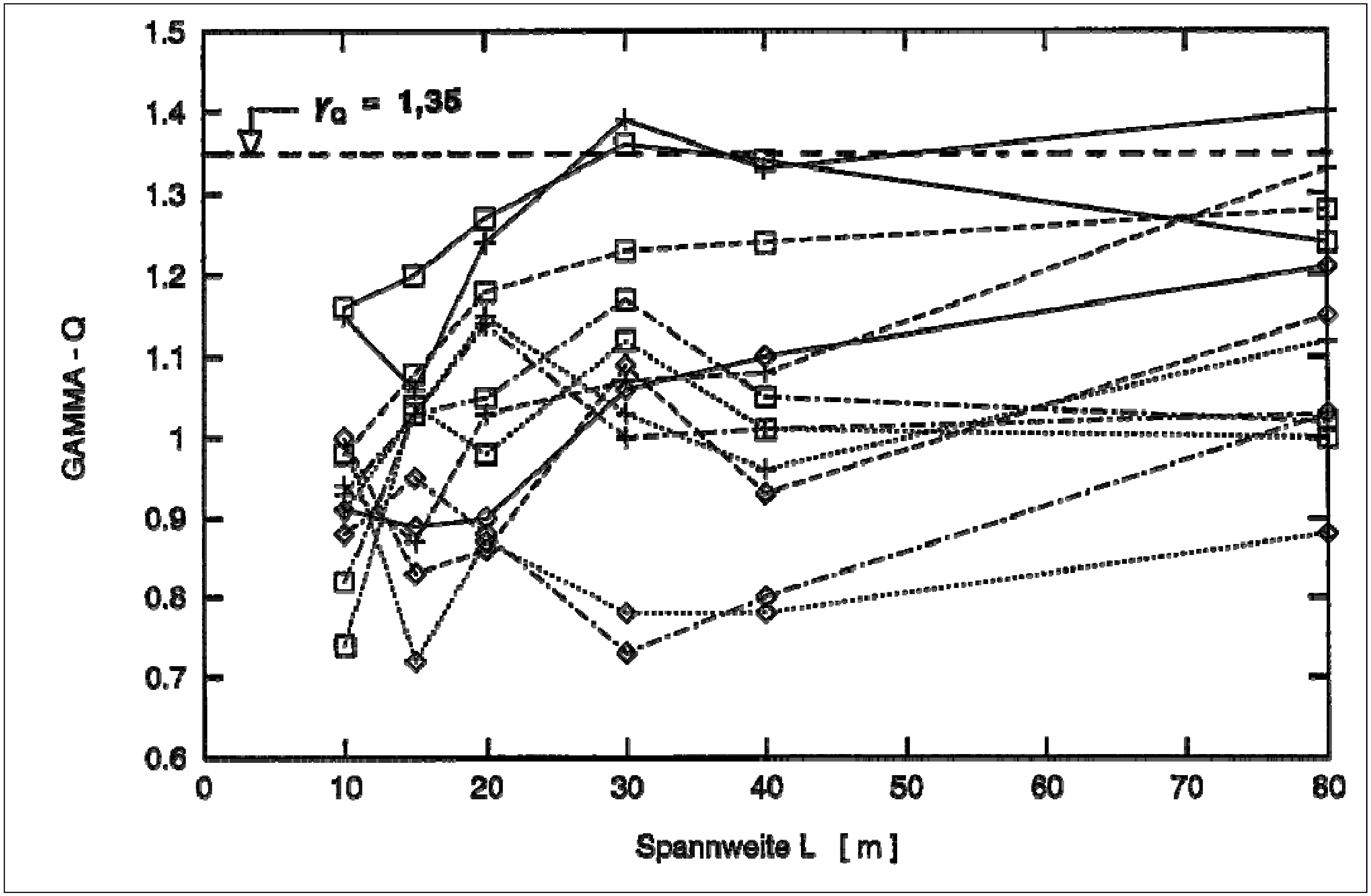
M_Q^{LM}

$$M_{Qd} = \gamma_Q \cdot M_Q^{LM}$$

$$\gamma_Q = \frac{M_{Qd}}{M_Q^{LM}}$$

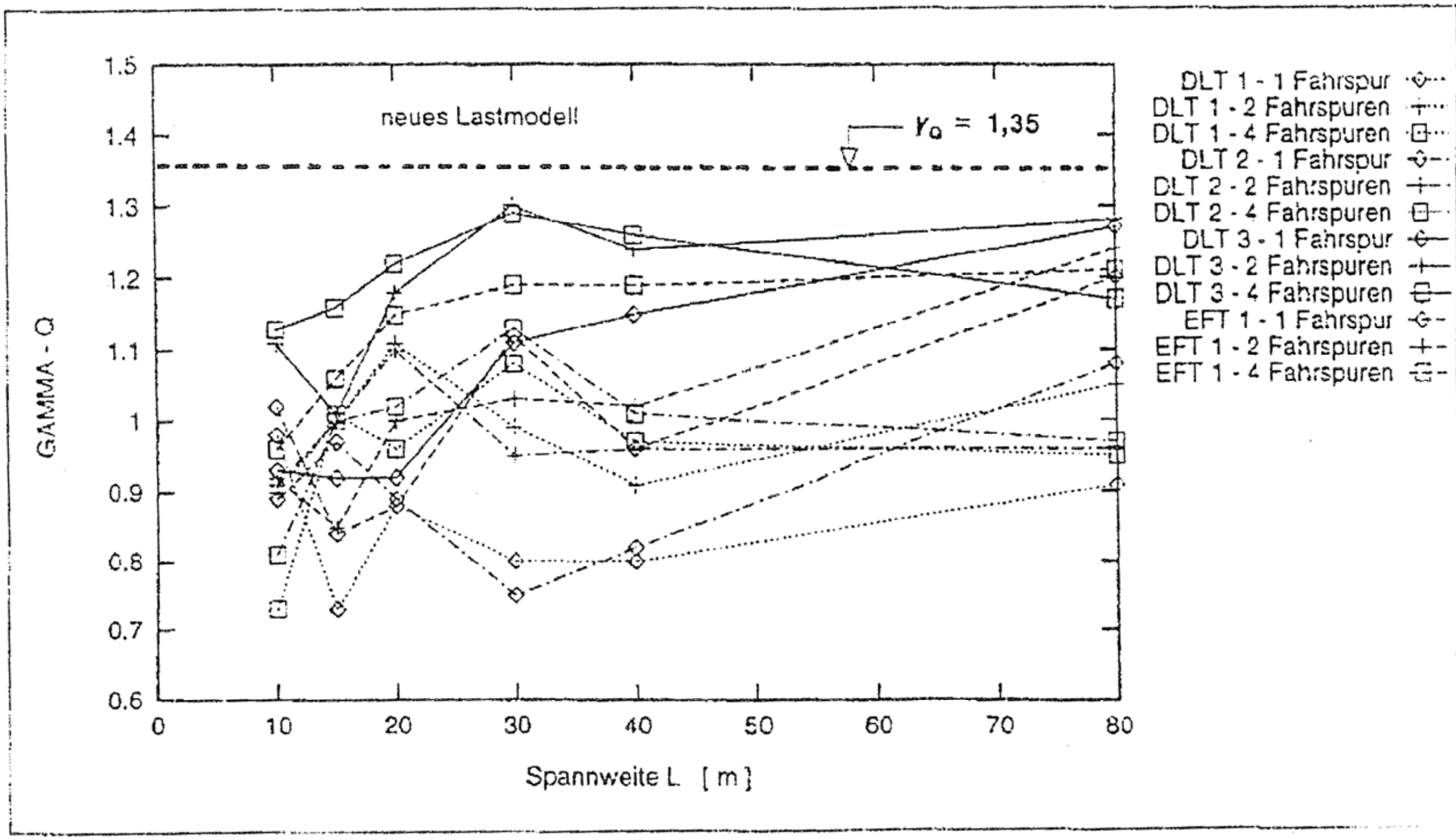
Definition of γ_Q-value

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



γ_Q-values from LM1

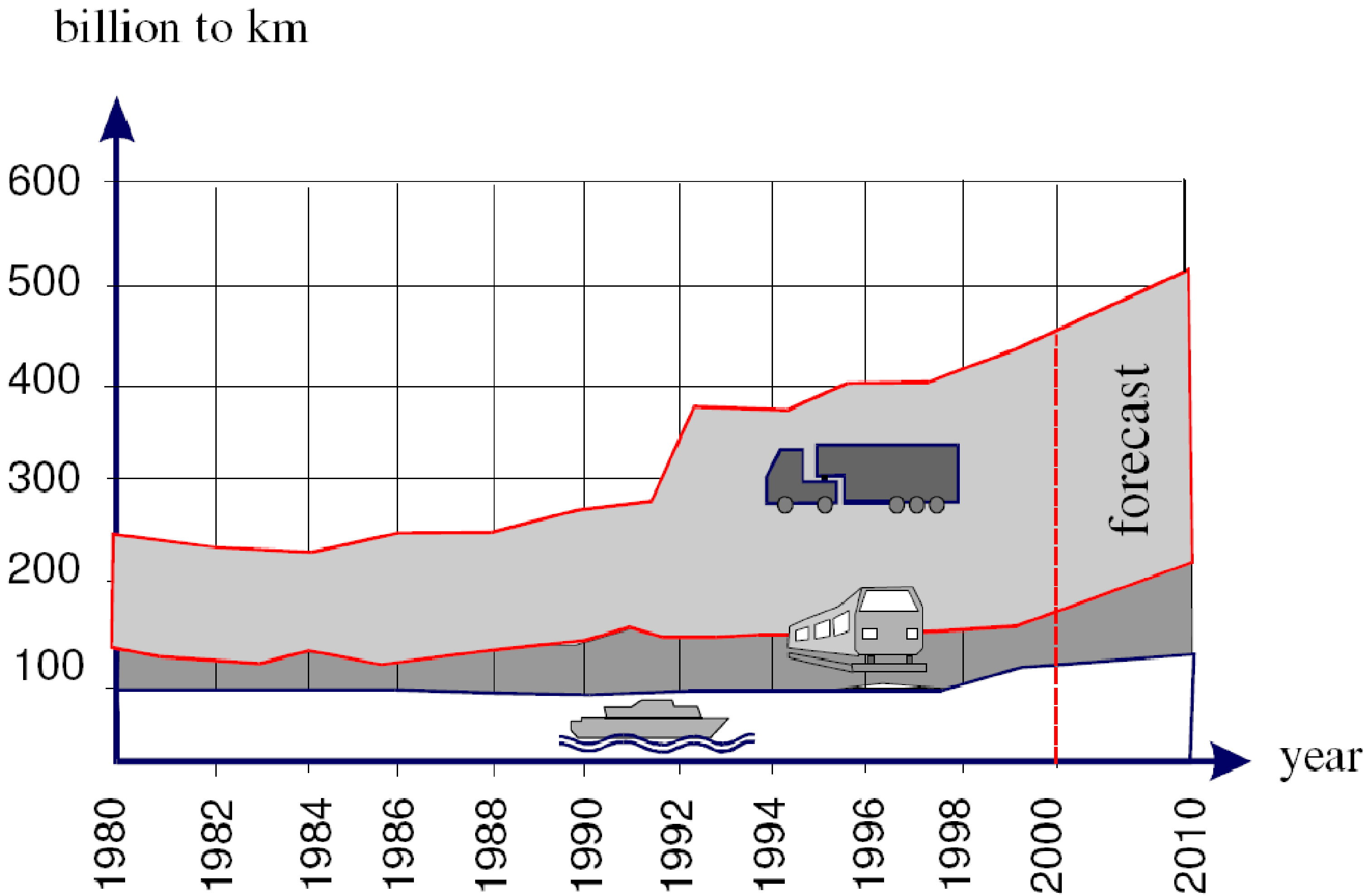
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



Effect of modification: $\alpha_{Q1}q_{1K}$ = 9 → 8 kN/m²

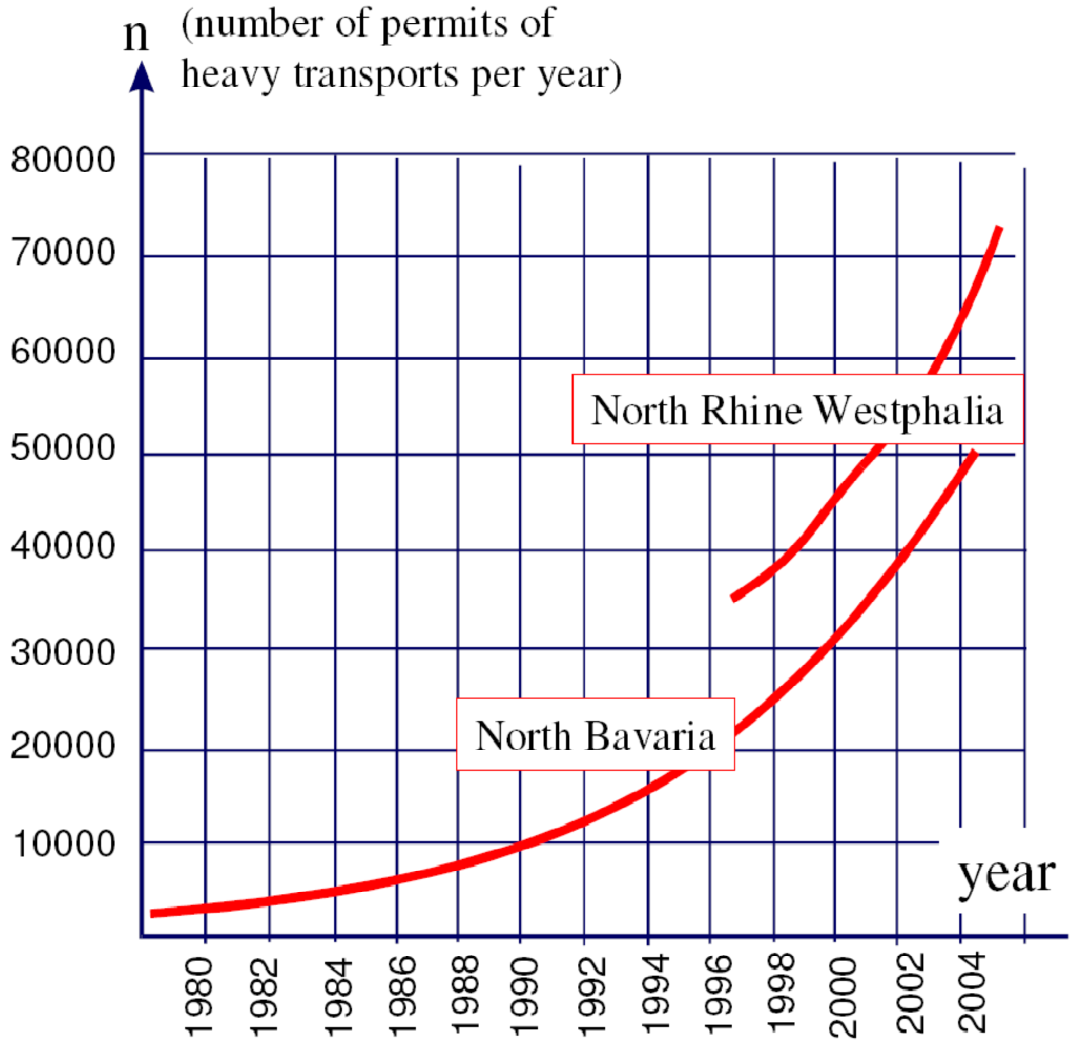
Effect of modification: $\alpha_{Q2}q_{2K}$ = 2,5 → 5 kN/m²

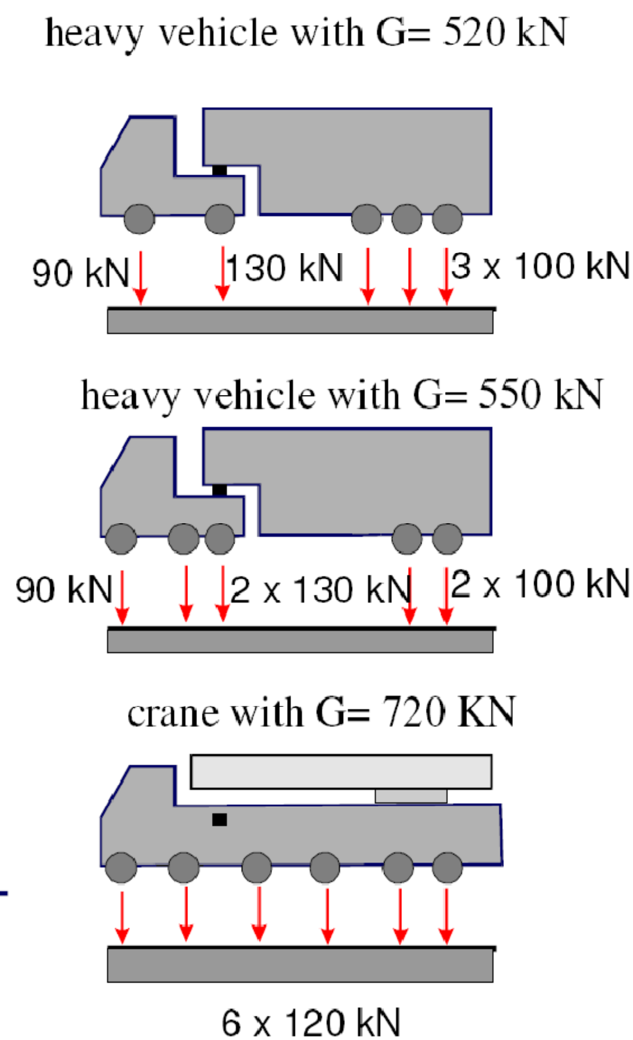
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



Forecast of freight-volume

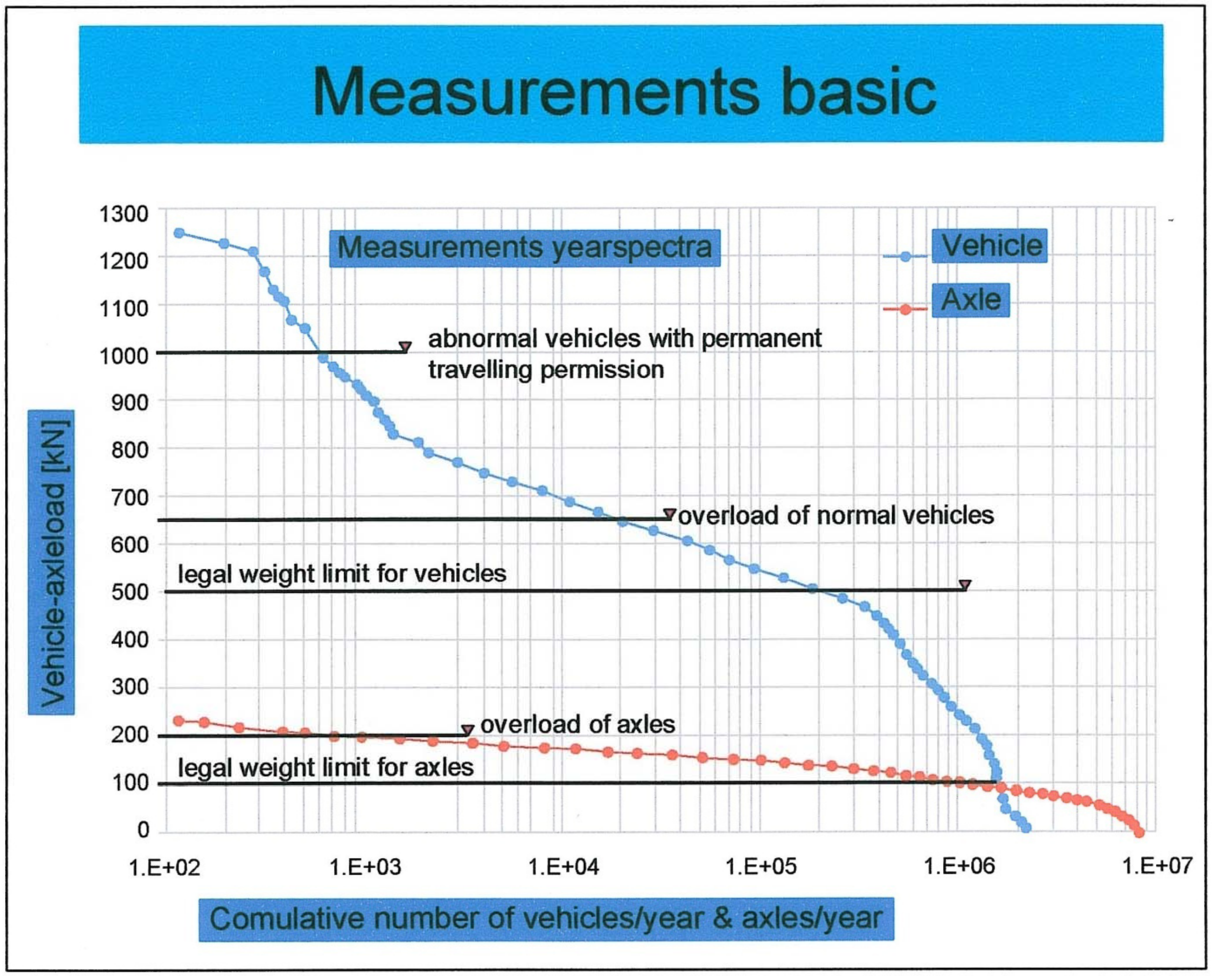
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES





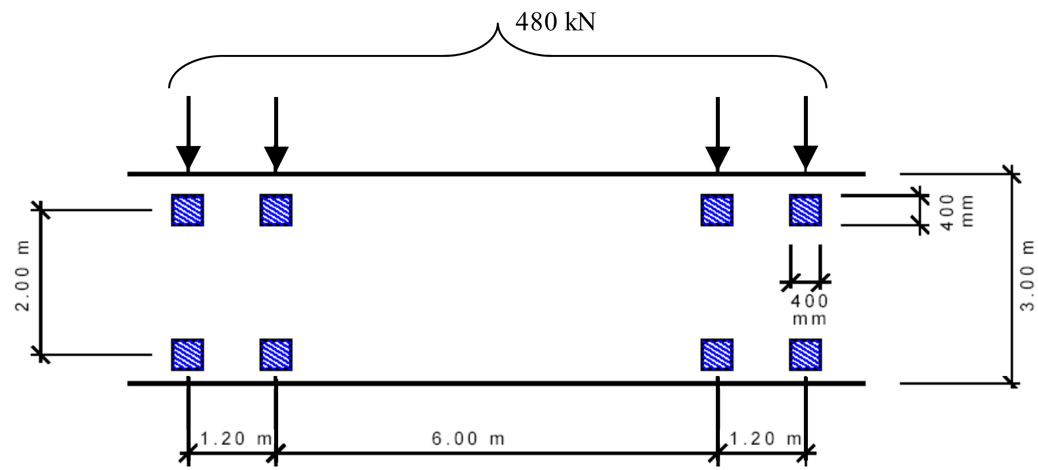
Development of permits for heavy vehicles

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES



Results of WIM-measurements in NL

Fatigue load model specified in EN 1991



Number of expected trucks per year for a single lane

Traffic Category	Number of heavy vehicles N
1: 2-Lane Highways with a high rate of heavy vehicles	$2 \cdot 10^6$ / a
2: Highways and roads with a medium rate of heavy vehicles	$0{,}5 \cdot 10^6$ / a
3: Main roads with a low rate of heavy vehicles	$0{,}125 \cdot 10^6$ / a
4: Country roads with a low rate of heavy vehicles	$0{,}05 \cdot 10^6$ / a

Fatigue loading model FLM 3

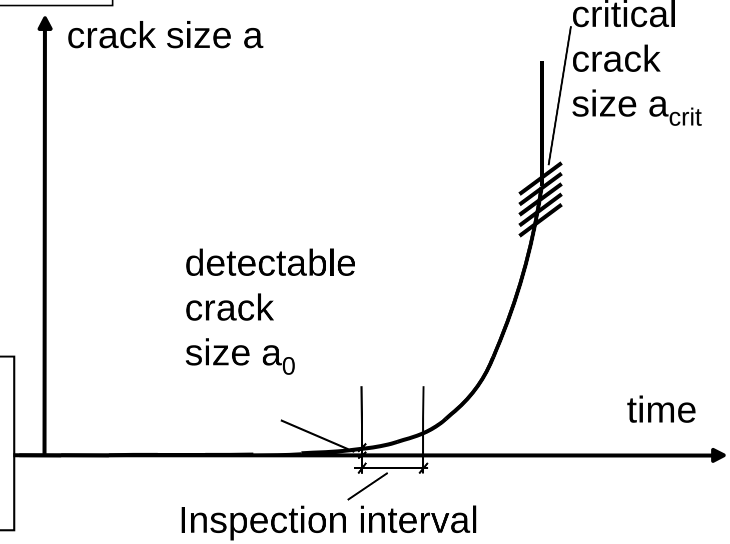
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

Concept for fatigue assessment with equivalent constant amplitude stress ranges

$$\gamma_{Ff} \cdot \varphi_{fat} \cdot \lambda \cdot \Delta\sigma_{max} \leq \Delta\sigma_c \,/\, \gamma_{Mf}$$

- γ_{Ff}: safety factor for fatigue load
- φ_{fat}: damage equivalent impact factor
- λ: damage equivalence factor representing the spectrum
- $\Delta\sigma_{max}$: maximum stress range from EC 1 -2 loadmodel
- $\Delta\sigma_c$: reference fatigue strength at 2 10^6 cycles
- γ_{Mf}: safety factor for fatigue strength

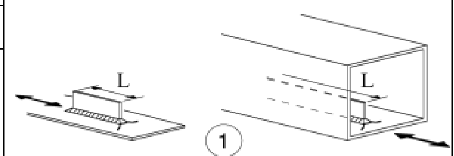
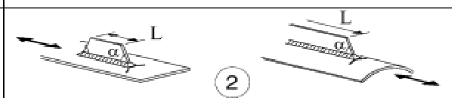
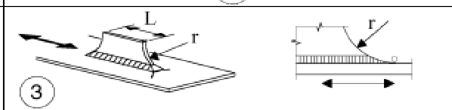
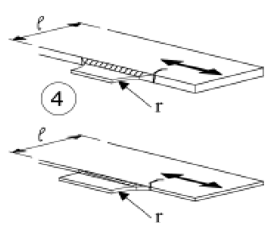
γ_{Ff} = 1,00
γ_{Mf} = 1,00 – 1,15 for damage tolerance
γ_{Mf} = 1,25 – 1,35 for safe life method



Assessment method for FLM 3

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

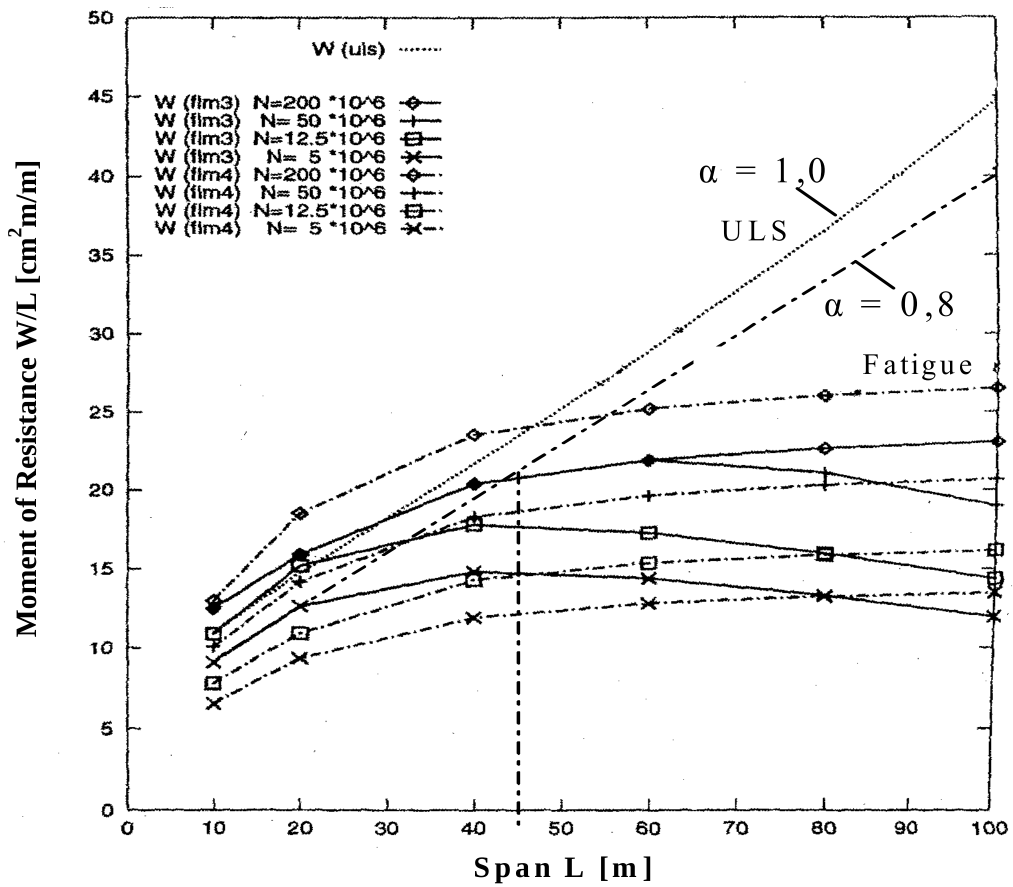
Fatigue details – welded attachments and stiffeners

Detail category	Constructional detail		New Evaluation for prEN 1993-1-9 (2002)					
			Detail	# of data	m		$\Delta\sigma_c$	
					variable	constant	m=var.	m=const.
80	L≤ 50mm			17	3,26	3	89,10	87,00
71	50<L≤ 80mm							
63	80<L≤ 100mm			109	2,45	3	67,04	77,14
56	L>100mm		1	62 18 15 17 6 8 12 4 9	3,24 3,32 3,05 3,27 3,81 3,48 3,54 4,59 2,43	3 3 3 3 3 3 3 3 3	58,06 76,08 94,57 79,37 80,59 84,22 69,12 78,39 53,43	55,96 72,31 94,73 76,49 59,53 76,73 60,14 50,12 74,94
71	L>100mm α<45°		2	53 27 39	2,92 2,99 2,73	3 3 3	69,24 58,97 78,95	70,58 59,85 83,41
80	r>150mm	 reinforced	3	6 4 4 10	3,06 3,29 3,31 3,12	3 3 3 3	100,94 97,27 36,16 59,00	105,20 96,41 62,94 63,76
90	$\frac{r}{L} \geq \frac{1}{3}$ or r>150mm							
71	$\frac{1}{6} \leq \frac{r}{L} \leq \frac{1}{3}$		4	13	1,26	3	18,43	72,84
50	$\frac{r}{L} < \frac{1}{6}$							

EN 1993-1-9 - Fatigue resistance

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

Required moment of inertia from ULS and fatigue design for detail category 71



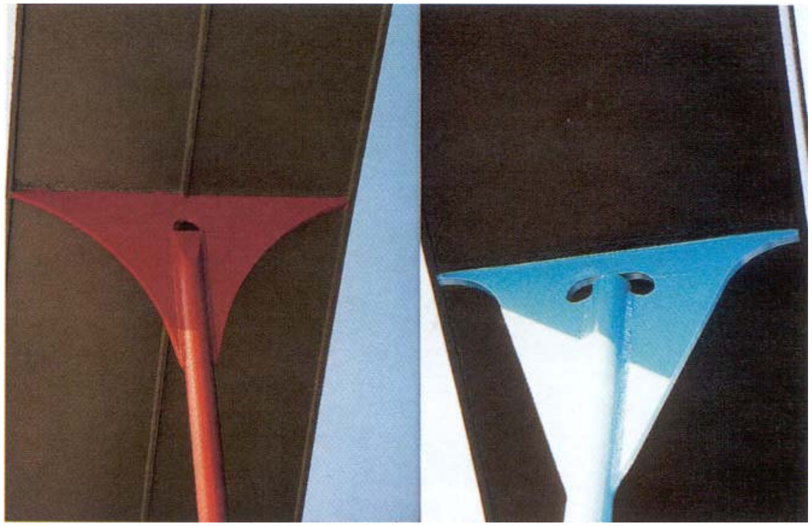
Span limits for fatigue design

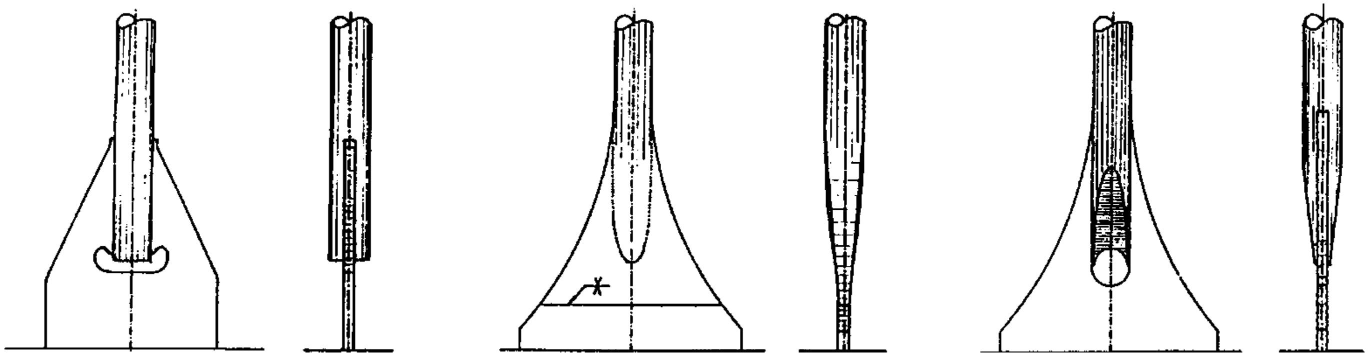
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

Joint for hanger

Alternatives for joints of hangers:
optimised joint:

- continuously increasing stiffness (K90)
  - ⇒ low curvature from bending
- end of hanger with hole and inclined cut
  - ⇒ low stresses at end of hanger for K50
- ratio of inclined cut and connecting plate
  - ⇒ avoiding of stress peak at end of hanger

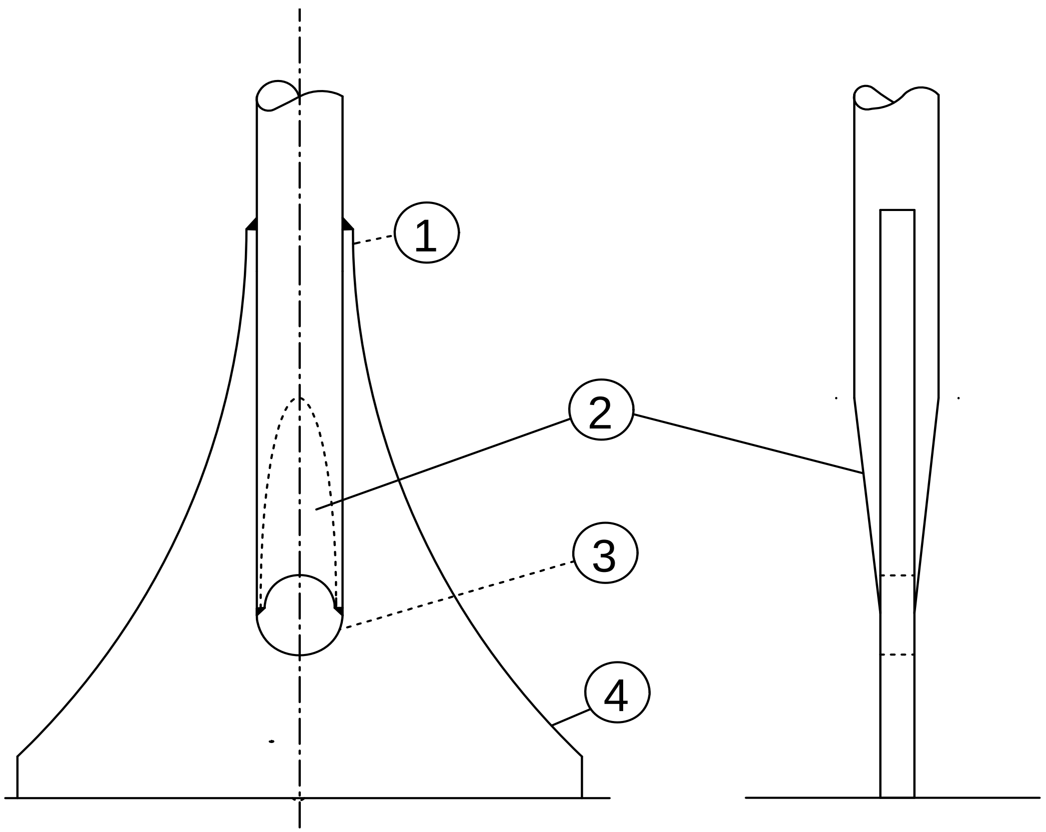




Recommendations for durable detailing

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

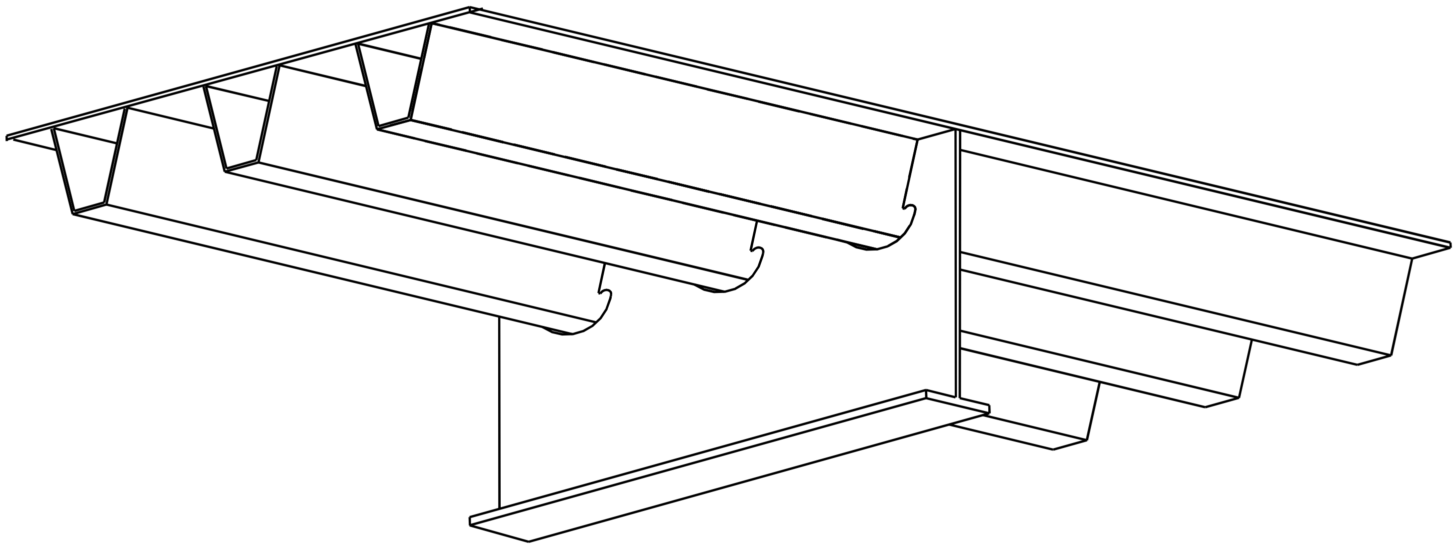
Hanger connection for arch bridges



Substitution of fatigue checks for critical details

2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

Standard orthotropic steel deck with continuous stringers with cope holes in the web of the cross beam

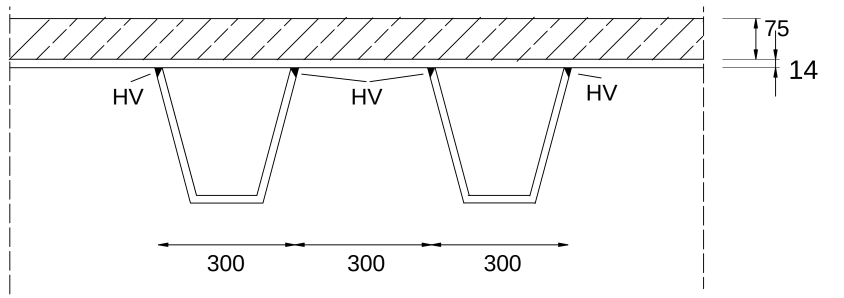


Substitution of fatigue checks by structural detailing rules

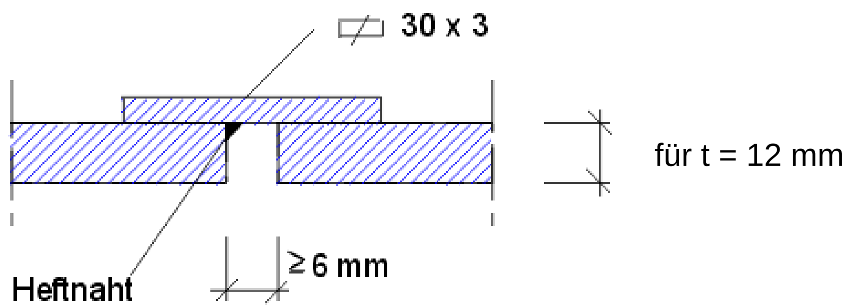
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

Structural detailing for deck plate

connection of deck plate to troughs

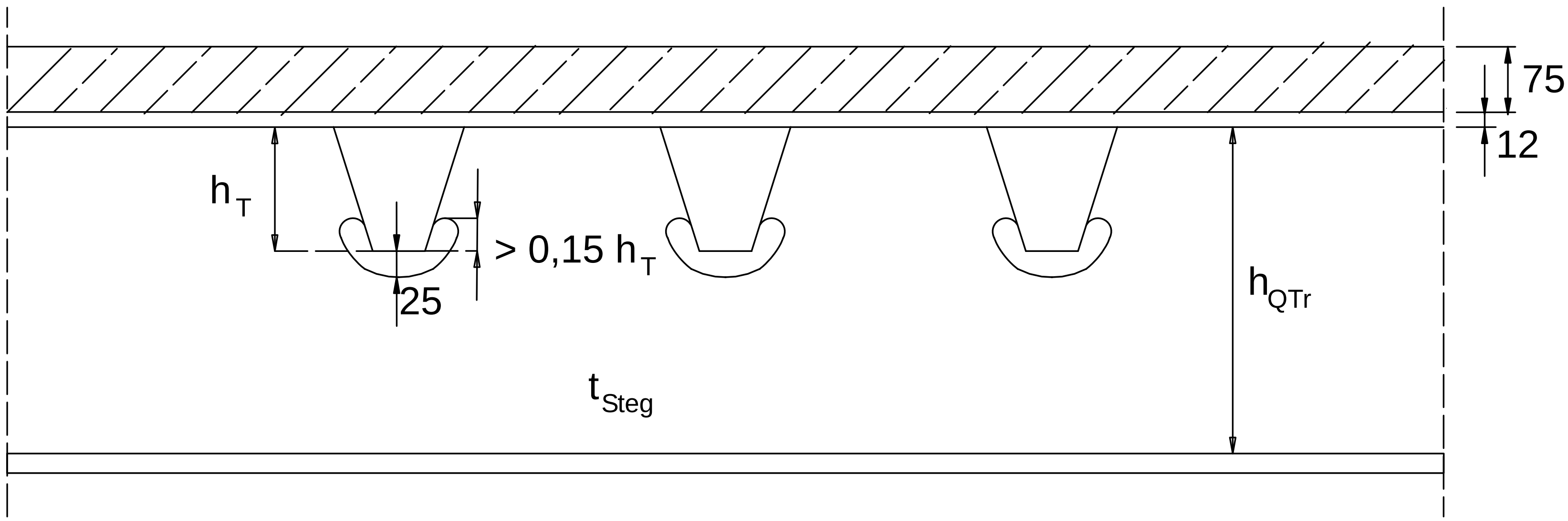


design life	load model 4
without layer	< 10 years
asphaltic sealing PmB 45	30 - 50 years
thermosetting resin PmB 25	70 - 90 years



Recommended details of orthotropic deck

Structural detailing for cross beams

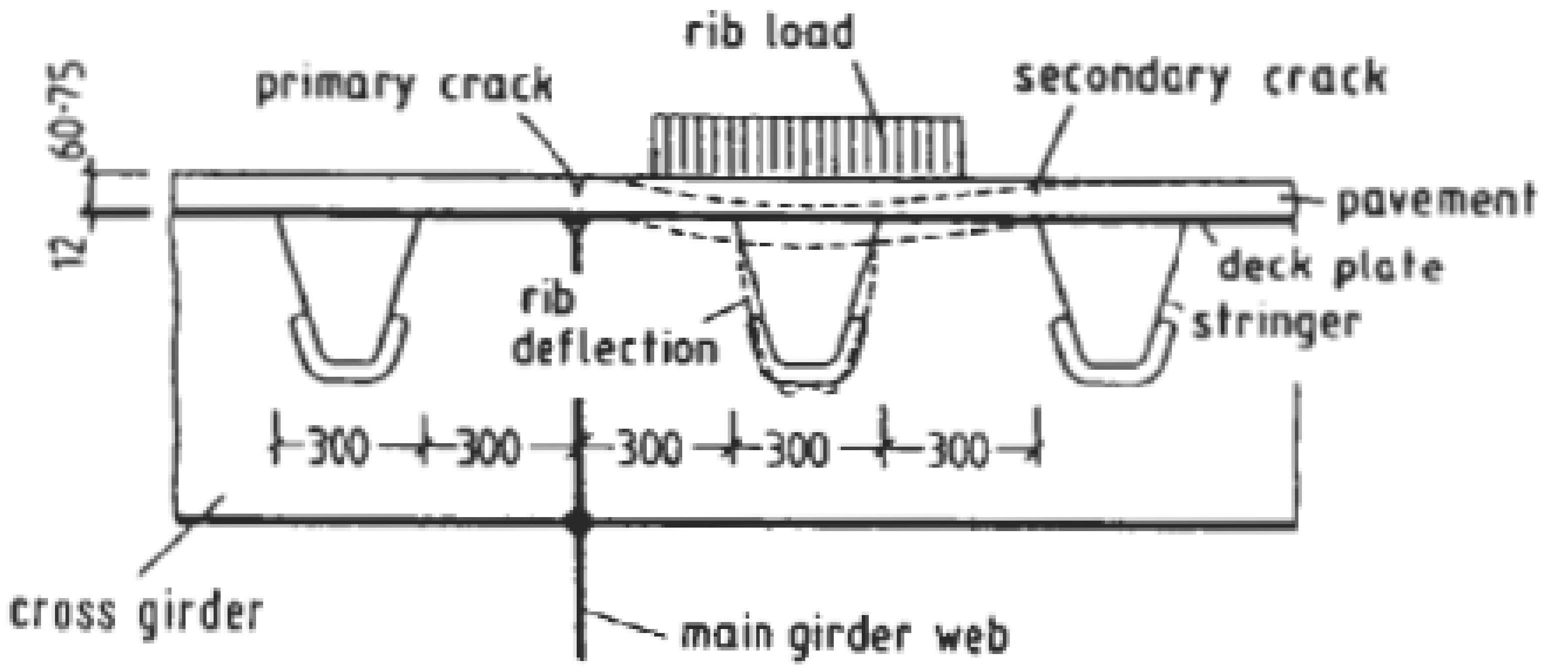


$t_{Ltrough}$ = 6 mm

t_{web} = 10 - 16 mm; verification of net web section required

$h_{crossbeam}$ ≈ 700 mm

Potential positions of cracks in the asphalt layer

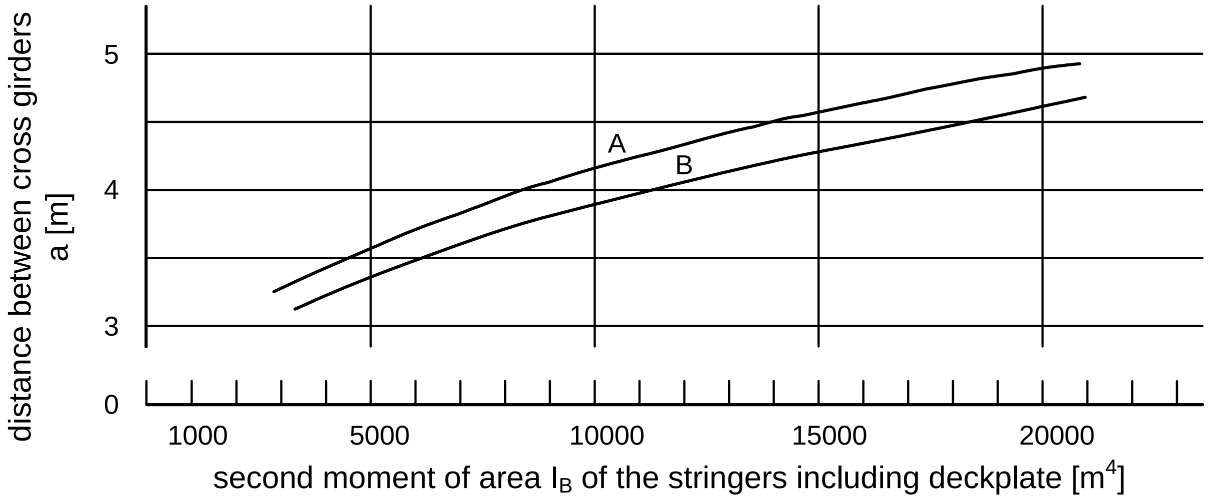


Durability of asphalt layer

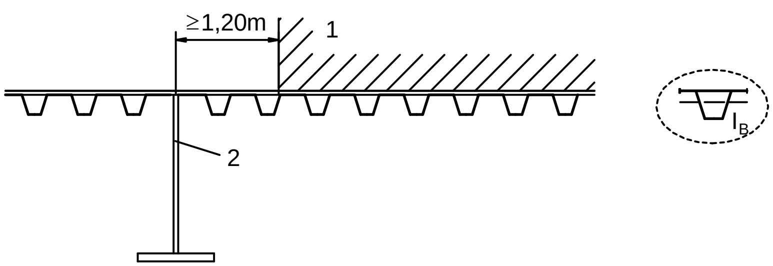
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

Steel bridges – serviceability limit state

Requirements for the minimum stiffness of stringers depending on the distance between crossbeams



Condition for curve A



1 heavy traffic lane

2 web of main girder or longitudinal girder

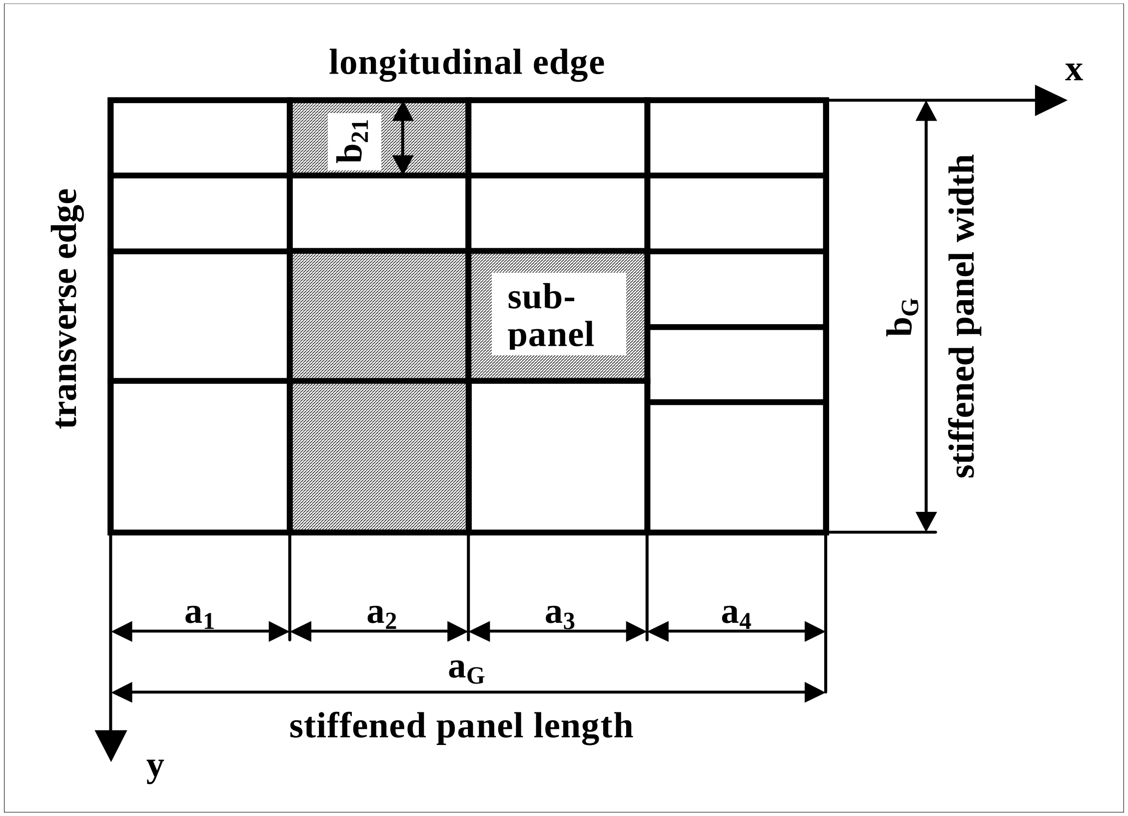
2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

Plate buckling

Verification to web breathing

$$\sqrt{\left(\frac{\sigma_{x,Ed,ser}}{k_{\sigma}\,\sigma_E}\right)^2 + \left(1{,}1\,\frac{\tau_{Ed,ser}}{k_{\tau}\,\sigma_E}\right)^2} \leq 1{,}15$$

Definition of a plated element



2. LOAD ASSUMPTIONS FOR STEEL BRIDGES

JRC Scientific and Technical Reports

Background document to EN 1991- Part 2 - Traffic loads for road bridges - and consequences for the design

G. Sedlacek, G. Merzenich, M. Paschen, A. Bruls, L. Sanpaolesi, P. Croce, J.A. Calgaro, M. Pratt, Jacob, M. Leendertz, v. de Boer, A. Vrouwenfelder, G. Hanswille

Support to the implementation, harmonization and further development of the Eurocodes

First Edition, XXXXX 2008

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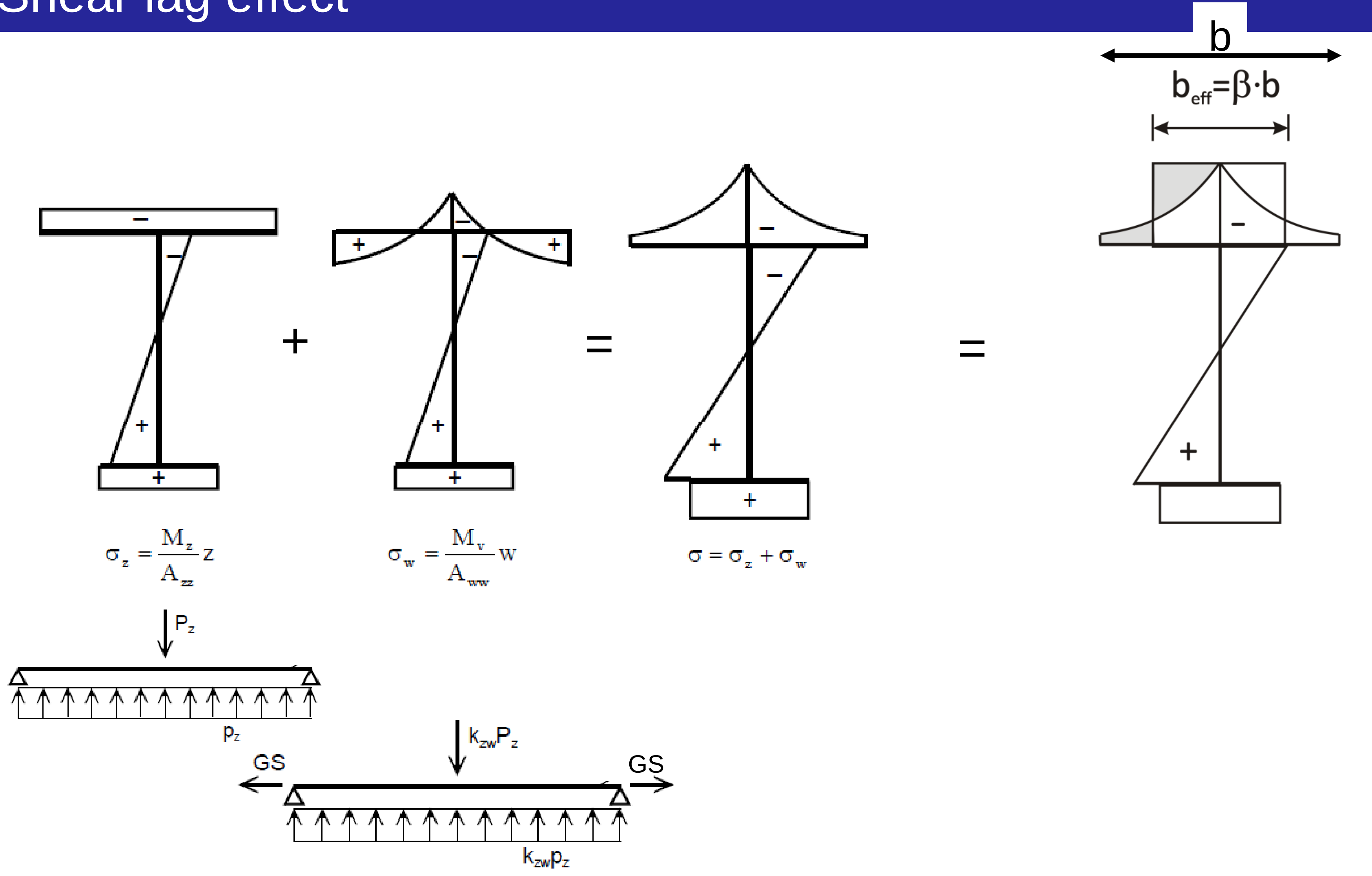
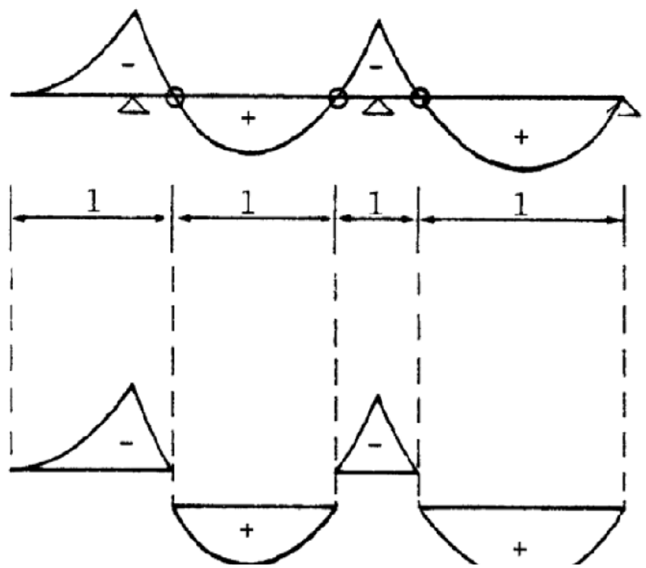
EUROPEAN COMMISSION

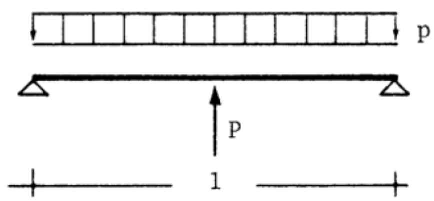
Shear lag effect



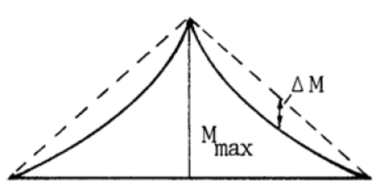
3. MODELLING OF STEEL BRIDGES

Subdivision of a moment-distribution to elements with standard shape



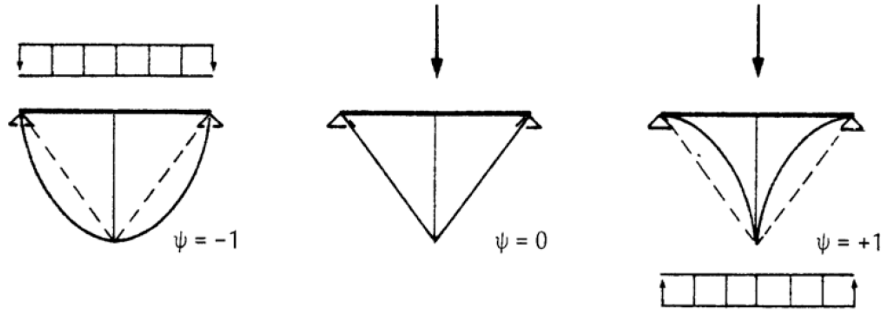


$$\eta = \frac{p\ell}{P}$$

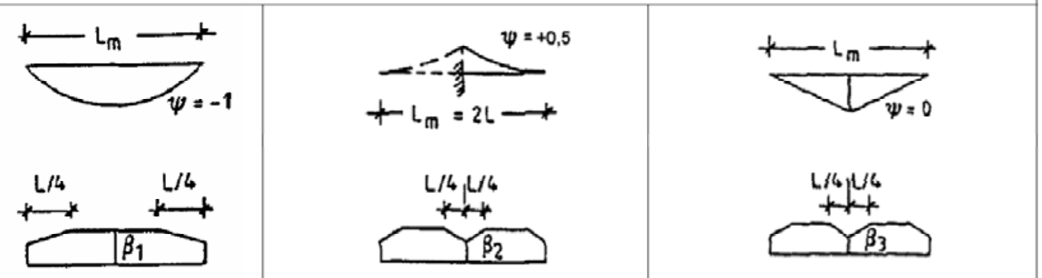


Shape parameter $\psi = \dfrac{4\,\Delta M}{M_{max}}$

β-factor for shear lag



$$\beta = \left[1 + 4{,}0\,(1+\psi)\,\frac{\alpha_0\, b}{L} + 3{,}2\,(1-\psi)\left(\frac{\alpha_0\, b}{L}\right)^2\right]^{-1}$$

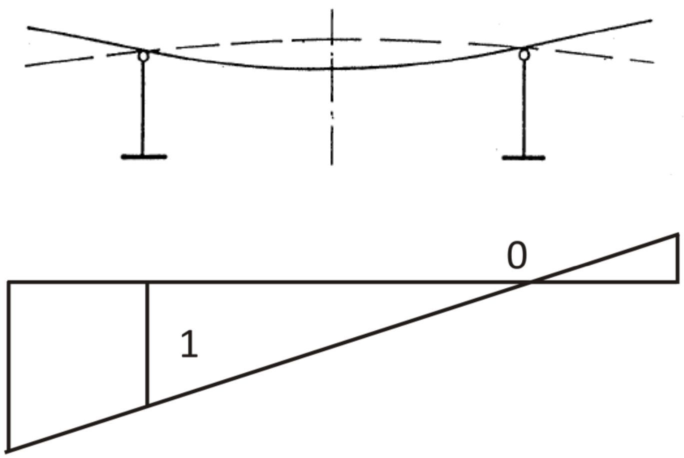
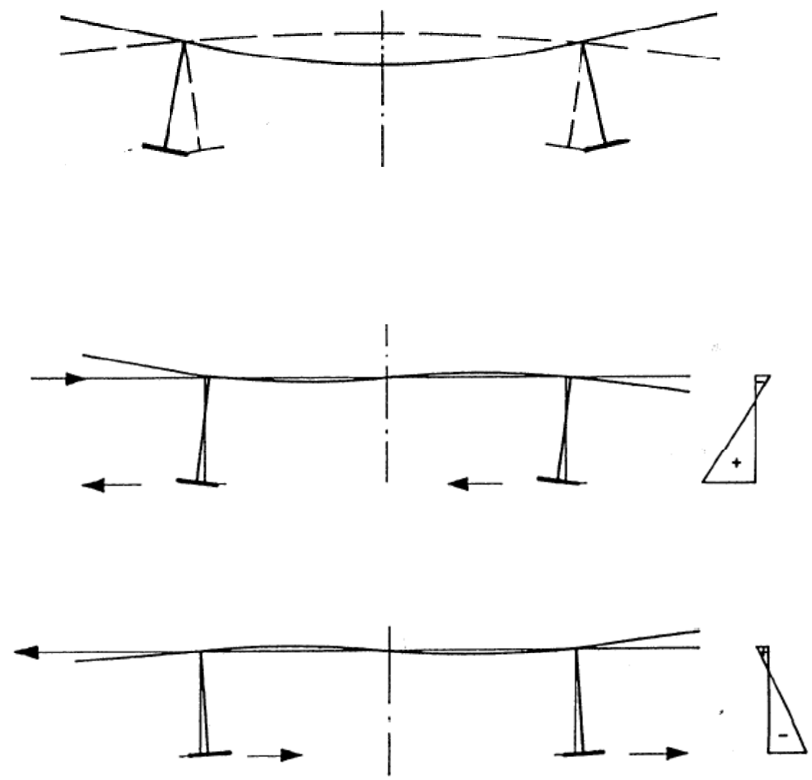


$$\beta_1 = \left[1 + 6{,}4\left(\frac{\alpha_0\, b}{L}\right)^2\right]^{-1}$$

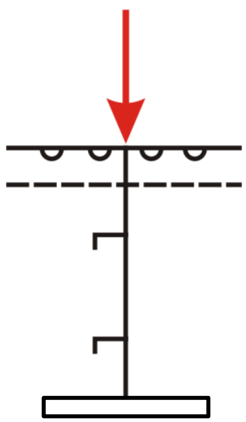
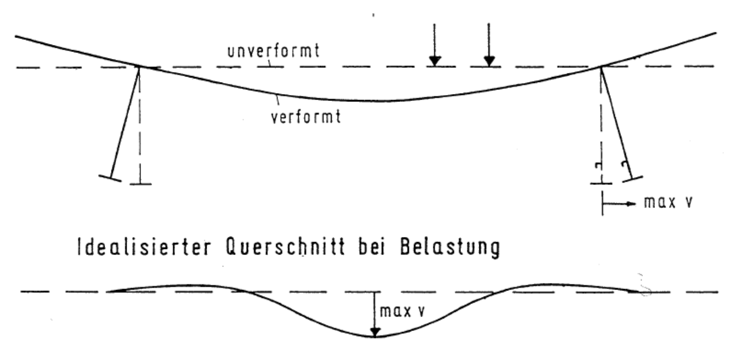
$$\beta_2 = \left[1 + 6\,\frac{\alpha_0\, b}{L} + 1{,}6\left(\frac{\alpha_0\, b}{L}\right)^2\right]^{-1}$$

$$\beta_3 = \left[1 + 4\,\frac{\alpha_0\, b}{L} + 3{,}2\left(\frac{\alpha_0\, b}{L}\right)^2\right]^{-1}$$

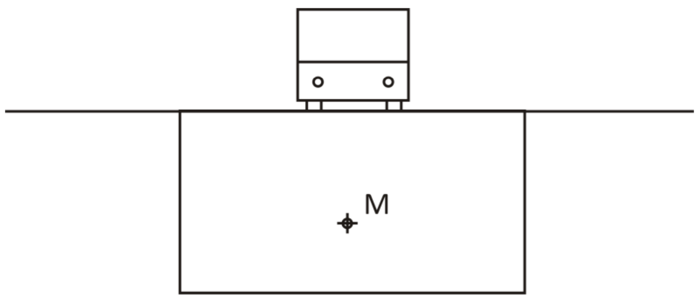
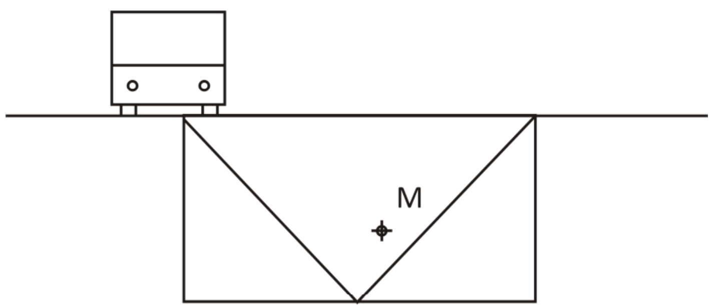
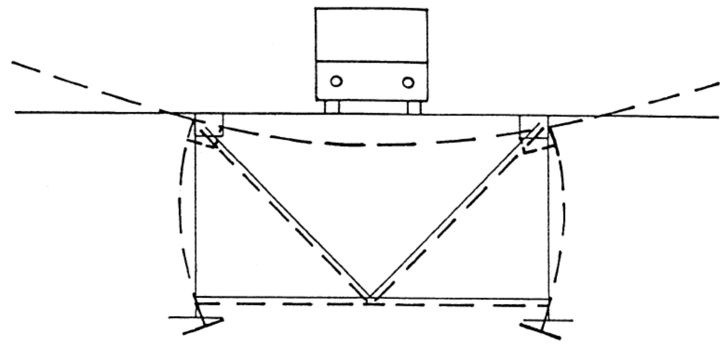
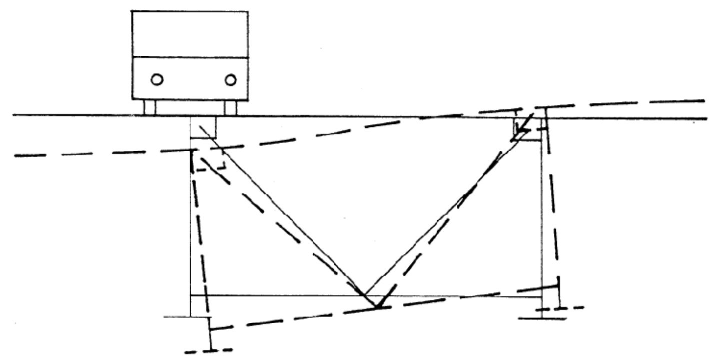
Differences in modelling

Modelling for ULS	Modelling for fatigue
	

Differences in modelling

Modelling for ULS	Fatigue effects on web stiffeners
	

Differences in modelling

Modelling for ULS	Frame and distorsional effects
 	 

4. SPECIFICATION FOR BEARINGS

Design principles for individual bearings

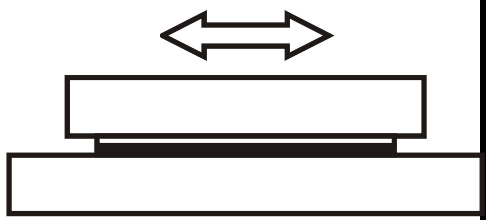
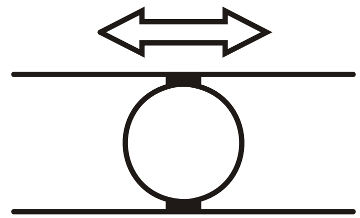
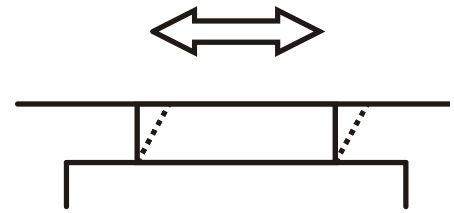
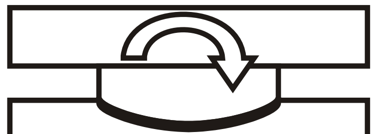
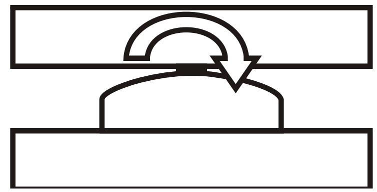
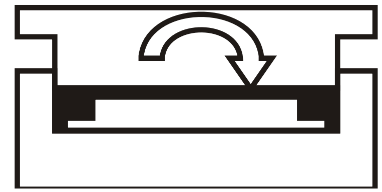
- Permission of movements minimizing the reaction forces
- No tensile forces
- No significant redistribution of forces to other bearings from accomodation to installation tolerances
- Specification of installation conditions with details of construction sequence and time variable conditions
- Measure to avoid unforeseen deformation of the bearings (non uniform contact)

4. SPECIFICATION FOR BEARINGS

Construction documents

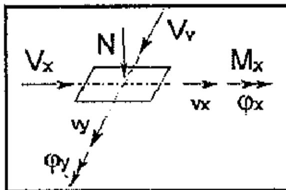
- Bearing plan (drawing of the bearing system)
- Bearing installation drawing (structural details)
- Bearing schedule (characteristic values from each action, design values from combination of action)

4. SPECIFICATION FOR BEARINGS

	sliding	rolling	deforming
displace-ment			
rotation			

Functional principles of bearings

4. SPECIFICATION FOR BEARINGS



Project:

Bearing No.:

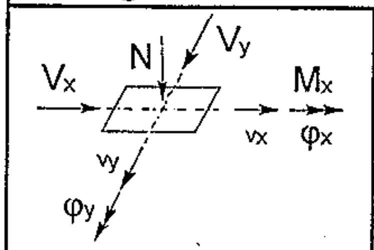
This bearing list gives the characteristic values of bearing forces and movements for the final stage of the bridge. Where bearings are installed during construction of the bridge and where the forces and movements in this stage exceed the values in the final stage the relevant forces and movements under construction should be given in a separate bearing list.

			Bearing forces and movements															
			N [kN]		V_x [kN]		V_y [kN]		M_x [kNm]		v_x [mm]		v_y [mm]		φ_x [mrad]		φ_y [mrad]	
			max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min
1.1		Self weight																
1.2		Dead load																
1.3	Permanent actions (G and P)	Prestressing by tendons																
1.4		Creep of concrete																
1.5		Shrinkage of concrete																
2.1		Traffic loads																
2.2		Special vehicles																
2.3		Centrifugal forces																
2.4		Nosing forces																
2.5		Braking and acceleration forces																
2.6		Foot path loading																
2.7		Wind on structure without traffic																
2.8	variable actions (Q)	Wind on structure with traffic																
2.9		Uniform temperature																
2.10		Vertical temperature difference																
2.11		Horizontal temperature difference																
2.12		Soil settlements																
2.13		Bearing resistance /friction																
2.14		replacement of bearings																
2.15		Pressure and suction from traffic																
3.1	seismic	Non collapse rupture(ULS)																
3.2		Minimisation of damage (SLS)																
4.1		derailment																
4.2	accidental actions (A)	impact																
4.3																		

4. SPECIFICATION FOR BEARINGS

Project:

Bearing No.:



This bearing list gives the characteristic values of bearing forces and movements for the final stage of the bridge. Where bearings are installed during construction of the bridge and where the forces and movements in this stage exceed the values in the final stage the relevant forces and movements under construction should be given in a separate bearing list.

			Related design values of bearing forces and movements acc. to the combination in clause E.5							
			N	V_x	V_y	M_x	v_x	v_y	φ_x	φ_y
			[kN]	[kN]	[kN]	[kNm]	[mm]	[mm]	[mrad]	[mrad]
Design values of bearing forces and movements at ultimate limit states										
Bearing forces of the fundamental combination acc. to clause E.5										
1.1		max N_{Ed}								
1.2		min N_{Ed}								
1.3		max $V_{x,Ed}$								
1.4		min $V_{x,Ed}$								
1.5		max $V_{y,Ed}$								
1.6		min $V_{y,Ed}$								
1.7		max $M_{x,Ed}$								
1.8		min $M_{x,Ed}$								
Bearing movements of the fundamental combination acc. to clause E.5										
2.1		max $v_{x,d}$								
2.2		min $v_{x,d}$								
2.3		max $v_{y,d}$								
2.4		min $v_{y,d}$								
2.5		max $\varphi_{x,d}$								
2.6		min $\varphi_{x,d}$								
2.7		max $\varphi_{y,d}$								
2.8		min $\varphi_{y,d}$								

4. SPECIFICATION FOR BEARINGS

Actions for permanent and transient design situations

No.	Action	Eurocode
	Reference to temperature T_0	DIN EN 1991-1-5:2004-07
1.1	Self-weight	DIN EN 1991-1-7:2007-02
1.2	Dead loads	DIN EN 1991-1-7:2007-02
1.3	Prestressing	DIN EN 1992-1:2005-10 and DIN EN 1994-2:2006-07
1.4	Creep concrete	DIN EN 1992-1:2005-10
1.5	Shrinkage of concrete	DIN EN 1992-1:2005-10
2.1	Traffic loads	DIN EN 1991-2:2004-05
2.2	Special vehicles	DIN EN 1991-2:2004-05
2.3	Centrifugal forces	DIN EN 1991-2:2004-05
2.4	Nosing forces	DIN EN 1991-2:2004-05
2.5	Brake and acceleration forces	DIN EN 1991-2:2004-05
2.6	Footpath loading	DIN EN 1991-2:2004-05
2.7	Wind on structure without traffic	DIN EN 1991-4:2005-07
2.8	Wind on structure with traffic	DIN EN 1991-4:2005-07
2.9	Range uniform temperature	DIN EN 1991-1-5:2004-07, 6.1.3 and 6.1.5
2.10	Vertical temperature difference	DIN EN 1991-1-5:2004-07, 6.1.4 and 6.1.5
2.11	Horizontal temperature difference	DIN EN 1991-1-5:2004-07, 6.1.4 and 6.2
2.12	Soil Settlements	DIN EN 1997-1:2009-09
2.13	Bearing resistance/friction forces	DIN EN 1337, Part 2 to 8
2.14	Replacement of bearing	DIN EN 1991-2:2004-05
2.15	Pressure and suction from traffic	DIN EN 1991-2:2004-05
2.16	Wind during erection	DIN EN 1991-4:2005-07 and DIN EN 1991-1-6:2005-09
2.17	Construction loads	DIN EN 1991-1-6:2005-09
2.18	Accidental actions	DIN EN 1991-1-7:2007-02

- For transient design situations reduction of variable actions due to limited duration → EN 1991-2, 4.5.3. For steel bridges also actions from installation of hot asphalt according to technical project specifications.

4. SPECIFICATION FOR BEARINGS

Actions in accidental design situations

- Specifications according to EN 1991-2
- Limitation of bridge movements by structural measures, e.g. stop devices at abutments

Actions in seismic design situations

Specifications according to EN 1998-1 and EN 1998-2

4. SPECIFICATION FOR BEARINGS

Determination of design values of movements and bearing forces
Principles

- Combination according to EN 1990, 6.5.3.2 (2) with partial factors according to EN 1990, A.2 and particular rules for climatic temperature effects
- Movements due to creep and shrinkage by multiplying mean values in EN 1992-2 and EN 1994-2 by a factor of 1.35
- Verification of static equilibrium (uplift of bearings) and anchoring devices by applying $\pm$ 0.05 G_K spanwise
- Consideration of deformations of foundation, piers and bearings in the modelling of the structure, see EN 1991-2, 6.5.4.2
- Use of 2nd order theory for accounting for deformations of piers after installation of bearings if required by EN 1992-1-1, 5.8.2 (6).
  For calculation of pier deformations k_y = 0,5 may be applied to geometric member imperfections in EN 1992-1-1, 5.2.

4. SPECIFICATION FOR BEARINGS

Determination of design values of movements and bearing forces

Climatic temperature effects

Maximum and minimum constant temperature component:

$$T_{ed,\,min} = T_0 - \gamma_F \cdot \Delta T_{N,con} - \Delta T_0$$

$$T_{ed,\,max} = T_0 + \gamma_F \cdot \Delta T_{N,exp} + \Delta T_0$$

- ΔT_0: additional safety element
- $\Delta T_{N,con}$, $\Delta T_{N,exp}$: charact. Values EN 1991-1-5, 6.1.3.3
- γ_F: partial factor γ_F = 1,35
- T_0: reference temperature during installation of the bearings, e.g. +10°C

Table E.4: Recommended values for ΔT_0

Case	Installation of bearing	ΔT_0 [°C]		
		steel bridges	**composite bridges**	**concrete bridges**
1	**Installation with measured Temperature and with correction Resetting with bridge set at T_0**	**0**	**0**	**0**
2	**Installation with estimated T_0 and without correction by resetting with bridge set T_0**	**10**	**10**	**10**
3	**Installation with estimated temperature T_0 and without correction by resetting and also one ore more changes in position of the fixed bearing**	**25**	**20**	**20**

$$\Delta T_d = T_{ed,max} - \Delta T_{ed,min}$$

For non-linear behaviour stepwise determination

$$\Delta T_d = \gamma_F \cdot \Delta T_N$$

4. SPECIFICATION FOR BEARINGS

Reaction forces at fixed points resulting form resistance of the bearing system

For sliding bearings:

$$F_{H_d} = \gamma_Q \cdot Q_{1k} + \begin{Bmatrix} \mu_a \left(\sum \gamma_{G,\sup} \cdot G_k + \gamma_Q \cdot \psi_1 \cdot Q_{ki} + \sum \gamma_{Qi} \cdot \psi_{0i} \cdot Q_{ki} \right) \\ - \mu_r \left[\sum \gamma_{G,\inf} \cdot G_k \right] \end{Bmatrix}$$

- $\gamma_Q \cdot Q_{1k}$: Forces from acceleration and braking
- μ_a, μ_r: coefficient of friction according EN 1337-1, 62. For PTFE sliding bearings μ_{max} = 0,03
- G_k: self weight, dead loads
- $\gamma_Q \cdot \psi_1 \cdot Q_{ki}$: vertical actions of traffic load
- $\psi_{0i} \cdot Q_{ki}$: other variable actions

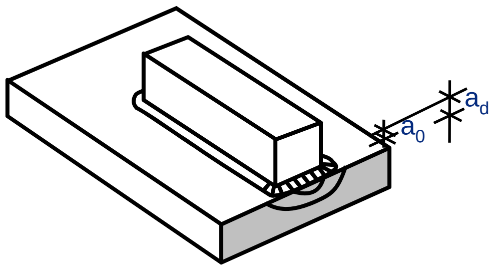
For elastomeric bearings

$$F_{H_d} = \gamma_Q \cdot Q_{k1} + \begin{Bmatrix} G_{\sup} \sum A_{\sup} \varepsilon_{q,d,\sup} \\ - G_{\inf} \sum A_{\inf} \varepsilon_{q,d,\inf} \end{Bmatrix}$$

- $\gamma_Q \cdot Q_{k1}$: forces from acceleration and braking
- $G_{\sup}$, $G_{\inf}$: nominal values of shear modulus G_{sup} = 1,05 N/mm^2, G_{inf} = 0,75 N/mm^2
- A: plan shear area of bearings
- $\varepsilon_{q,d}$: Shear deformations of the bearings according EN 1337-3

5. CHOICE OF MATERIAL

Assumption for a_0



$$a_d = a_0 \cdot f\left(\frac{\Delta\sigma_c^{\,3} \cdot 2 \cdot 10^6}{4}\right)$$

fatigue loading

initial crack

design crack

Safety assessment based on fracture mechanics

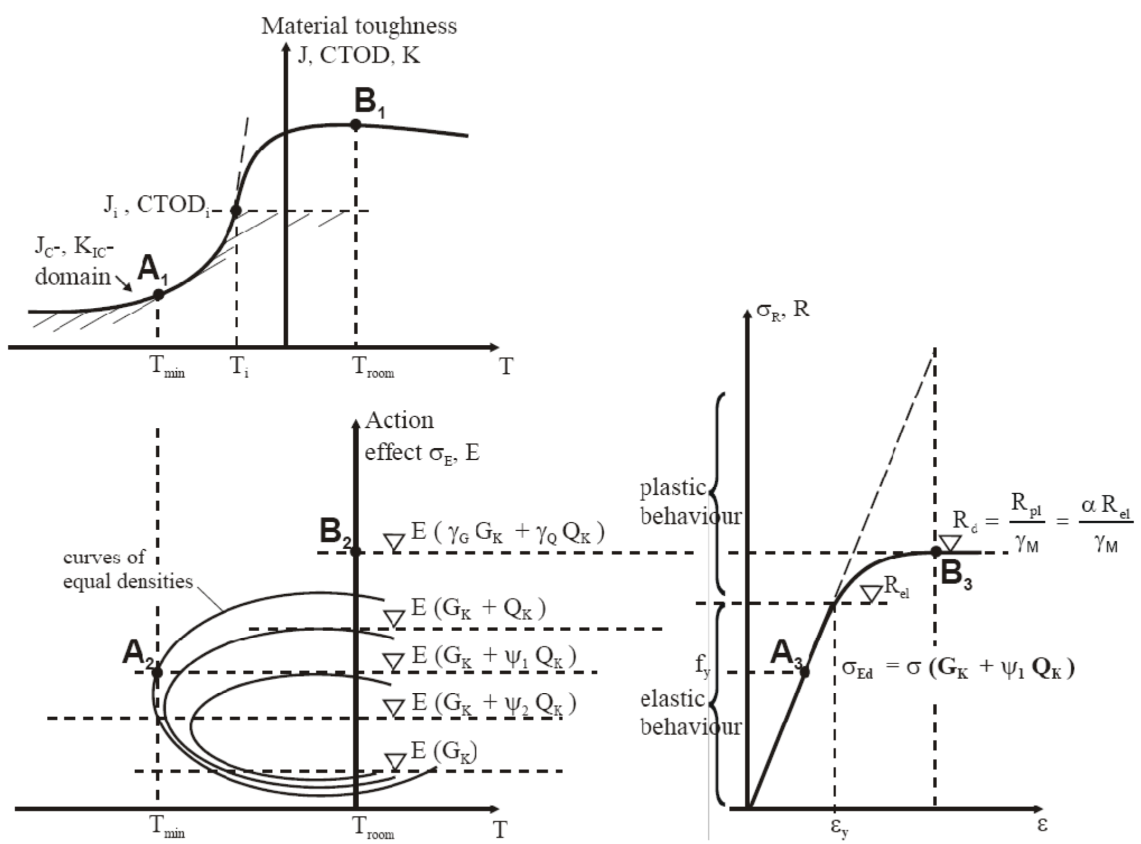
$$K_{appl,d} \leq K_{mat,d}$$

$K_{mat,d}$ (T_{27J}, T_{Ed})

$K_{appl,d}$ (member shape, a_d, $\psi_1 \cdot \sigma_{Ed}$)

5. CHOICE OF MATERIAL

Toughness-temperature - Load-strain-diagram



Design situations in the upper-shelf region B and the transition region A of the toughness-temperature diagram

5. CHOICE OF MATERIAL

Safety assessment based on temperature

$K^*_{appl,d} \leq K_{mat,d}$ → Transformation → $T_{Ed} \geq T_{Rd}$

Assessment scheme

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

Action side

$T_{Ed} = \Delta T_{min} + \Delta T_r + \Delta T_\sigma + \Delta T_R \; [\Delta T_\varepsilon + \Delta T_{\varepsilon pl}]$

- lowest air temperature in combination with σ_{Ed}:
  $T_{min} = -25\ °C$
- radiation loss:
  $\Delta T_r = -5\ °C$
- influence of stress, crack imperfection and member shape and dimension:

$$\Delta T_\sigma = -52 \ln \left[\frac{\left(\frac{K_{appl}}{k_{R6} - \rho} - 20 \right) \left(\frac{b_{eff}}{25} \right)^{1/4} - 10}{70} \right] \quad [C°]$$

- additive safety element:
  $\Delta T_R = +7\ °C$ (with $\beta = 3{,}8$)

Resistance

$T_{Rd} = T_{100}$

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

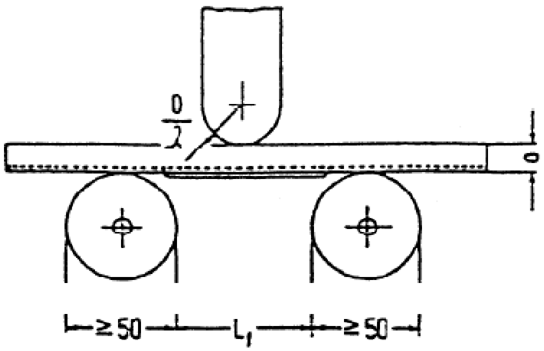
5. CHOICE OF MATERIAL

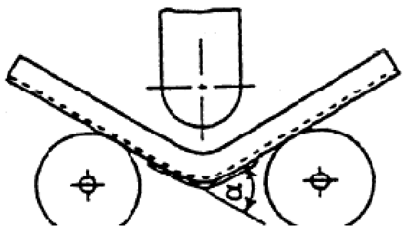
Choice of material to EN 1993-1-10

Steel grade	Sub-grade	Charpy energy CVN		Reference temperature T_{Ed} [°C]																				
		at T [°C]	J_{min}	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50
				$\sigma_{Ed} = 0,75\, f_y(t)$							$\sigma_{Ed} = 0,50\, f_y(t)$							$\sigma_{Ed} = 0,25\, f_y(t)$						
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	45	40	35	135	115	100	85	75	65	60
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	65	55	45	175	155	135	115	100	85	75
	J2	-20	27	125	105	90	75	60	50	40	170	145	125	105	90	75	65	200	200	175	155	135	115	100
S275	JR	20	27	55	45	35	30	25	20	15	80	70	55	50	40	35	30	125	110	95	80	70	60	55
	J0	0	27	75	65	55	45	35	30	25	115	95	80	70	55	50	40	165	145	125	110	95	80	70
	J2	-20	27	110	95	75	65	55	45	35	155	130	115	95	80	70	55	200	190	165	145	125	110	95
	M,N	-20	40	135	110	95	75	65	55	45	180	155	130	115	95	80	70	200	200	190	165	145	125	110
	ML,NL	-50	27	185	160	135	110	95	75	65	200	200	180	155	130	115	95	230	200	200	200	190	165	145
S355	JR	20	27	40	35	25	20	15	15	10	65	55	45	40	30	25	25	110	95	80	70	60	55	45
	J0	0	27	60	50	40	35	25	20	15	95	80	65	55	45	40	30	150	130	110	95	80	70	60
	J2	-20	27	90	75	60	50	40	35	25	135	110	95	80	65	55	45	200	175	150	130	110	95	80
	K2,M,N	-20	40	110	90	75	60	50	40	35	155	135	110	95	80	65	55	200	200	175	150	130	110	95
	ML,NL	-50	27	155	130	110	90	75	60	50	200	180	155	135	110	95	80	210	200	200	200	175	150	130
S420	M,N	-20	40	95	80	65	55	45	35	30	140	120	100	85	70	60	50	200	185	160	140	120	100	85
	ML,NL	-50	27	135	115	95	80	65	55	45	190	165	140	120	100	85	70	200	200	200	185	160	140	120
S460	Q	-20	30	70	60	50	40	30	25	20	110	95	75	65	55	45	35	175	155	130	115	95	80	70
	M,N	-20	40	90	70	60	50	40	30	25	130	110	95	75	65	55	45	200	175	155	130	115	95	80
	QL	-40	30	105	90	70	60	50	40	30	155	130	110	95	75	65	55	200	200	175	155	130	115	95
	ML,NL	-50	27	125	105	90	70	60	50	40	180	155	130	110	95	75	65	200	200	200	175	155	130	115
	QL1	-60	30	150	125	105	90	70	60	50	200	180	155	130	110	95	75	215	200	200	200	175	155	130
S690	Q	0	40	40	30	25	20	15	10	10	65	55	45	35	30	20	20	120	100	85	75	60	50	45
	Q	-20	30	50	40	30	25	20	15	10	80	65	55	45	35	30	20	140	120	100	85	75	60	50
	QL	-20	40	60	50	40	30	25	20	15	95	80	65	55	45	35	30	165	140	120	100	85	75	60
	QL	-40	30	75	60	50	40	30	25	20	115	95	80	65	55	45	35	190	165	140	120	100	85	75
	QL1	-40	40	90	75	60	50	40	30	25	135	115	95	80	65	55	45	200	190	165	140	120	100	85
	QL1	-60	30	110	90	75	60	50	40	30	160	135	115	95	80	65	55	200	200	190	165	140	120	100

5. CHOICE OF MATERIAL

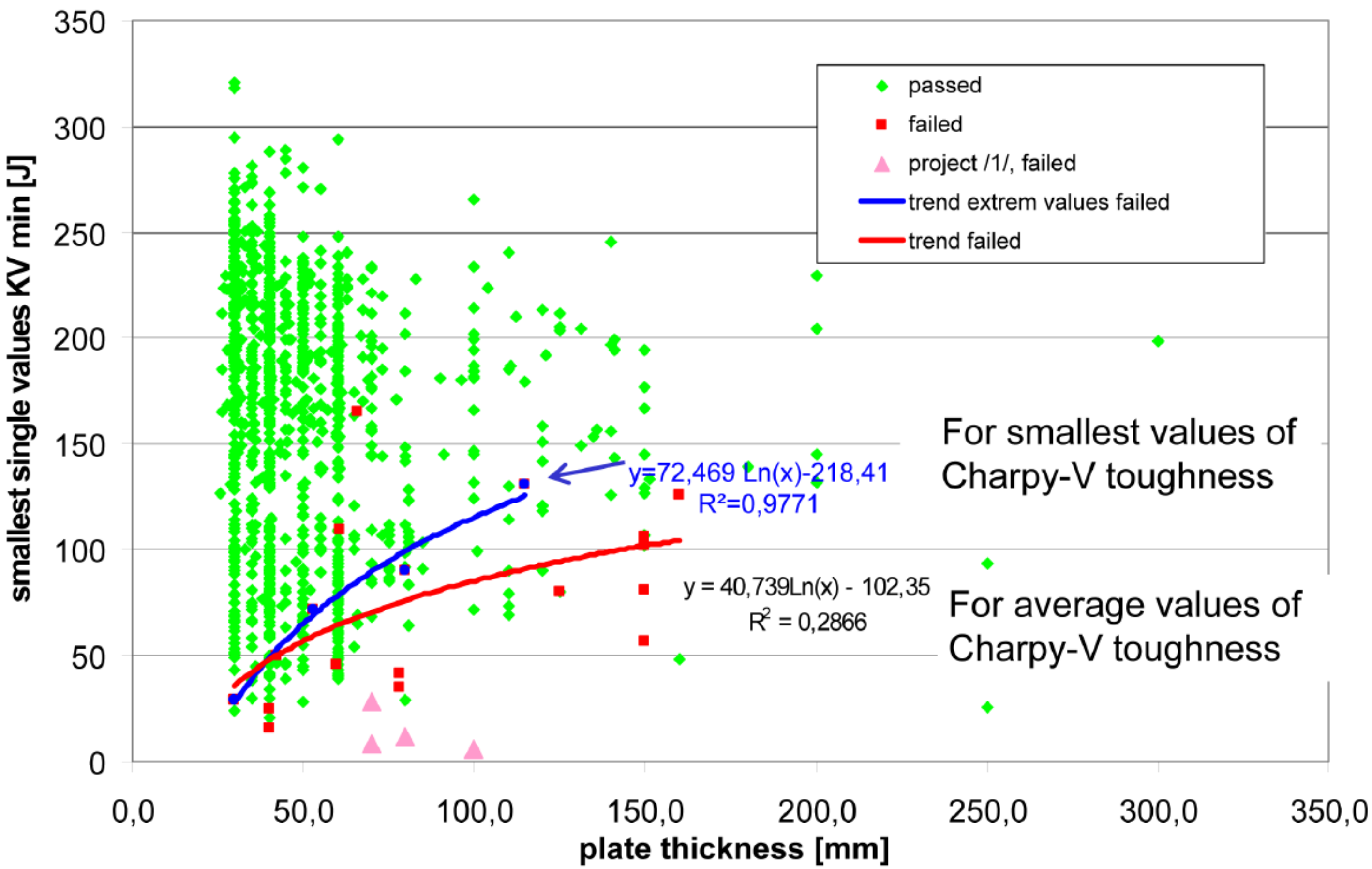
National quality tests





AUBI-test according to SEP 1390 (1996)

5. CHOICE OF MATERIAL



trend analysis for the AUBI correlation

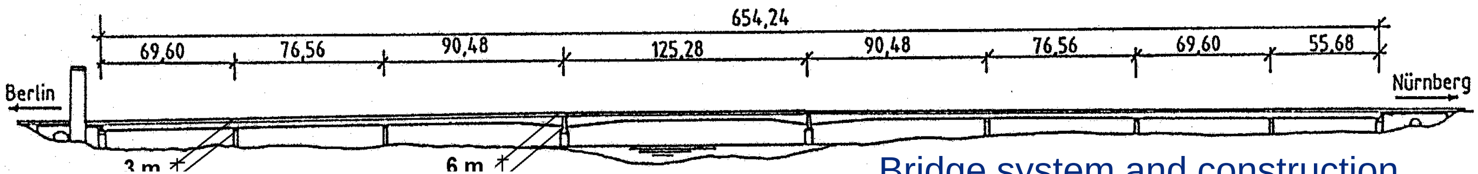
5. CHOICE OF MATERIAL

Example	Nominal plate thickness	Additional requirement
1	t ≤ 30 mm	T_{27J} = -20 °C acc. to EN 10025
	30 < t ≤ 80 mm	Fine grained steel acc. to EN 10025, e.g. S355N/M
	t > 80 mm	Fine grained steel acc. to EN 10025, e.g. S355NL/ML

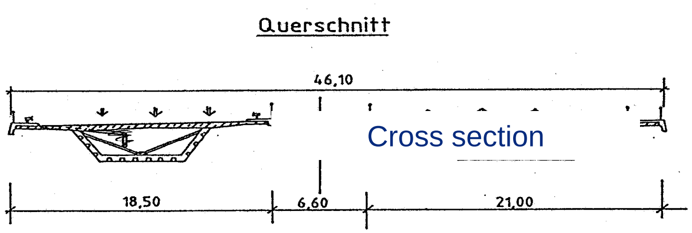
Choice of material given in Table 3.1 of EN 1993-2

5. CHOICE OF MATERIAL

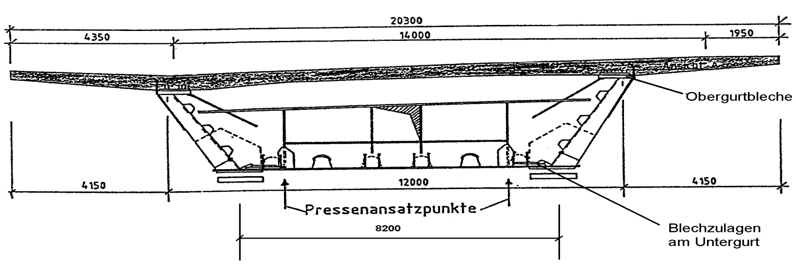
Example: Thick plates for the composite “Elbebridge Vockerode“ (EN 1993-1-10)



Bridge system and construction

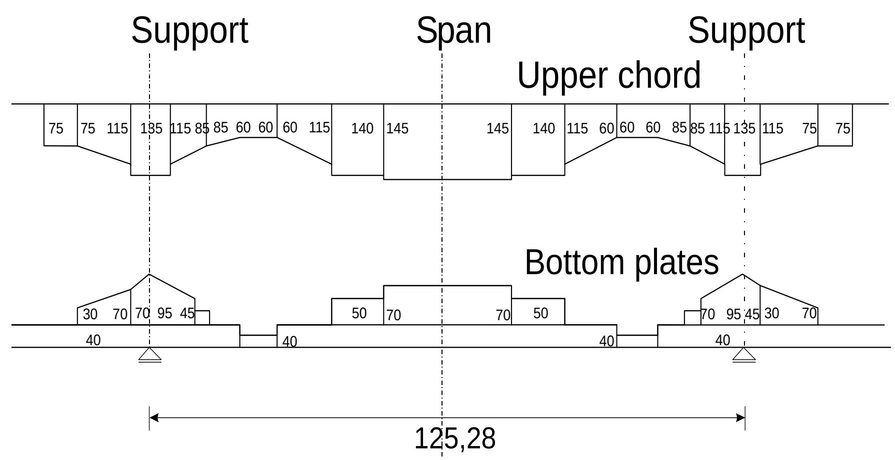


Cross section



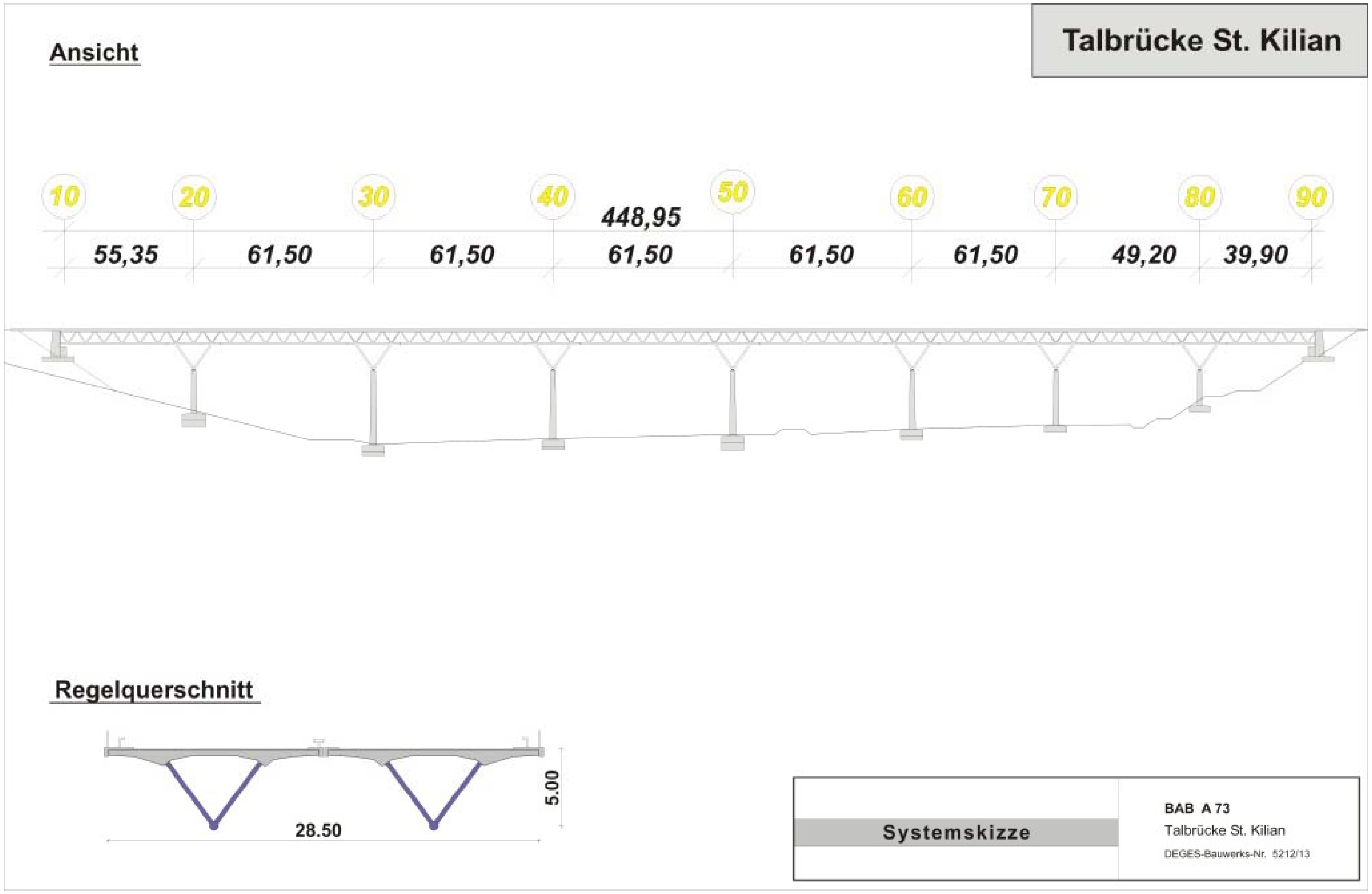
Construction at supports

Plate thickness for S355 J2G3



5. CHOICE OF MATERIAL

Bridge St. Kilian



5. CHOICE OF MATERIAL

Bridge St. Kilian

5. CHOICE OF MATERIAL

Cast node for the bridge St. Kilian

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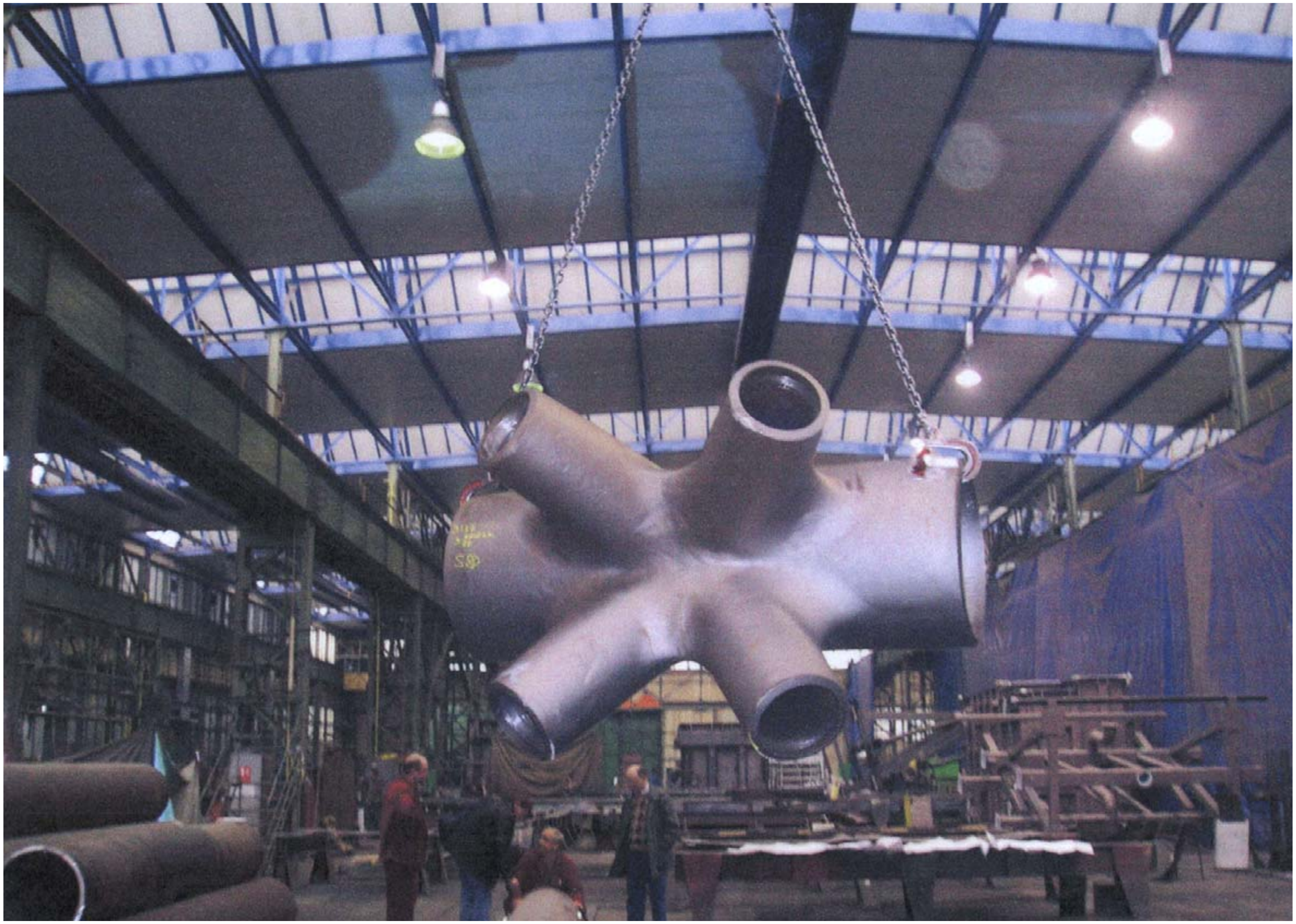
Cast node for the bridge St. Kilian



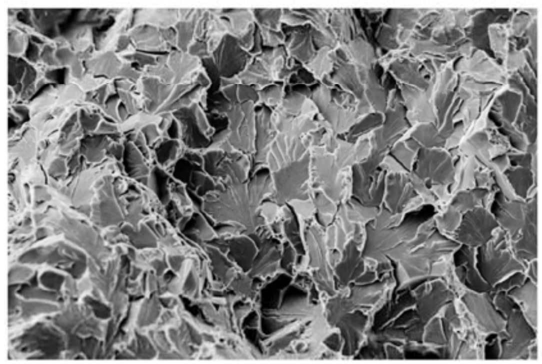
5. CHOICE OF MATERIAL

JRC Scientific and Technical Reports

COMMENTARY AND WORKED EXAMPLES
to EN 1993-1-10 "Material toughness and through thickness properties"
and other toughness oriented rules in EN 1993

G. Sedlacek, M. Feldmann, B. Kühn, D. Tschickardt, S. Höhler, C. Müller, W. Hensen, N. Stranghöner
W. Dahl, P. Langenberg, S. Münstermann, J. Brozetti, J. Raoul, R. Pope, F. Bijlaard

Background documents in support to the implementation, harmonization and further development of the Eurocodes



Joint Report
Prepared under the JRC – ECCS cooperation agreement for the evolution of Eurocode 3 (programme of CEN / TC 250)

Editors: M. Géradin, A. Pinto and S. Dimova

First Edition, September 2008

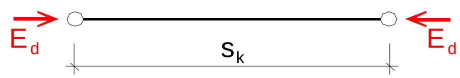
EUR 23510 EN - 2008

JRC EUROPEAN COMMISSION

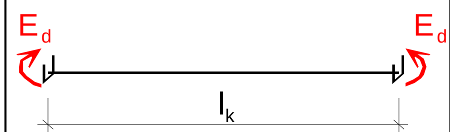
ECCS CECM EKS

6. DESIGN OF BRIDGE-ELEMENTS
6.1 STABILITY RULES

Common design rules for column, lateral torsional, plate and shell buckling



column buckling



lat. tors. buckl.

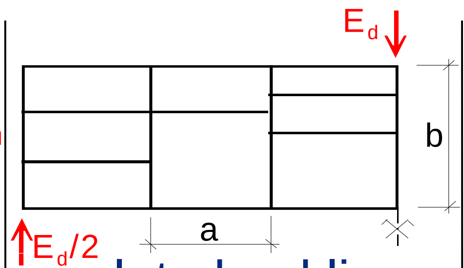
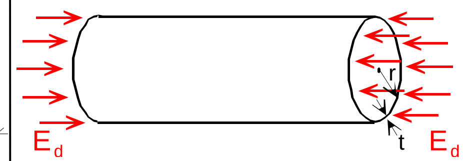


plate buckling



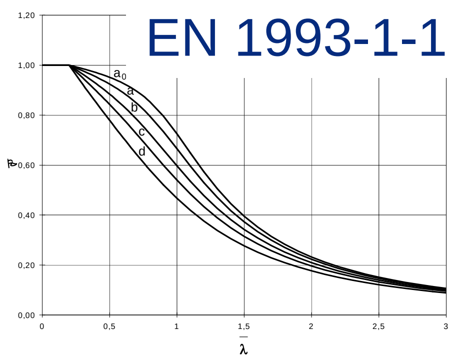
shell buckling

$$\alpha_{ult,k} E_d = R_k$$
$$\alpha_{crit} E_d = R_{crit}$$

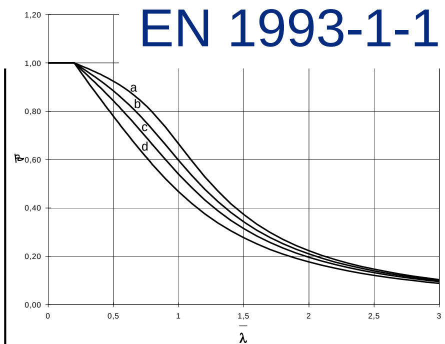
$$\bar{\lambda} = \sqrt{\frac{R_k}{R_{crit}}} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{crit}}}$$

$$\chi = \chi\left(\bar{\lambda}\right)$$

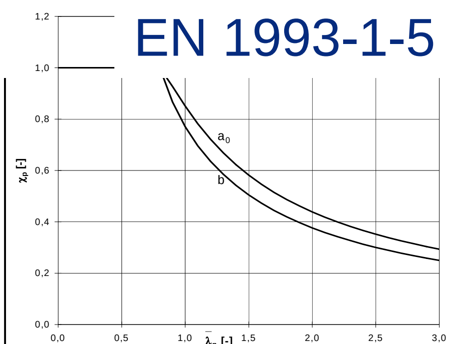
EN 1993-1-1



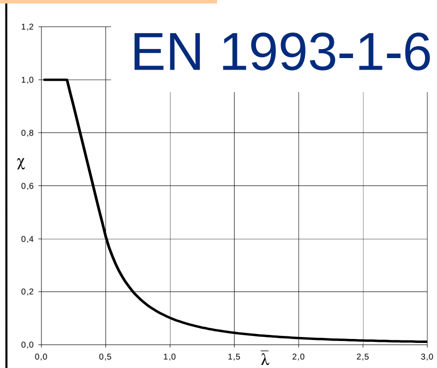
EN 1993-1-1



EN 1993-1-5



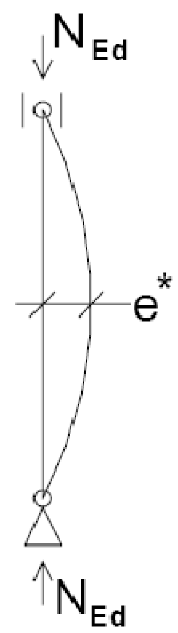
EN 1993-1-6



$$E_d \leq \frac{\chi R_k}{\gamma_M} \qquad 1 \leq \frac{\chi \alpha_{ult,k}}{\gamma_M}$$

6.1 STABILITY RULES

Column buckling



$$\frac{N_{Ed}}{N_{pl,k}} + \frac{N \cdot e^*}{M_{Rk}} \cdot \frac{1}{1 - \frac{N}{N_{crit}}} = 1 \qquad (1)$$

$$\frac{N_{Ed}}{N_{pl,k}} = \chi; \quad \frac{N_{plk}}{N_{crit}} = \bar{\lambda}^2 \qquad (2)$$

$$\chi + \chi \frac{N_{plk}}{M_{Rk}} \cdot e^* \cdot \frac{1}{1 - \chi \cdot \bar{\lambda}^2} = 1 \qquad (3)$$

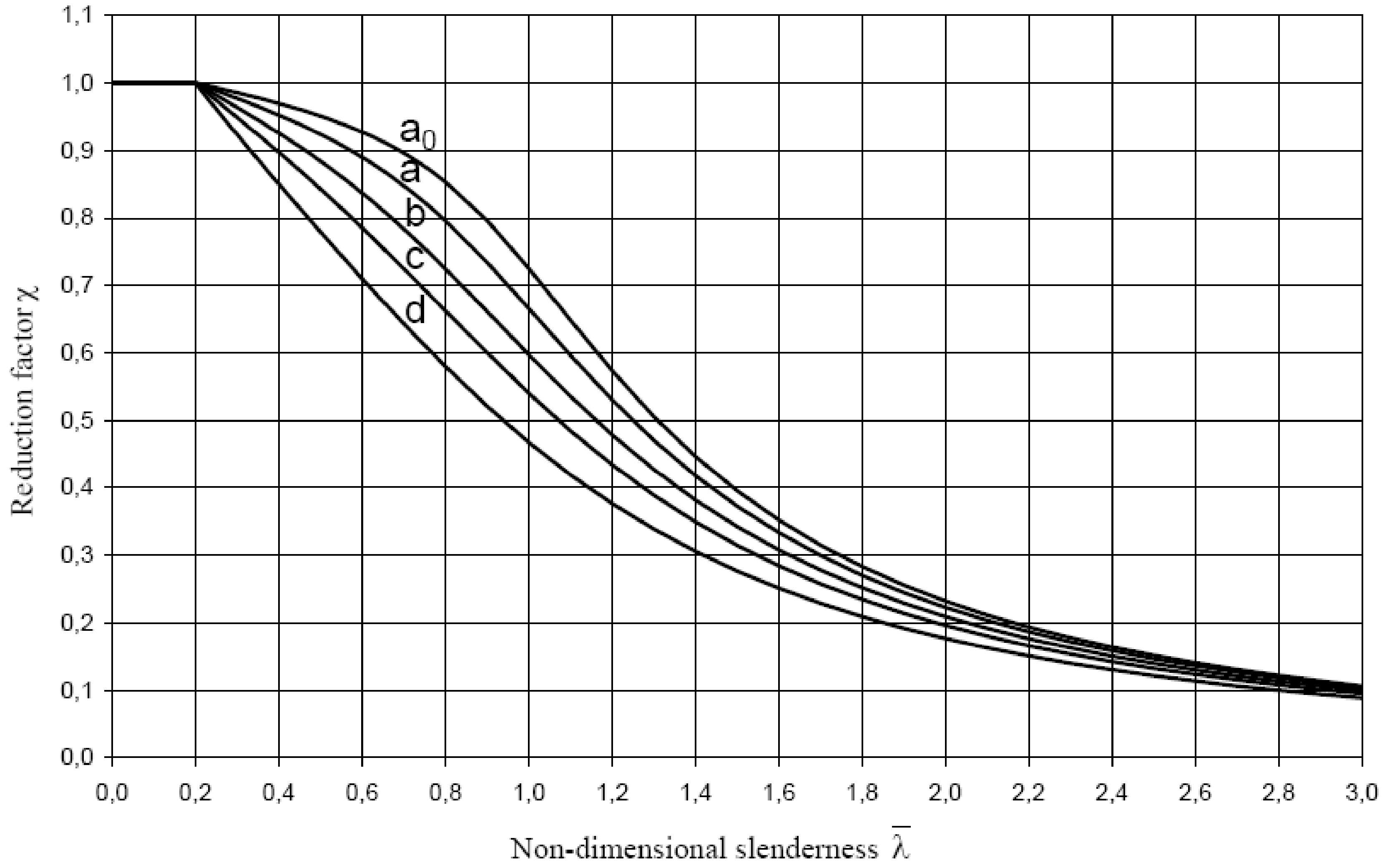
$$e^* = \alpha \cdot (\bar{\lambda} - 0{,}2) \cdot \frac{M_{Rk}}{N_{plk}} \qquad (4)$$

$$\chi + \chi \cdot \alpha(\bar{\lambda} - 0{,}2) \frac{1}{1 - \chi \bar{\lambda}^2} = 1 \qquad (5)$$

$$\chi = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}^2}} \qquad (6)$$

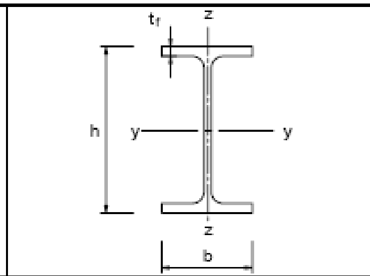
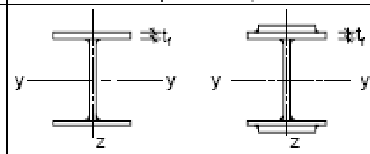
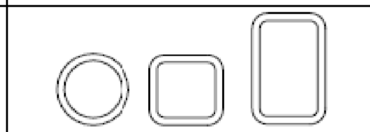
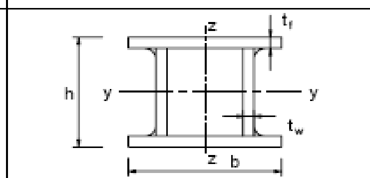
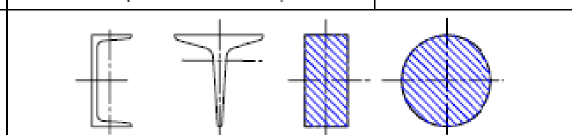
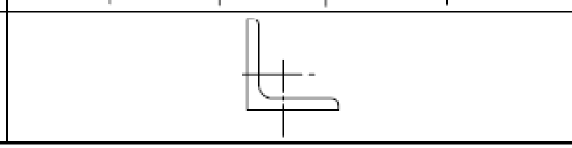
mit $\varphi = 0{,}5 \cdot [1 + \alpha(\bar{\lambda} - 0{,}2) + \bar{\lambda}^2]$

6.1 STABILITY RULES



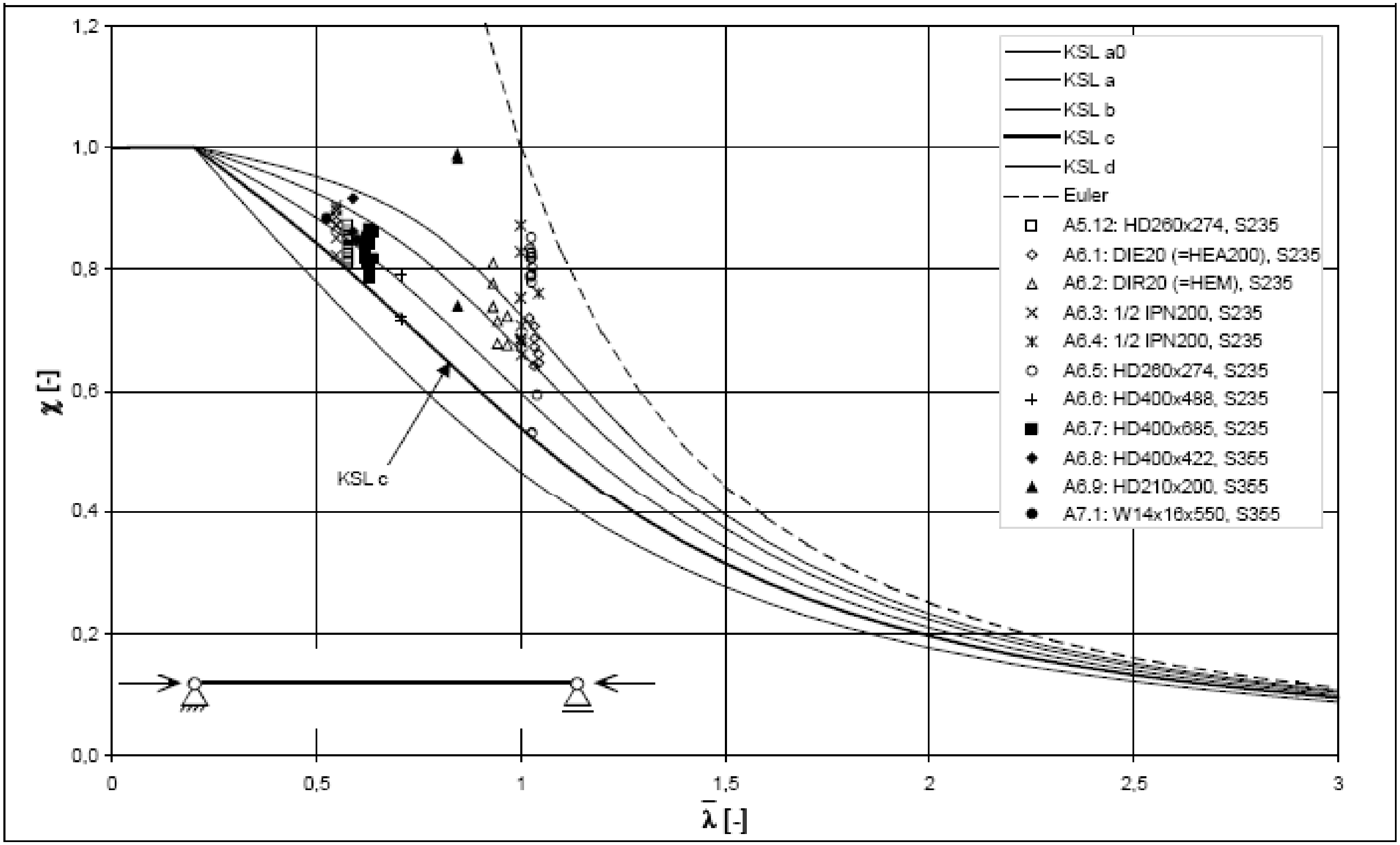
Column buckling curves

6.1 STABILITY RULES

Cross section		Limits		Buckling about axis	Buckling curve S 235, S 275, S 355, S 420	Buckling curve S 460
Rolled sections		$h/b > 1,2$	$t_f \leq 40$ mm	y – y z – z	a b	a_0 a_0
		$h/b > 1,2$	40 mm < $t_f \leq 100$	y – y z – z	b c	a a
		$h/b \leq 1,2$	$t_f \leq 100$ mm	y – y z – z	b c	a a
		$h/b \leq 1,2$	$t_f > 100$ mm	y – y z – z	d d	c c
Welded I-sections		$t_f \leq 40$ mm		y – y z – z	b c	b c
		$t_f > 40$ mm		y – y z – z	c d	c d
Hollow sections		hot finished		any	a	a_0
		cold formed		any	c	c
Welded box sections		generally (except as below)		any	b	b
		thick welds: $a > 0,5t_f$ $b/t_f < 30$ $h/t_w < 30$		any	c	c
U-, T- and solid sections				any	c	c
L-sections				any	b	b

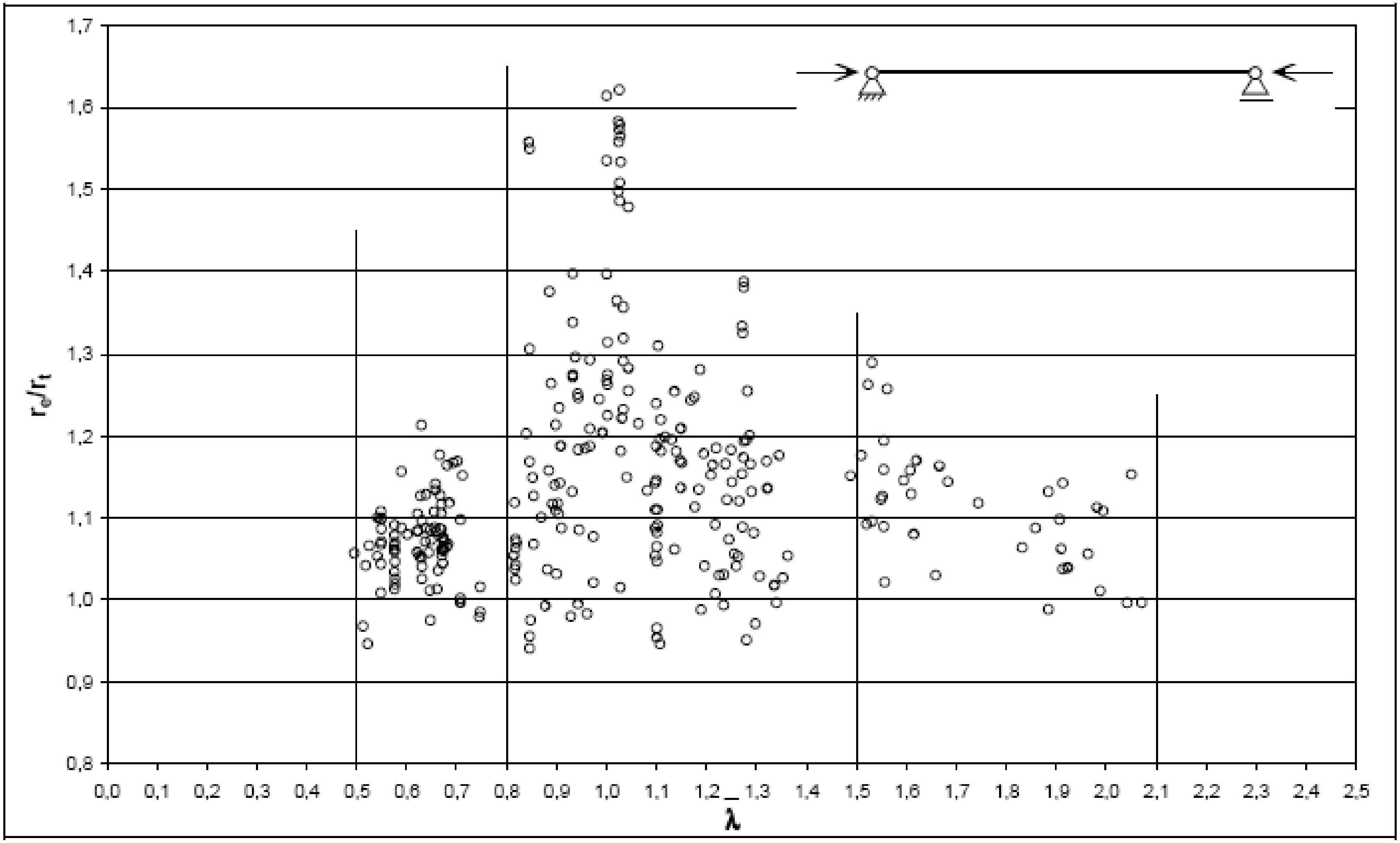
Selection of buckling curves

6.1 STABILITY RULES



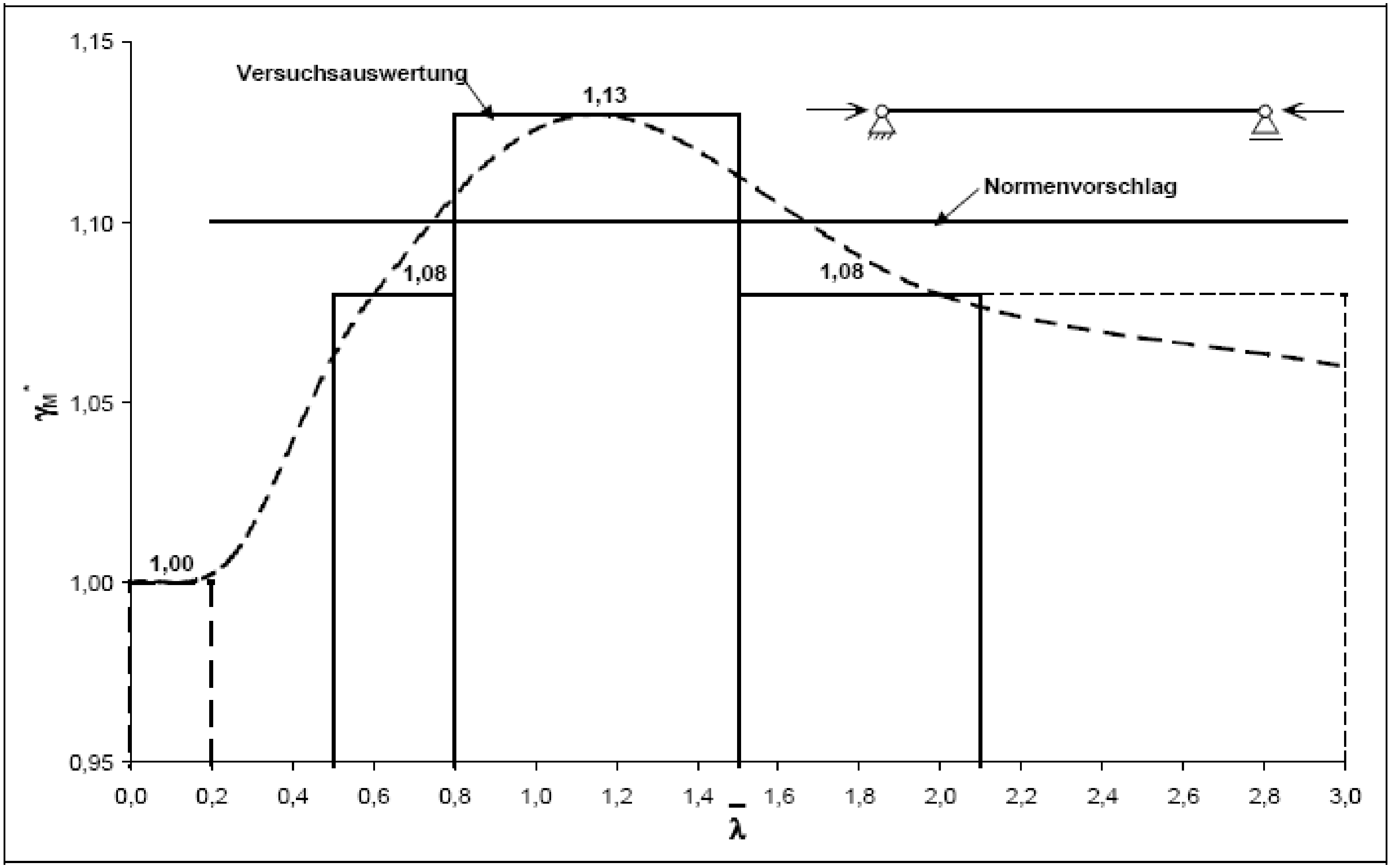
Test evaluation – weak axis buckling

6.1 STABILITY RULES



Test evaluation – weak axis buckling

6.1 STABILITY RULES



γ_M-values according to EN 1990 – Annex D

6.1 STABILITY RULES

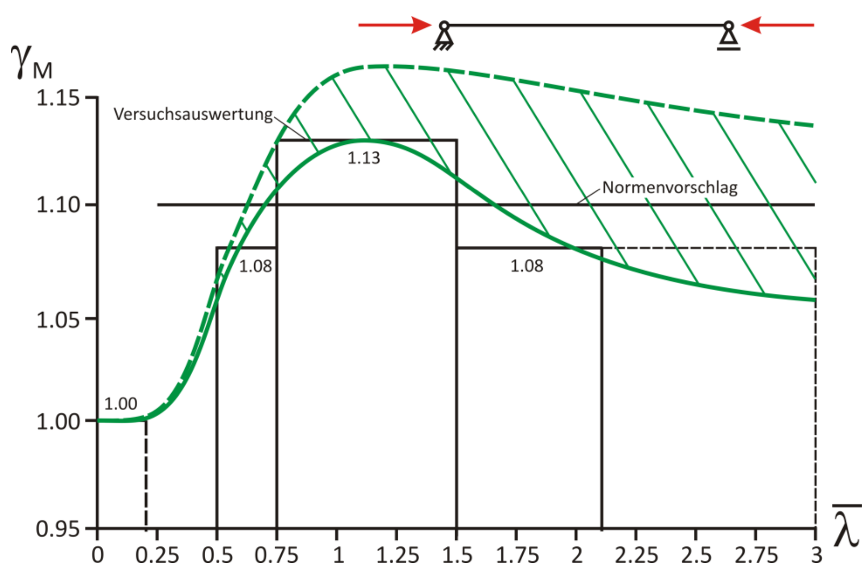
European buckling curve	2nd order theory with imperfection
$E_d \overset{!}{=} R_k$ $\bar{\lambda} = \sqrt{\frac{N_{pl}}{N_{crit}}}$ $\chi = (\alpha, \bar{\lambda})$ $R_k = \chi, N_{pl}$ $R_d = \frac{R_k}{\gamma_M}$	$E_d \overset{!}{=} R_d$ $\bar{\lambda}_d = \sqrt{\frac{N_{pl,d}}{N_{crit}}}$ $\chi_d = (\alpha, \bar{\lambda}_d)$ $R_d = \frac{\chi_d \cdot N_{pl}}{\gamma_M}$
	<u>Consequences:</u> Option 1: $\bar{E}_d = \gamma_M . E_d$ Option 2: $\bar{N}_{crit,d} = \frac{N_{crit}}{\gamma_M}$ Option 3: $\gamma_M = 1{,}0$ Option 4: $e_d = e_0 \frac{1 - \frac{\chi \bar{\lambda}^2}{\gamma_M}}{1 - \chi \bar{\lambda}^2}$ Option 5: $\gamma_M^* = \frac{\chi_d}{\chi} \cdot \gamma_M$

Equivalence of buckling curves and 2nd order theory

6.1 STABILITY RULES

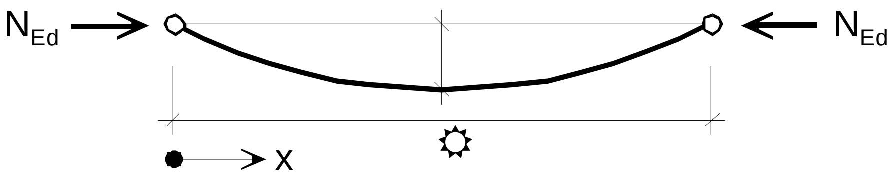
γ_M-values for 2nd order analysis

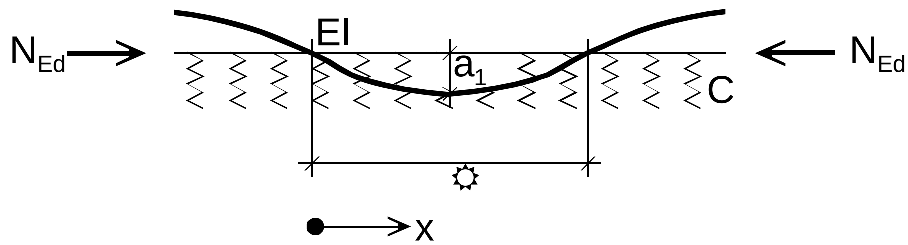
λ	ϕ	χ	λ_d	ϕ_d	χ_d	$g = \frac{\chi_d}{\chi}$
0,5	0,685	0,870	0,477	0,661	0,895	1,03
1,0	1,136	0,597	0,953	1,082	0,627	1,05
1,5	1,846	0,342	1,43	1,734	0,369	1,08
2,0	2,806	0,209	1,906	2,605	0,228	1,09
3,0	5,476	0,10	2,859	5,039	0,109	1,09



6.1 STABILITY RULES

Imperfections for members with various boundary conditions





$$\eta_{ini} = e_{0d} \sin \frac{\pi x}{\ell}$$

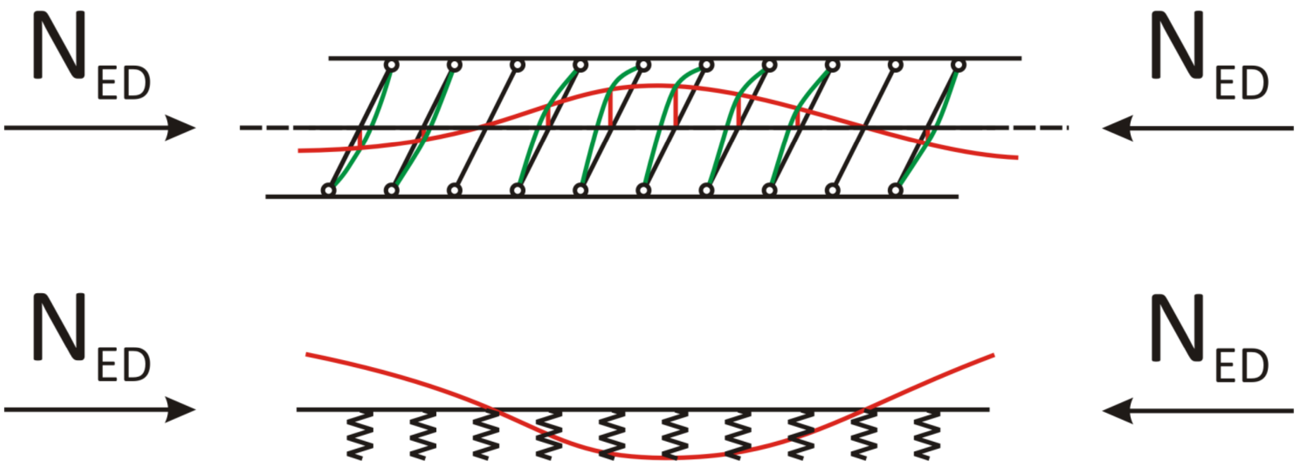
$$M_e = e_{0d} N_{Ed} \frac{1}{1 - \frac{N_{Ed}}{N_{crit}}} \sin \frac{\pi x}{\ell}$$

$$\eta_{ini} = e_{0d} \frac{\alpha_{crit}^2}{\eta''_{crit,max}} \eta_{crit}$$

$$M_e = e_{0d} \frac{N_{Ed}}{1 - \frac{N_{Ed}}{EI\alpha_{crit}^2}} \frac{\eta''_{crit}}{\eta''_{crit,max}}$$

Use of buckling mode as imperfection

6.1 STABILITY RULES



Example for a column on elastic supports

6.1 STABILITY RULES

Column buckling	Lateral torsional buckling
$\frac{N_{Ed}}{N_{pl,Rk}} + \frac{M_{Ed}}{M_{y,Rk}} = 1$	$\frac{N_{Ed}^{Fl}}{N_{pl,Rk}^{Fl}} + \frac{M_{y,Ed}^{Fl}}{M_{y,Rk}^{Fl}} = 1$
$\frac{N_{Ed}}{N_{pl,Rk}} + \frac{N_{Ed} e^*}{M_{y,Rk}} \frac{1}{1 - \frac{N_{Ed}}{N_{crit}}} = 1$	$\frac{M_{z,Ed}}{M_{z,Rk}} + \frac{M_{z,Ed}}{M_{z,crit}} \frac{N_{crit}^{Fl}}{M_{y,Rk}^{Fl}} e^* \frac{1}{1 - \frac{M_{z,Ed}}{M_{z,crit}}} = 1$
$e^* = \alpha\left(\bar{\lambda}_N - 0{,}2\right)\frac{M_{y,Rk}}{N_{pl,Rk}}$ $\chi_N + \chi_N \overbrace{\alpha}^{=\alpha} \left(\bar{\lambda}_N - 0{,}2\right)\frac{1}{1 - \chi_N \bar{\lambda}_N^2} = 1$	$e^* = \alpha\left(\bar{\lambda}_M - 0{,}2\right)\frac{M_{y,Rk}^{Fl}}{N_{pl,Rk}^{Fl}}$ $\chi_M + \chi_M \overbrace{\alpha \frac{\bar{\lambda}_M^2}{\bar{\lambda}_{Fl}^2}}^{=\alpha^*} \left(\bar{\lambda}_M - 0{,}2\right)\frac{1}{1 - \chi_M \bar{\lambda}_M^2} = 1$

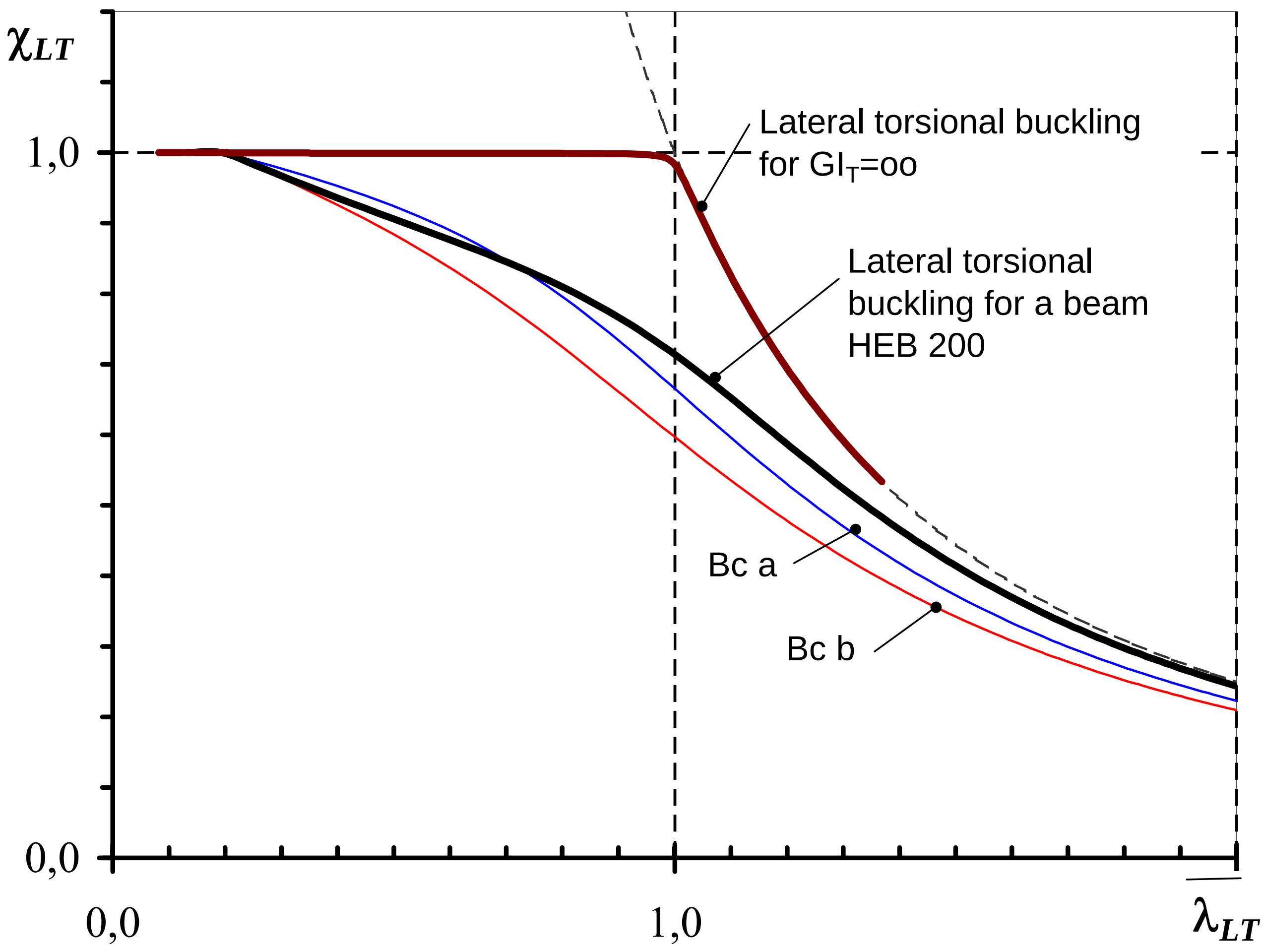
$$\chi = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}^2}}$$

$$\varphi = 0{,}5\left(1 + \alpha\left(\bar{\lambda} - 0{,}2\right) + \bar{\lambda}^2\right)$$

Equivalence of flexural and lateral torsional buckling

6.1 STABILITY RULES

Comparison of LTB-curves



6.1 STABILITY RULES

Procedure for lateral torsional buckling assessments using the buckling curves:

1. Input parameters:

$$\alpha_{ult,k} = \frac{R_k}{E_d}$$

$$\alpha_{crit} = \frac{R_{crit}}{E_d}$$

$$\overline{\lambda} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{critt}}}$$

2. Modification of imperfection factor:

$$\alpha^* = \frac{\alpha^*_{crit}}{\alpha_{crit}} \cdot \alpha$$

where α^*_{crit} is determined without effect of $G \cdot I_D$

3. Use of flexural buckling curve:

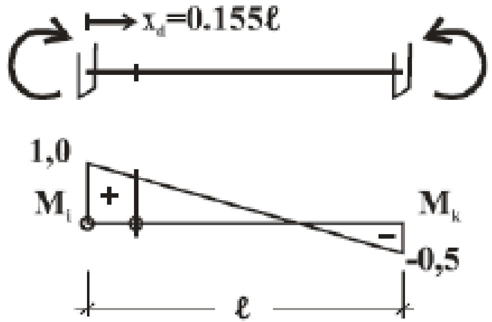
$$\phi = 0{,}5\left[1 + \alpha^*\left(\lambda - 0{,}2\right) + \overline{\lambda}^2\right]$$

$$\chi = \frac{1}{\phi - \sqrt{\phi^2 - \overline{\lambda}^2}}$$

4. Assessment for design point x_d

$$\frac{\chi \alpha_{ult,k}}{\gamma_M} \geq 1$$

6.1 STABILITY RULES



$x = 0$

$$\chi_{mod} = \frac{\beta}{\phi + \sqrt{\phi^2 - \beta \cdot \bar{\lambda}_{mod}^2}}$$

$$\phi = 0.5 \cdot \left[1 + \alpha^* \left(\sqrt{\beta} \cdot \bar{\lambda}_{mod} - 0.2\right) + \beta \cdot \bar{\lambda}_{mod}^2\right]$$

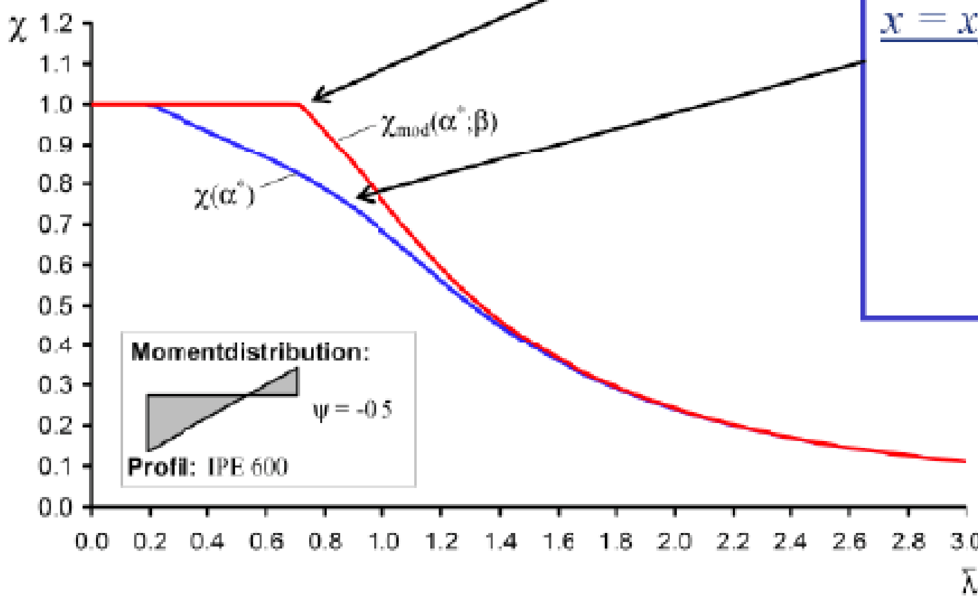
$$\bar{\lambda}_{mod} = \sqrt{\frac{\alpha_{ult,k,min}}{\alpha_{crit}}}$$

$x = x_d$

$$\chi = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}^2}}$$

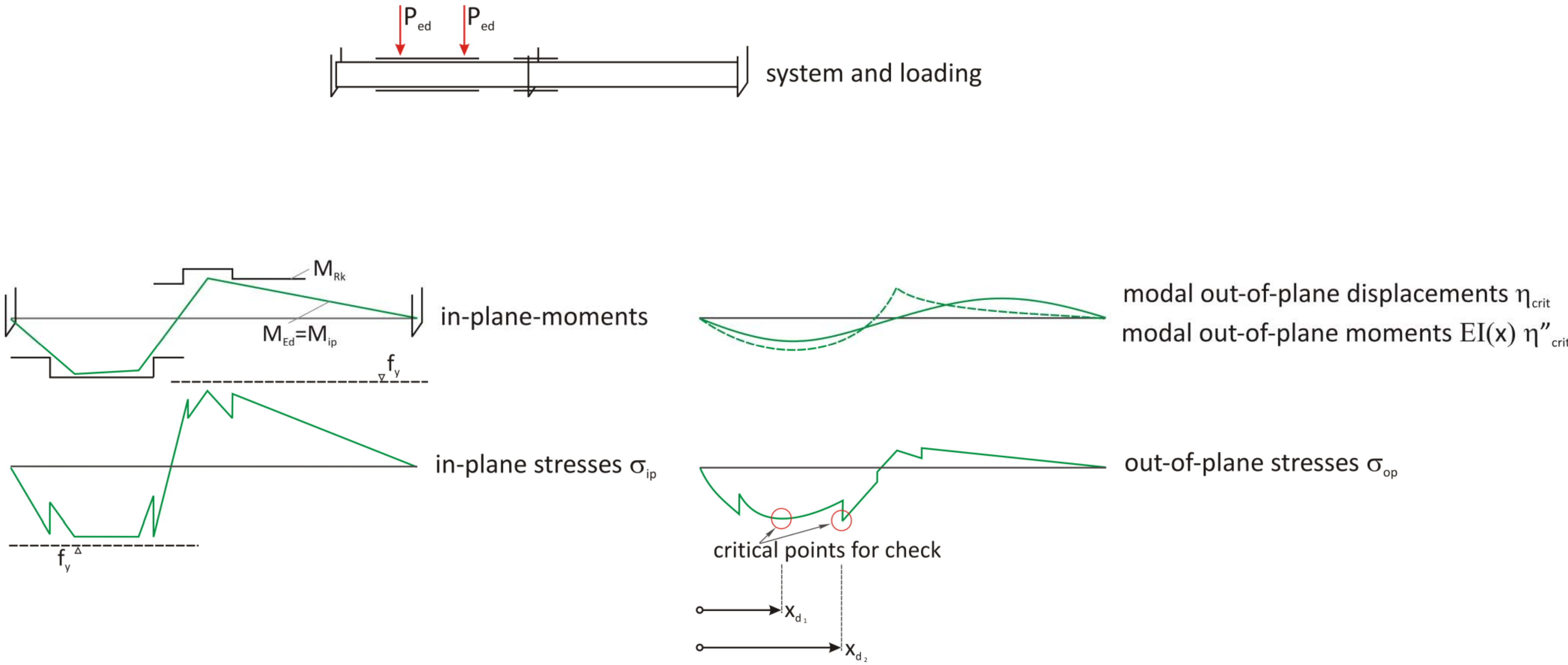
$$\varphi = 0.5 \cdot \left[1 + \alpha^* \left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right]$$

$$\bar{\lambda} = \sqrt{\frac{\alpha_{ult,k}(x_d)}{\alpha_{crit}}}$$



Comparison of laterial torsional buckling curves

6.1 STABILITY RULES



check:

$$\bar{\lambda} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{crit}}}$$

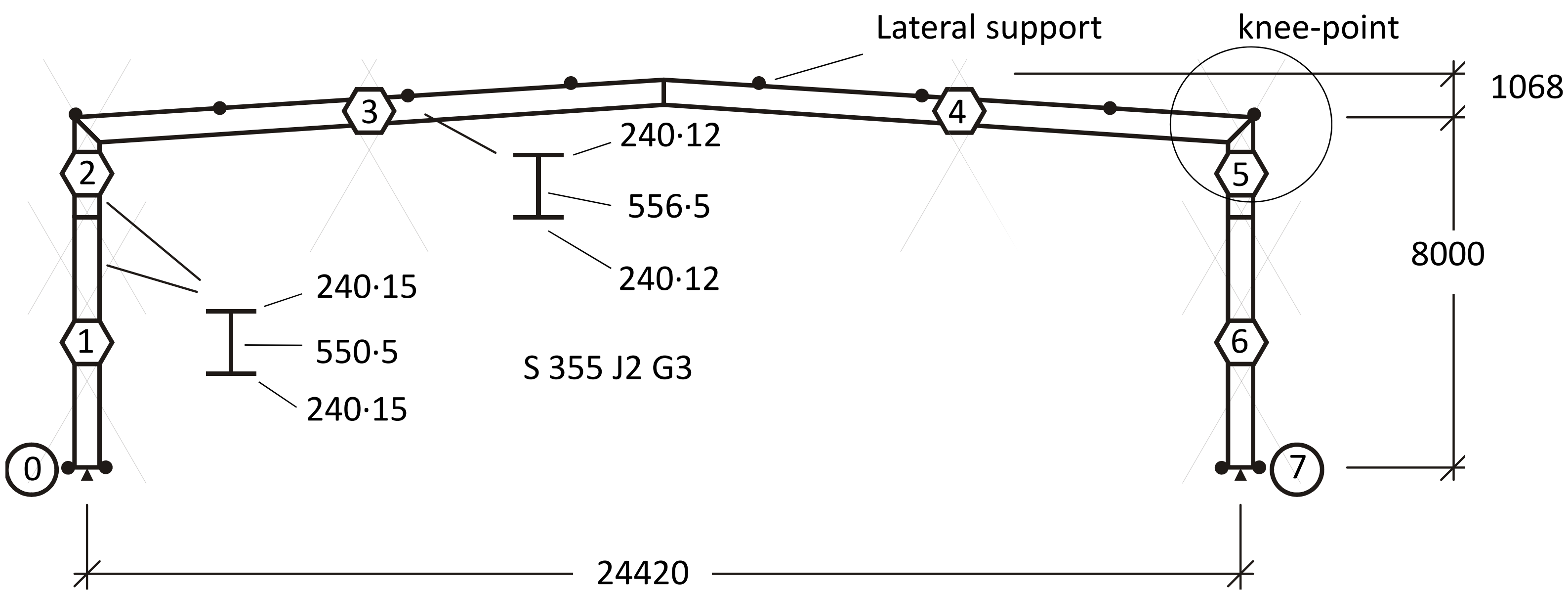
$$\chi = \chi\left(\alpha^*, \bar{\lambda}\right)$$

$$\frac{\chi \cdot \alpha_{ult,k}}{\gamma_M} \geq 1$$

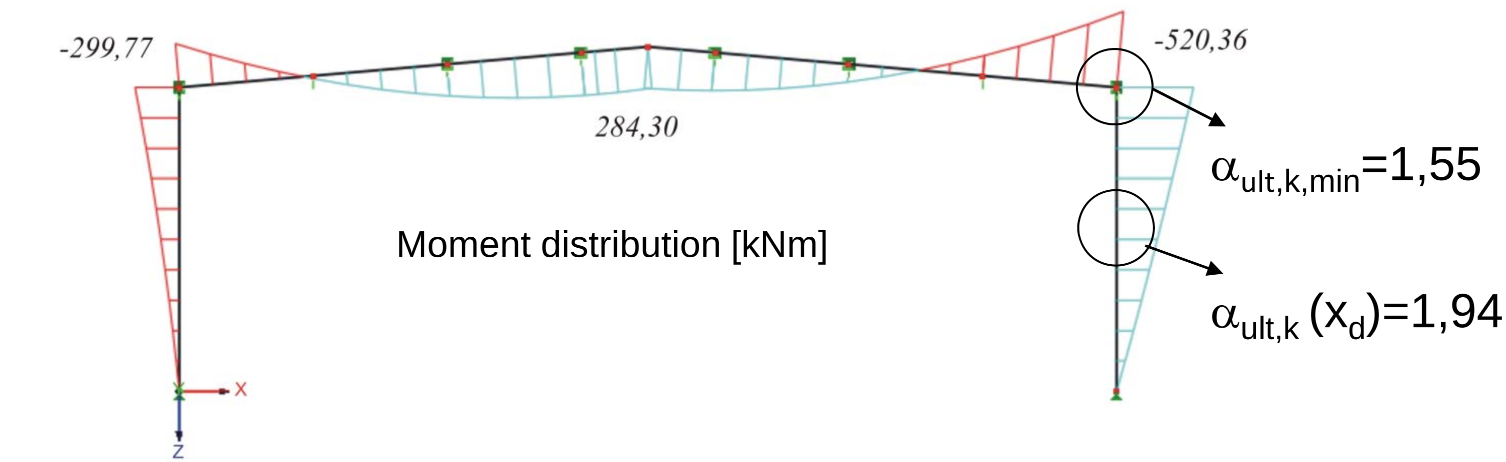
Determination of design point x_d

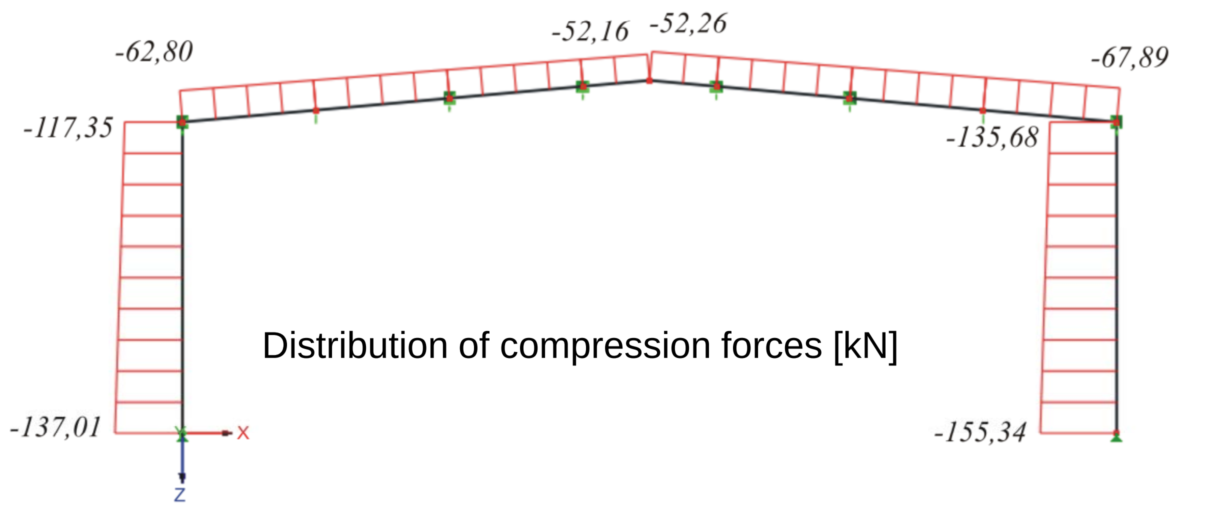
6.1 STABILITY RULES

Example: Portal frame



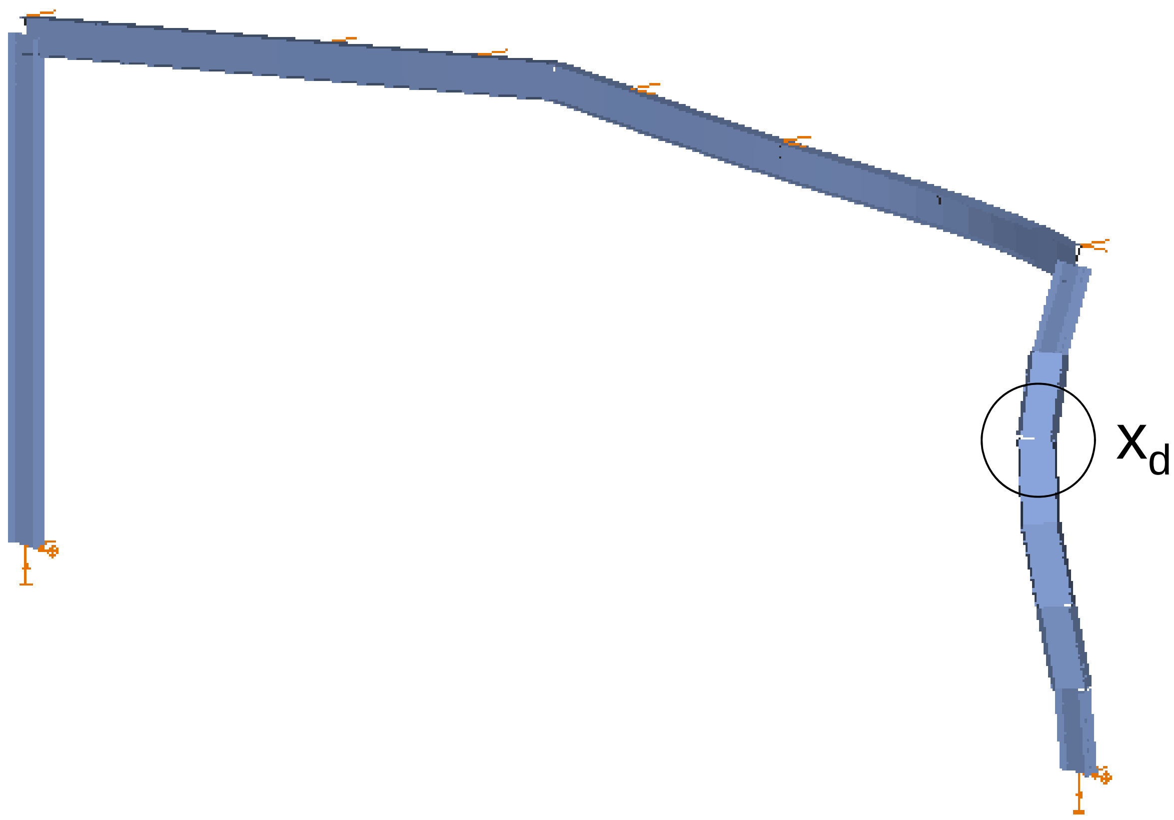
6.1 STABILITY RULES





6.1 STABILITY RULES

Example: Modal out-of-plane deformation α_{crit}=1.85



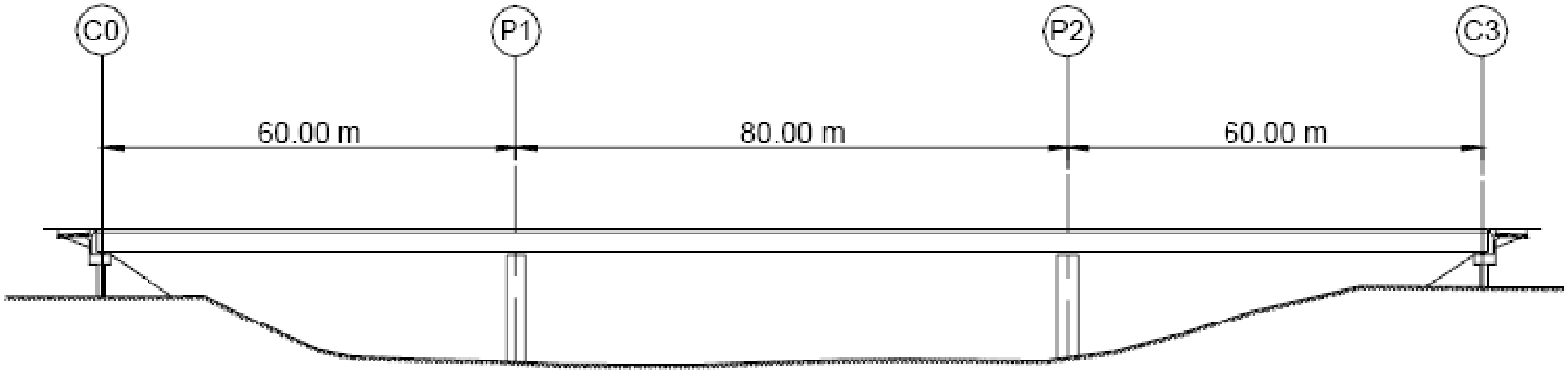
6.1 STABILITY RULES

1. Calculation with extreme value $\alpha_{ult,k,min}$	2. Calculation design point x_d
$\alpha_{ult,k} = 1.55$	$\alpha_{ult,k} = 1.94$
$\alpha_{crit} = 1.85$	
$\alpha^*_{crit} = 1.84$	
$\bar{\lambda} = \sqrt{\frac{1.55}{1.85}} = 0.915$	$\bar{\lambda} = \sqrt{\frac{1.94}{1.85}} = 1.05$
$\alpha^* = \frac{\alpha^*_{crit}}{\alpha_{crit}} \alpha = \frac{1.54}{1.85} \cdot 0.49 = 0.408$	
$\phi_{LT} = 0.5\left[1 + \alpha^*\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] = 1.064$	$\phi_{LT} = 1.225$
$\chi = \frac{1}{\phi + \phi^2 -^{\lambda} 2} = 0.622 > 0.50$	$\chi = 0.59 > 0.50$
contact splice sufficient	contact splice sufficient
$\frac{\chi \cdot \alpha_{ult}}{\gamma_M} = \frac{0.622 \cdot 1{,}55}{1.10} = 0.88 < 1.00$	$\frac{\chi \cdot \alpha_{ult,k}}{\gamma_M} = \frac{0.59 \cdot 1.94}{1.10} = 1.04 > 1.00$

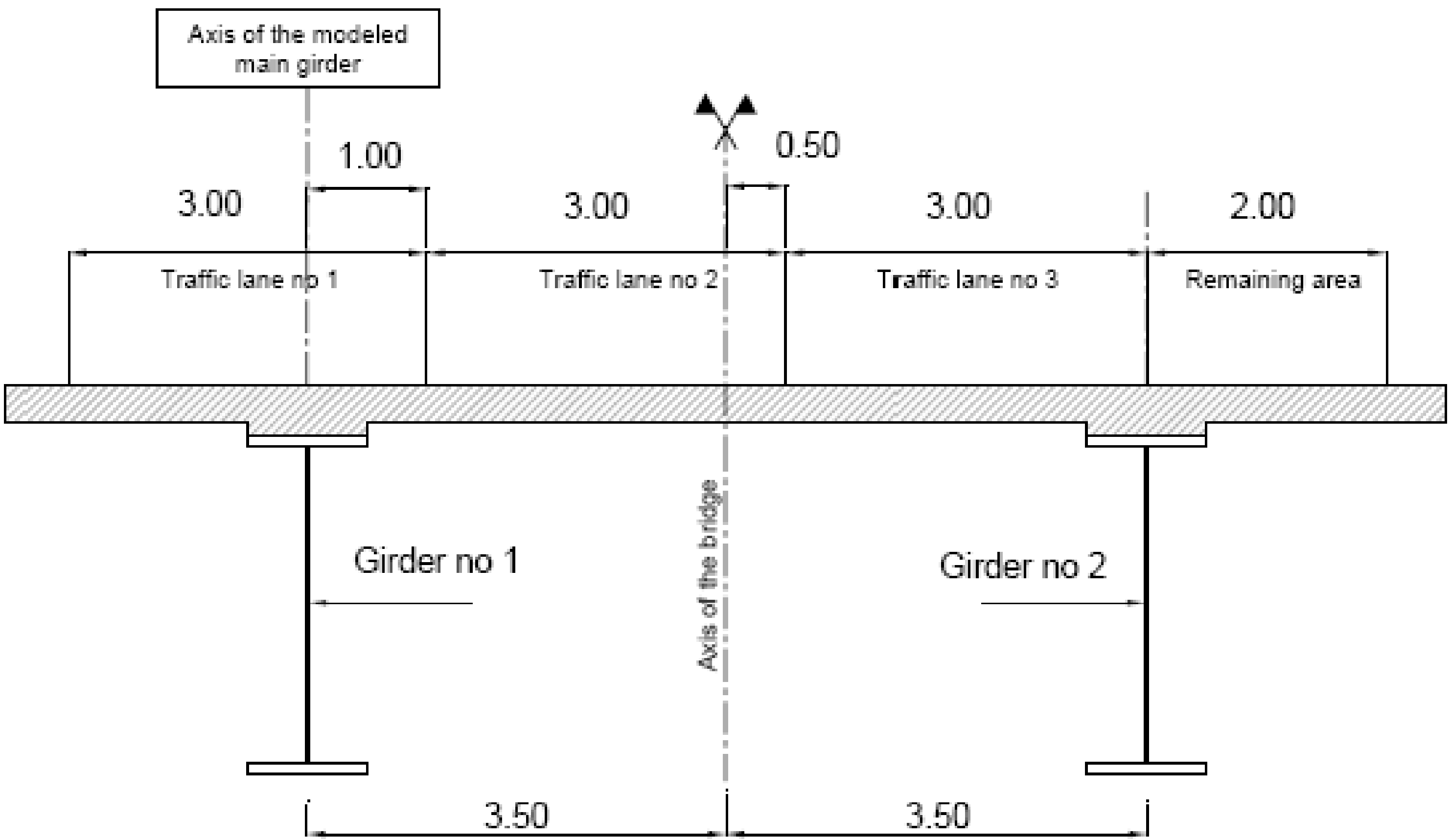
Check of out-of-plane stability

6.1 STABILITY RULES

Example: Composite bridge

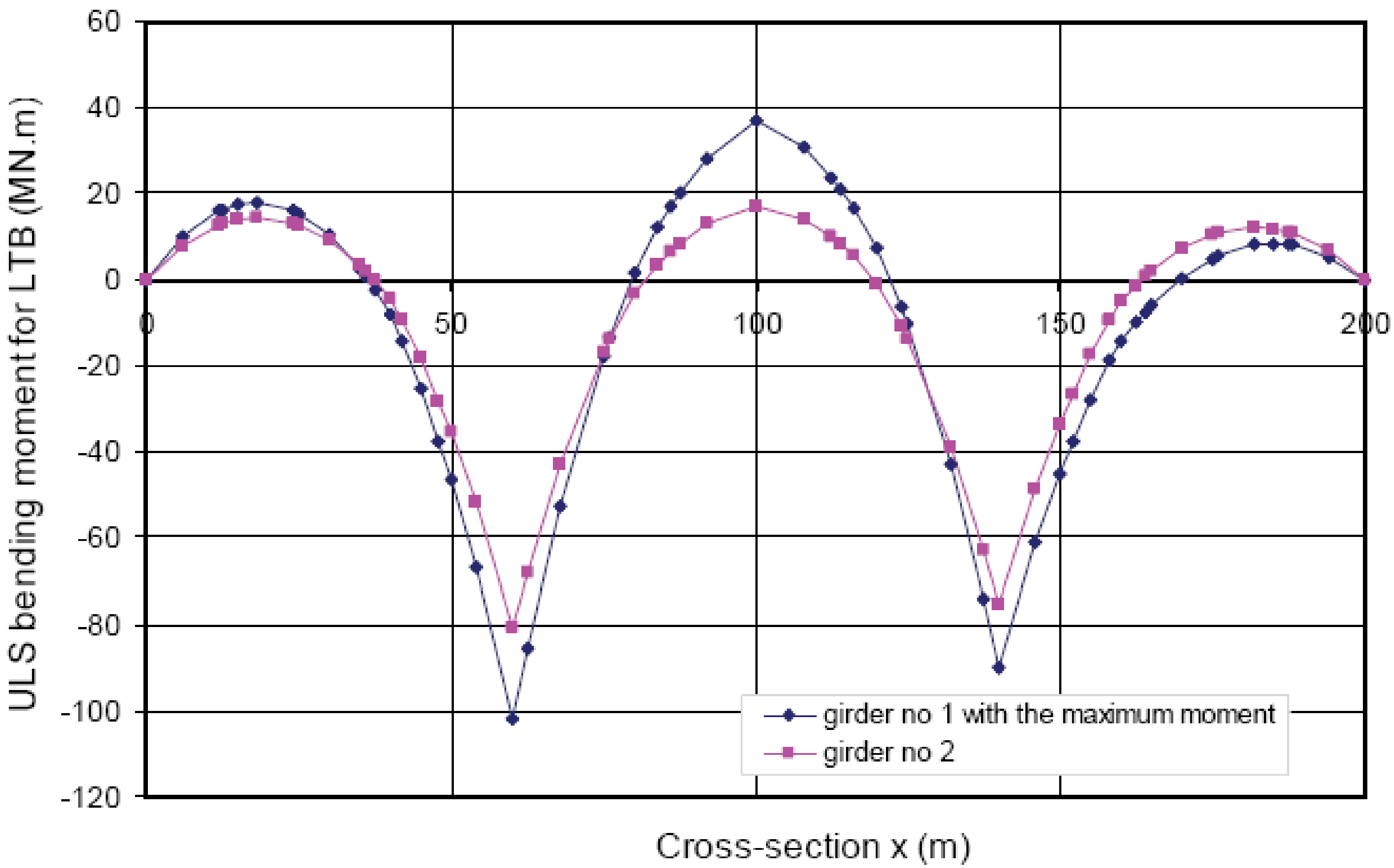


Example: Cross-section of the composite bridge



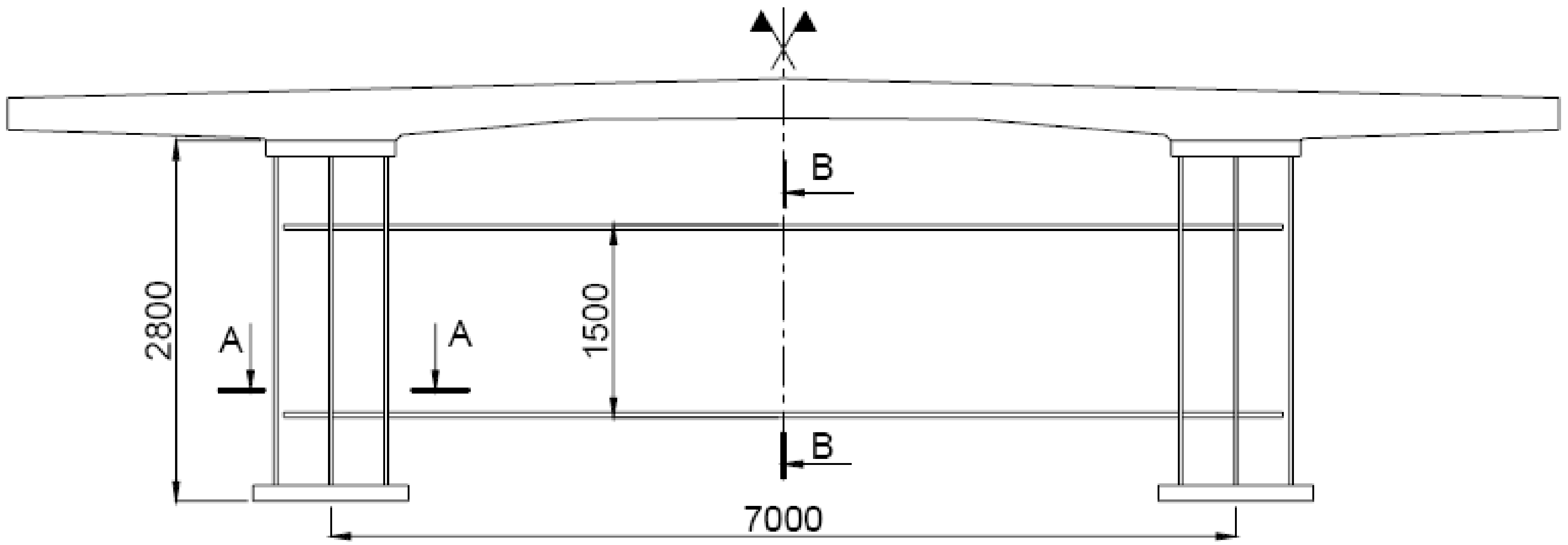
6.1 STABILITY RULES

Example: Moment distribution critical for out-of-plane stability of main girders



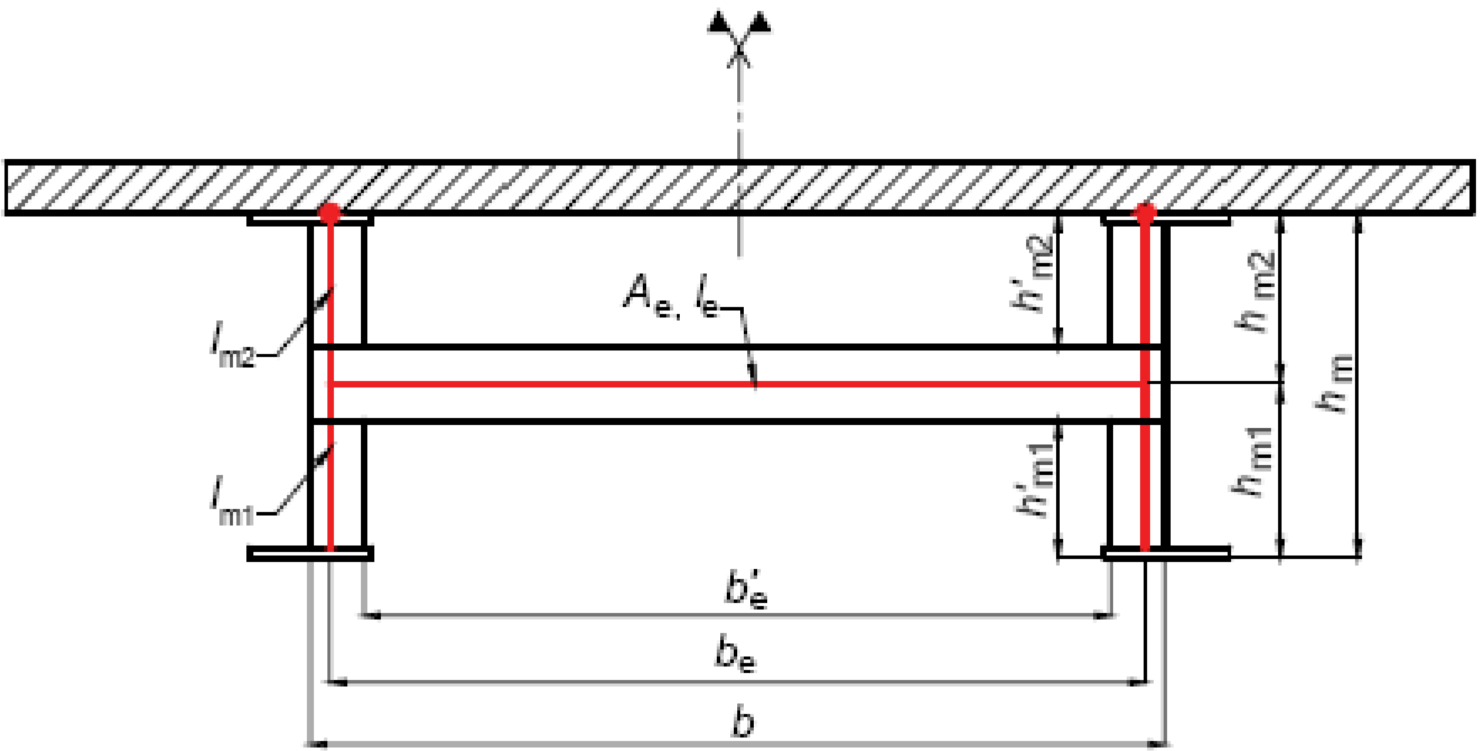
6.1 STABILITY RULES

Example: cross-beam at supports

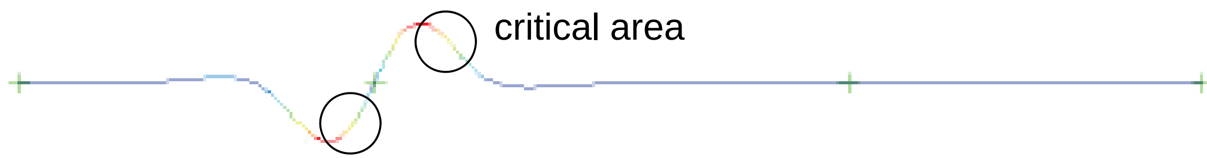
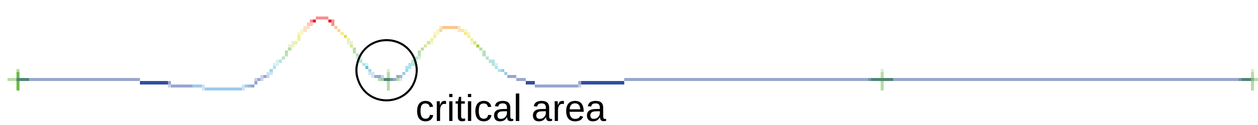


6.1 STABILITY RULES

Example: intermediate cross-beam all 7,50 m

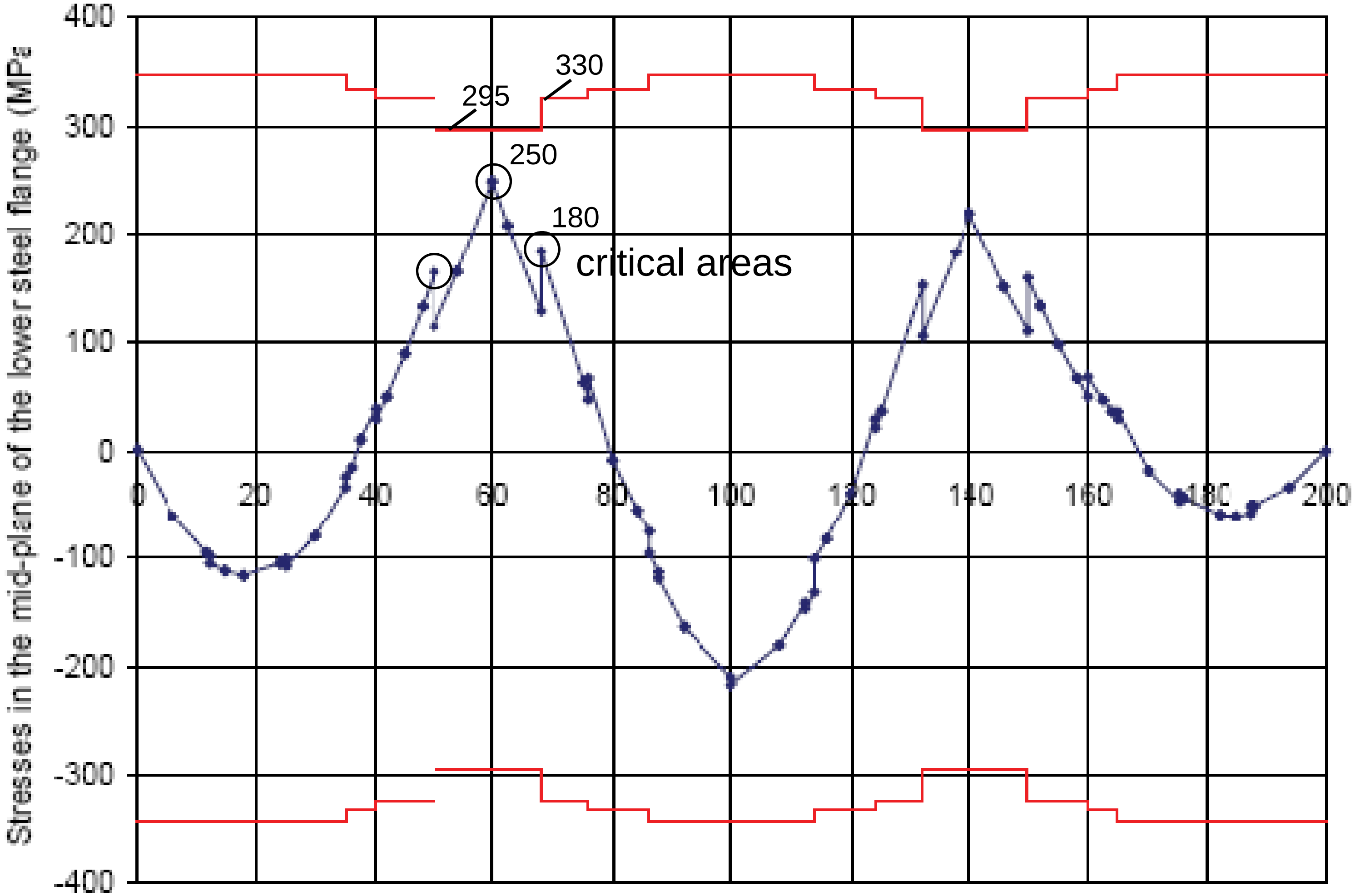


Example: α_{crit}-values and modal out-of-plane deformations

Mode	$\alpha_{cr,op}$	Description of the observed transverse displacement
1	8.8576	 Anti-symmetric waves with a length ℓ_f = 20 m around the support P1
2	10.258	 Anti-symmetric waves with a length ℓ_f = 20 m around the support P2
3	17.489	 Quasi-symmetric waves with a length ℓ_f = 20 m around the support P1

6.1 STABILITY RULES

Example: Input for $\alpha_{ult,k}$-values



6.1 STABILITY RULES

Checks for lateral-torsional buckling

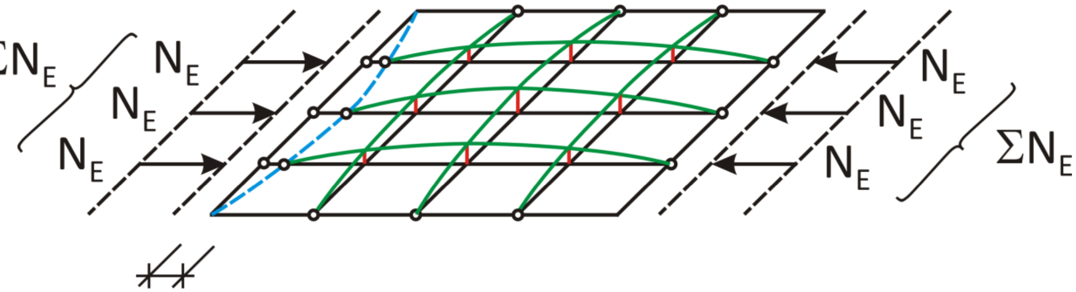
in field at point P1	at support (point P1)
$\alpha_{ult,k} = \frac{330}{180} = 1{,}83$	$\alpha_{ult,k} = \frac{295}{250} = 1{,}184$
$\alpha_{crit} = 8{,}8576$	$\alpha_{crit} = 17{,}489$
$\bar{\lambda} = \sqrt{\frac{1{,}83}{8{,}8576}} = 0{,}45$	$\bar{\lambda} = \sqrt{\frac{1{,}184}{17{,}489}} = 0{,}26$
$\alpha^{*}_{crit} = 8{,}37$	$\alpha^{*}_{crit} = 15{,}20$
$\alpha^{*} = \frac{8{,}37}{8{,}86} \cdot 0{,}76 = 0{,}72$	$\alpha^{*} = \frac{15{,}20}{17{,}49} \cdot 0{,}76 = 0{,}66$
$\phi = 0{,}69$	$\phi = 0{,}554$
$\chi = 0{,}82$	$\chi = 0{,}96$
$\frac{\chi \cdot \alpha_{ult,k}}{\gamma_M} = \frac{0{,}82 \cdot 1{,}89}{1{,}10} = 1{,}37 > 1{,}00$	$\frac{\chi \cdot \alpha_{ult,k}}{\gamma_M} = \frac{0{,}96 \cdot 1{,}184}{1{,}10} = 1{,}03 > 1{,}00$

6.1 STABILITY RULES

Column buckling and plate buckling

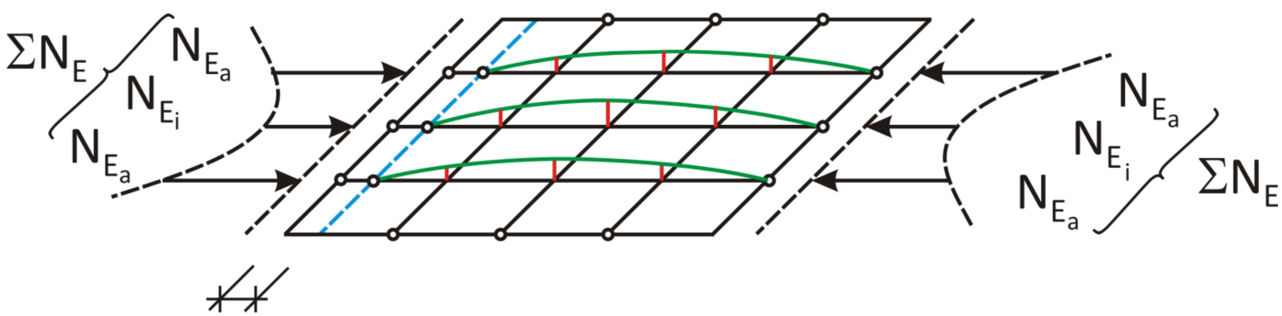
Column-like behaviour:

imposed loads
on loaded edge



resulting displacements δ_i
at loaded edge

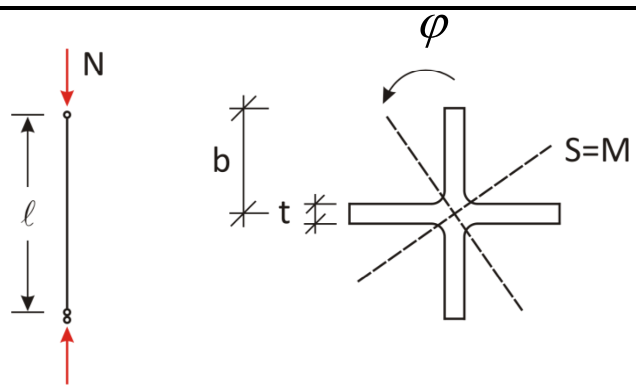
Plate-like behaviour:



resulting loads
on loaded edge

imposed displacement δ
on loaded edge

Example: Torsional buckling according to EN 1993-1-1



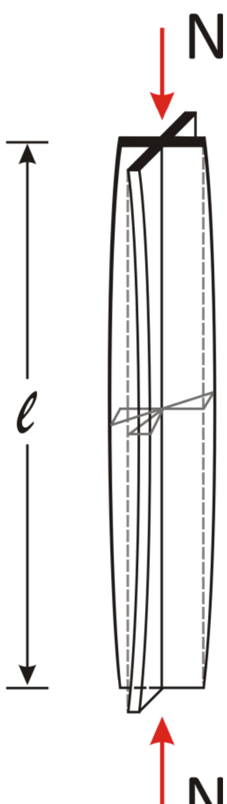
$$C_M = \frac{b^3 \cdot t^3}{9}$$

$$I_M = 4\frac{b^3}{3}t$$

Column: $\varphi = A \cdot \sin\frac{\pi x}{e}; G = \frac{E}{2(1+\nu)}$	Plate: $w = A \cdot \frac{y}{b} \sin\frac{\pi x}{\ell}$
$N_{cr} = \dfrac{EC_M\left(\frac{\pi}{\ell}\right)^2 + G \cdot I_M}{i_M^2}$	$\delta\Pi_i - \delta\Pi_a = 0$
$\sigma_{cr} = \dfrac{N_{crit}}{A}$	$\sigma_{cr} = \dfrac{N_{crit}}{A}$
$= \underbrace{\dfrac{E \cdot t^2}{12(1-\nu^2)}\dfrac{\pi^2}{b^2}}\left[\underbrace{(1-\nu^2)\left(\frac{b}{\ell}\right)^2} + \underbrace{\dfrac{6}{\pi^2}(1-\nu)}\right]$	$= \underbrace{\dfrac{E \cdot t^2}{12(1-\nu^2)}\dfrac{\pi^2}{b^2}}\left[\underbrace{\left(\frac{b}{\ell}\right)^2} + \underbrace{\dfrac{6}{\pi^2}(1-\nu)}\right]$
$= \sigma_e \cdot \left[\underbrace{0{,}9\left(\frac{b}{\ell}\right)^2 + 0{,}429}_{k_\sigma}\right]$	$= \sigma_e \cdot \left[\underbrace{\left(\frac{b}{\ell}\right)^2 + 0{,}429}_{k_\sigma}\right]$

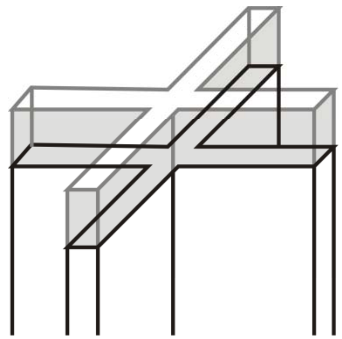
6.1 STABILITY RULES

Torsional buckling	column-like behaviour	plate-like behaviour



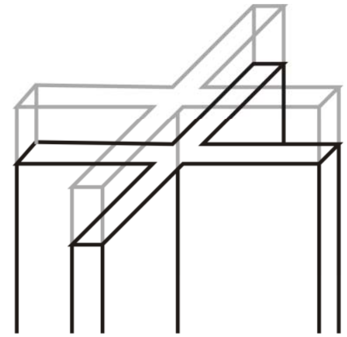
geometric strain effect:

$$\varepsilon_{geom}(s)=\left(\frac{e_o}{l}\right)^2\frac{\pi^2}{4}\left(\frac{s}{b}\right)^2\frac{\frac{N}{N_{crit}}\left(2-\frac{N}{N_{crit}}\right)}{\left(1-\frac{N}{N_{crit}}\right)^2}$$



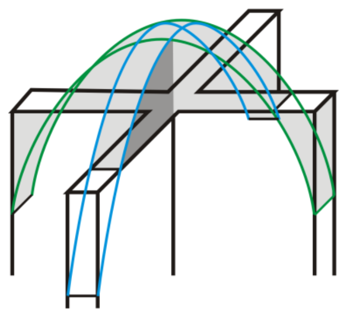
compression stress

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

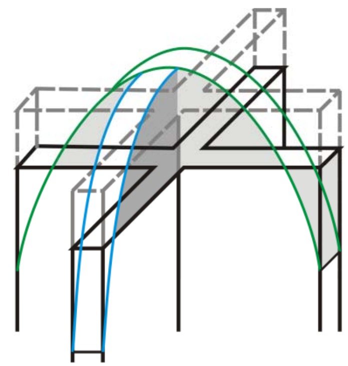


compression strain

$$\varepsilon_N=\frac{N}{A\cdot E}$$

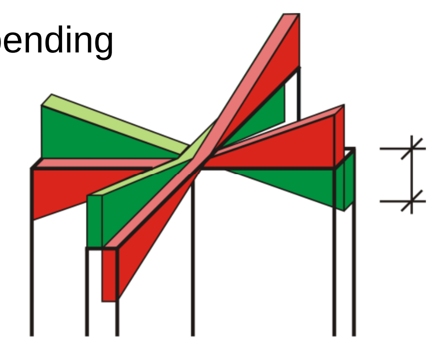


response strain ε



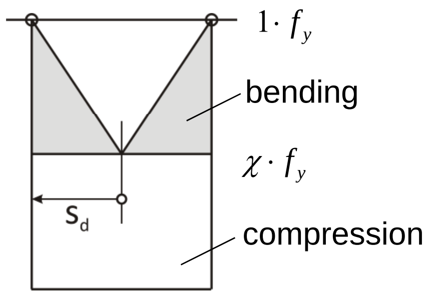
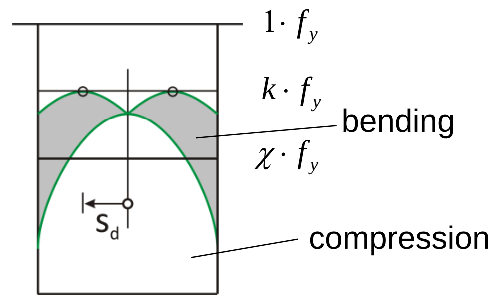
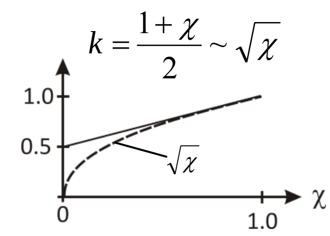
response stress σ

bending



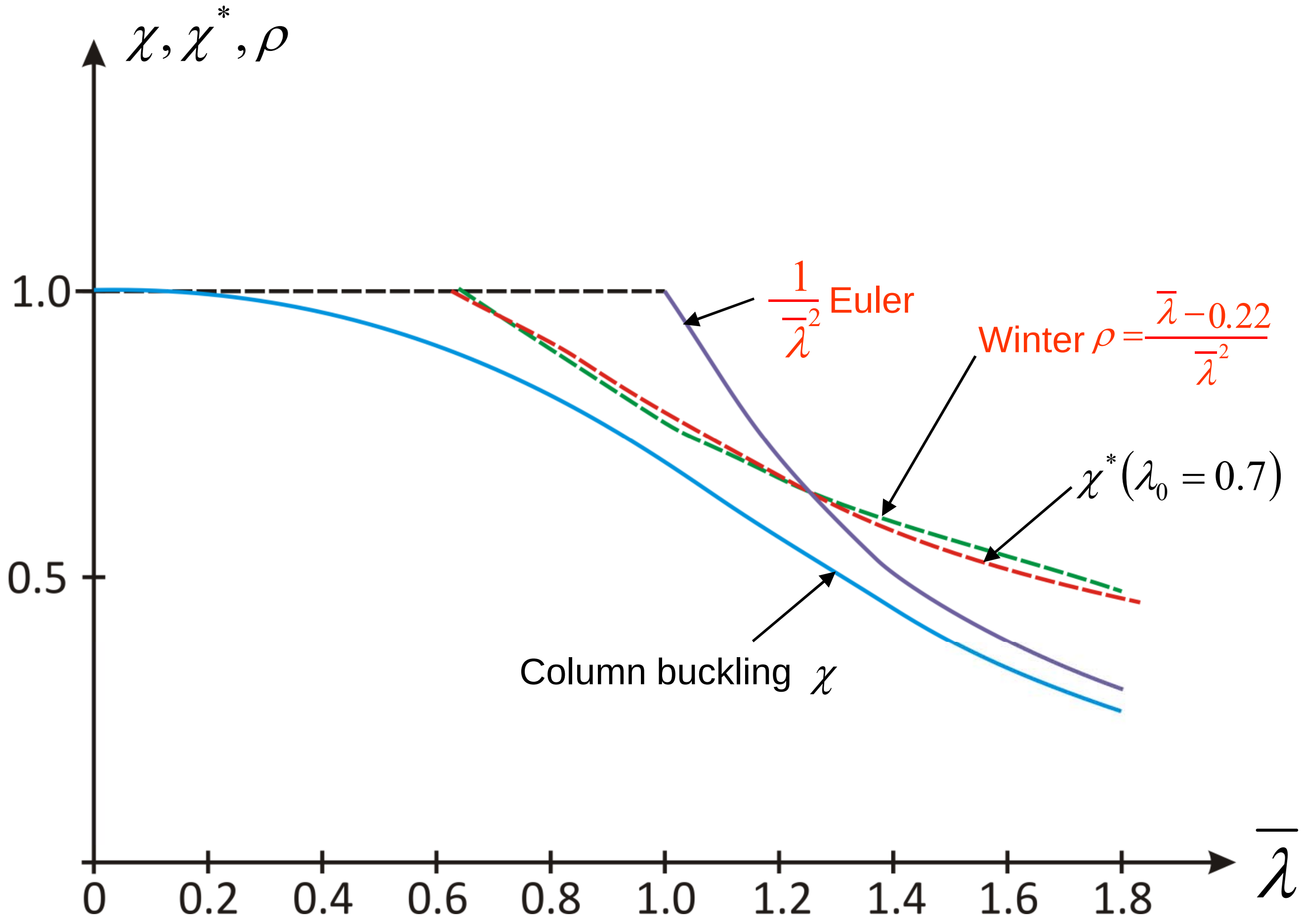
$$\sigma_M=(1-\chi)\,f_y$$

6.1 STABILITY RULES

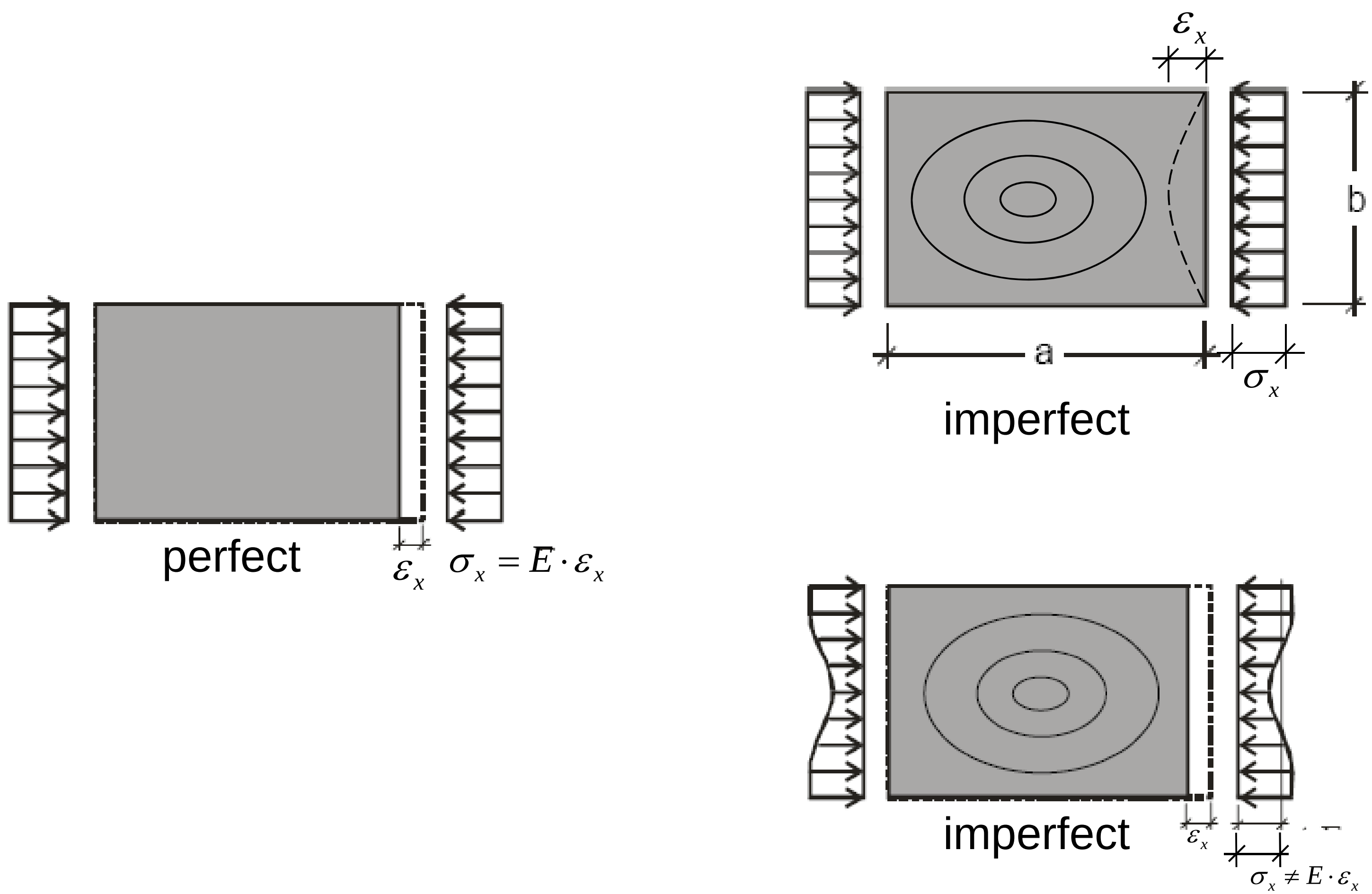
column buckling	plate buckling
 $\chi + \chi\alpha^*(\bar{\lambda} - \lambda_0)\frac{1}{1 - \chi\bar{\lambda}^2} = 1$	  $\chi + \chi\alpha^*(\bar{\lambda} - \lambda_0)\frac{1}{1 - \chi\bar{\lambda}^2} = \sqrt{\chi}$
assumption: $s_d = b$ $\lambda_0 = 0.2$	assumption: $s_d < b$ $\lambda_0 = 0.7$ $\sqrt{\chi} = \frac{1}{\bar{\lambda}}$
$\chi + \chi\alpha^*(\bar{\lambda} - 0.2)\frac{1}{1 - \chi\bar{\lambda}^2} = 1$	$\underbrace{\chi\bar{\lambda}} + \underbrace{\chi\bar{\lambda}}\alpha^*(\bar{\lambda} - 0.2)\frac{1}{1 - \underbrace{\chi\bar{\lambda}} \cdot \bar{\lambda}} = 1$ $\chi^* + \chi^*\alpha^*(\bar{\lambda} - 0.2)\frac{1}{1 - \chi^*\bar{\lambda}} = 1$
$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}$ $\phi = 0.5\left[1 + \alpha^*(\bar{\lambda} - 0.2) + \bar{\lambda}^2\right]$	$\chi^* = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\bar{\lambda}}}}$ $\phi = 0.5\left[1 + \alpha^*(\bar{\lambda} - 0.2) + \bar{\lambda}\right]$

6.1 STABILITY RULES

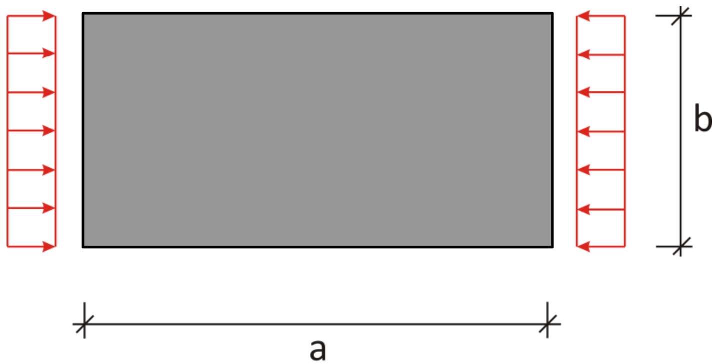
Column buckling curve and plate buckling curve



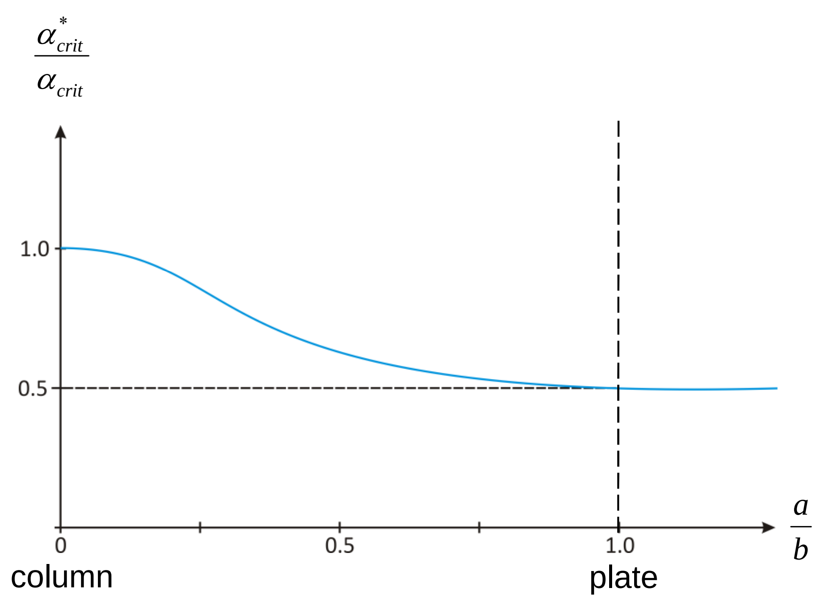
Stress- and strain-controlled plate buckling



Modification of imperfection factor

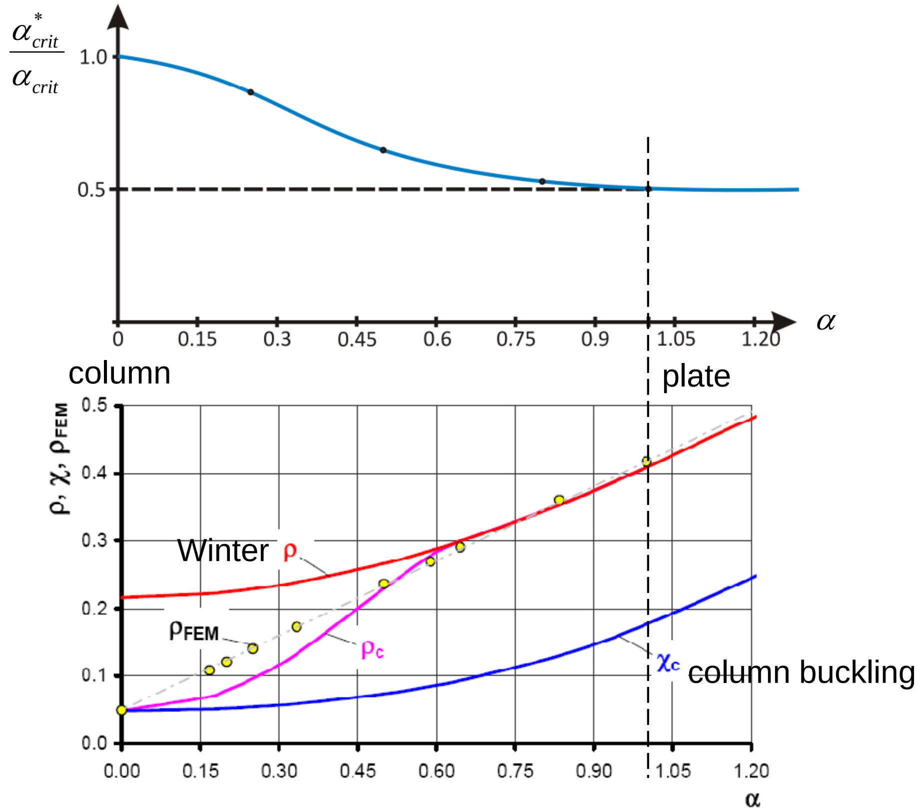


$$\frac{\alpha^*_{crit}}{\alpha_{crit}} = \frac{\left(\frac{b}{a}\right)^4 + 1}{\left\{\left(\frac{b}{a}\right)^2 + 1\right\}^2}$$



6.1 STABILITY RULES

Interaction between column buckling χ and plate buckling $\chi^* = \rho$



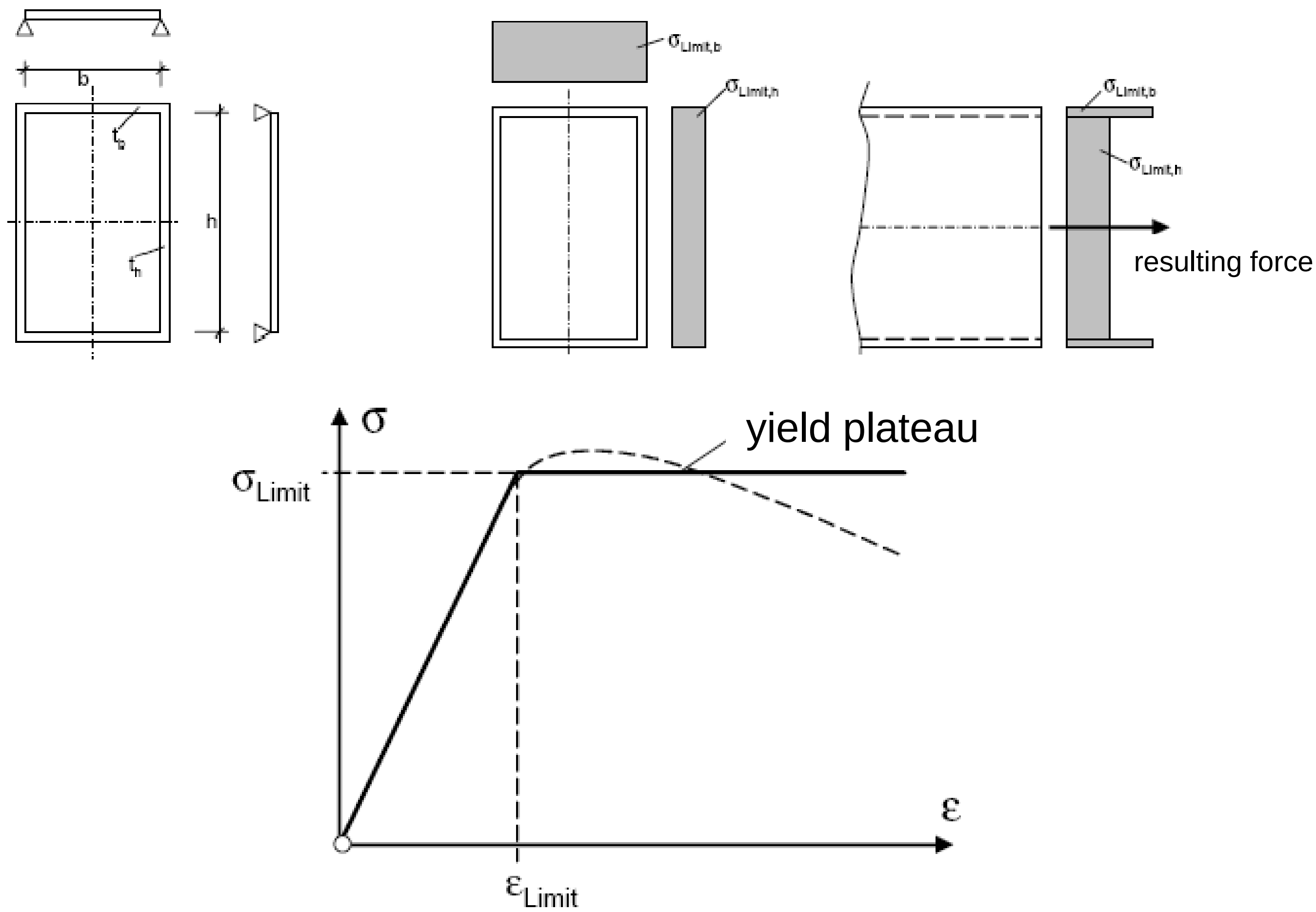
$$\rho_c = (\rho - \chi_c)\,\xi\,(2 - \xi) + \chi_c$$

$$\xi = \frac{\sigma_{cr,p}}{\sigma_{cr,c}} - 1; \quad 0 \le \xi \le 1$$

$$\frac{\sigma_{cr,p}}{\sigma_{cr,c}} = \frac{\alpha_{crit}}{\alpha^*_{crit}}$$

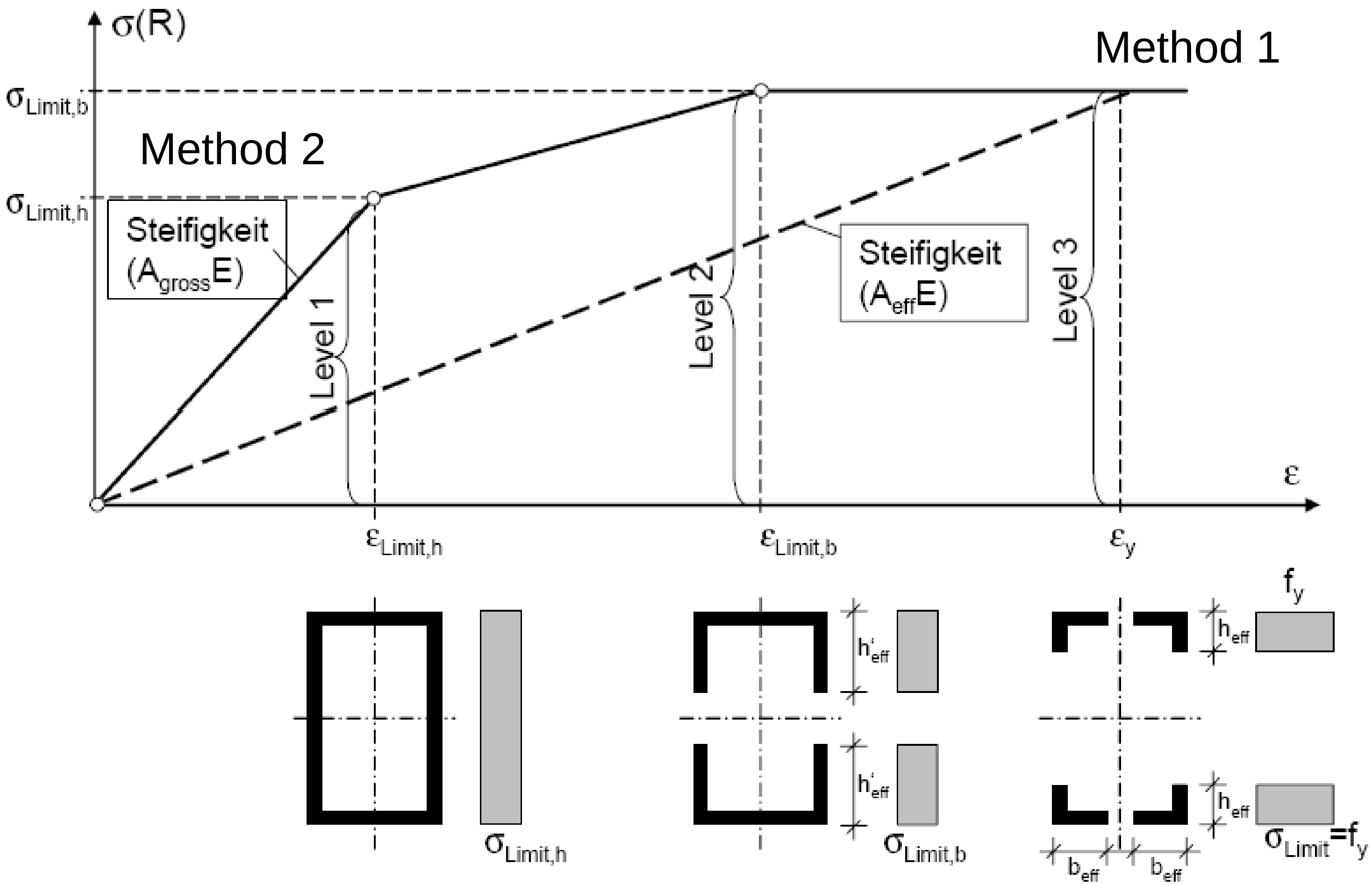
6.1 STABILITY RULES

"Hybrid cross-section" due to different stress-limits

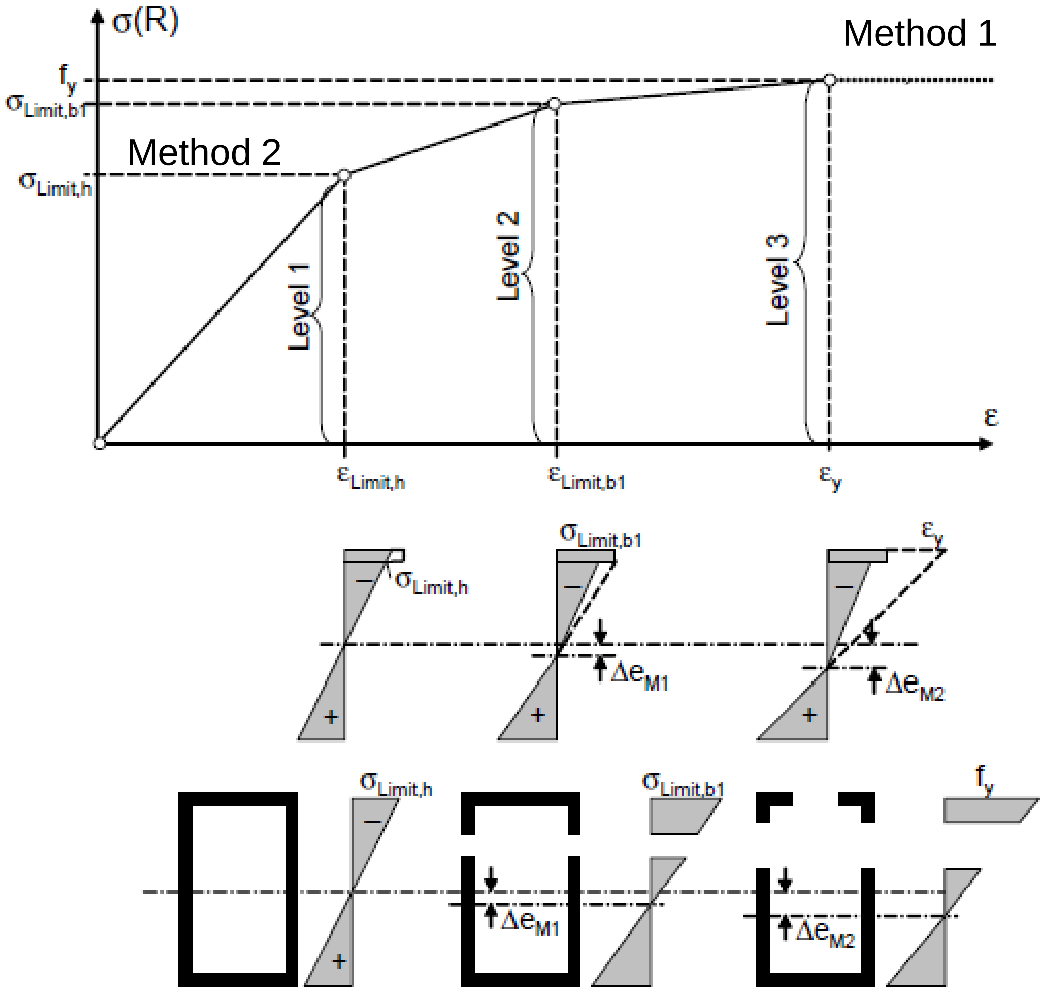


6.1 STABILITY RULES

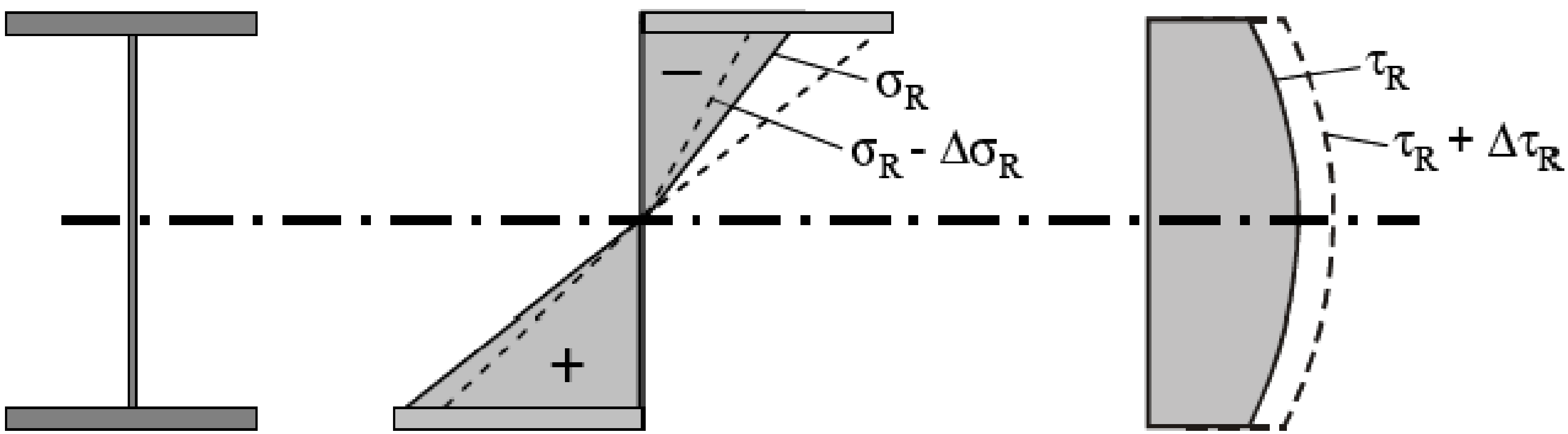
"Yielding effect" in hybrid cross-sections



”Yielding effect” in bending



Extension of method 2



6.1 STABILITY RULES

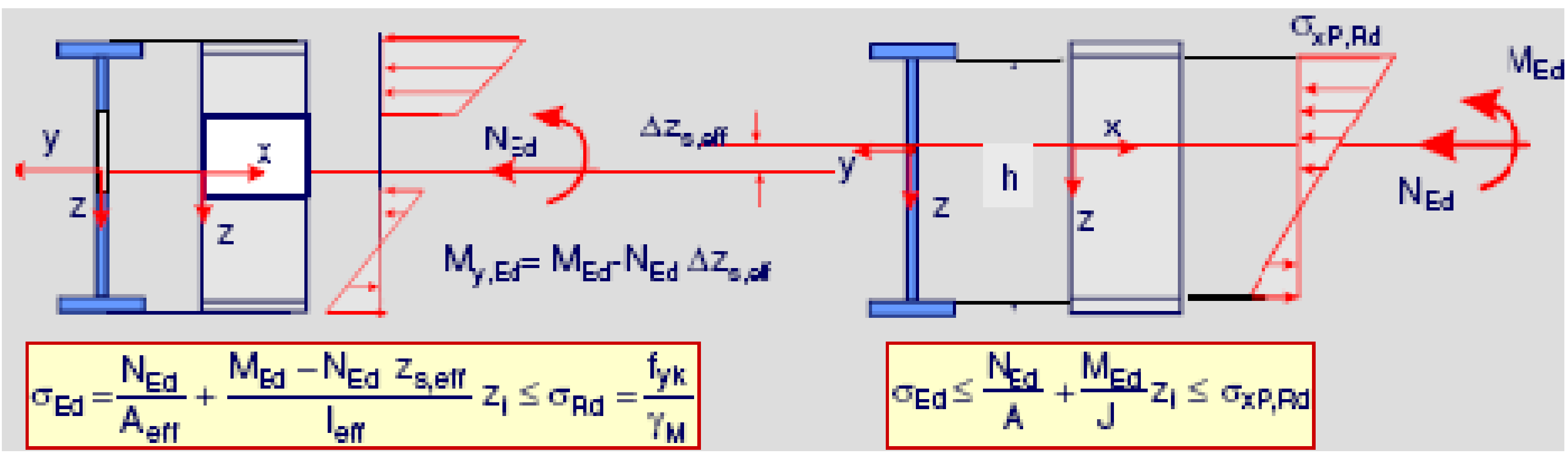
Methods in bridge design

Method 1

Use of effective cross-section

Method 2

Use of stress-limit



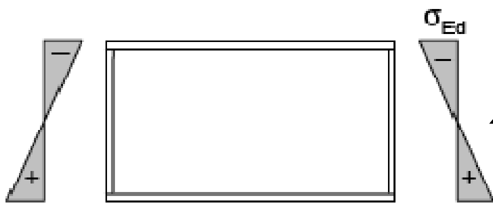
6.1 STABILITY RULES

Method 1

plate buckling for stress components

$\sigma_{x,Ed}$

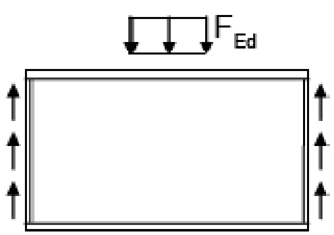
α_{crit,σ_x}



$\bar{\lambda}_{\sigma_x}$

$\sigma_{z,Ed}$

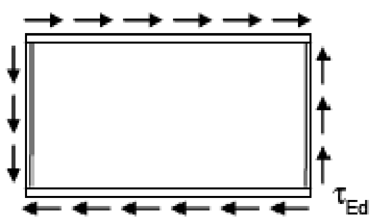
α_{crit,σ_z}



$\bar{\lambda}_{\sigma_z}$

τ_{Ed}

$\alpha_{crit,\tau}$

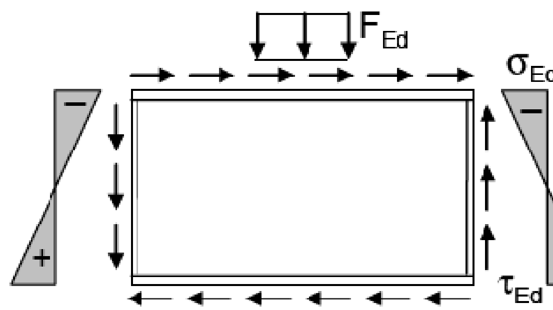


$\bar{\lambda}_{\tau}$

Method 2

global plate buckling

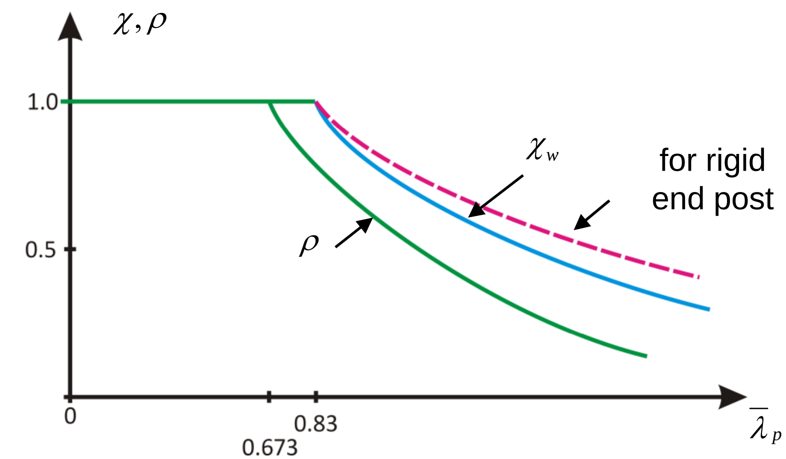
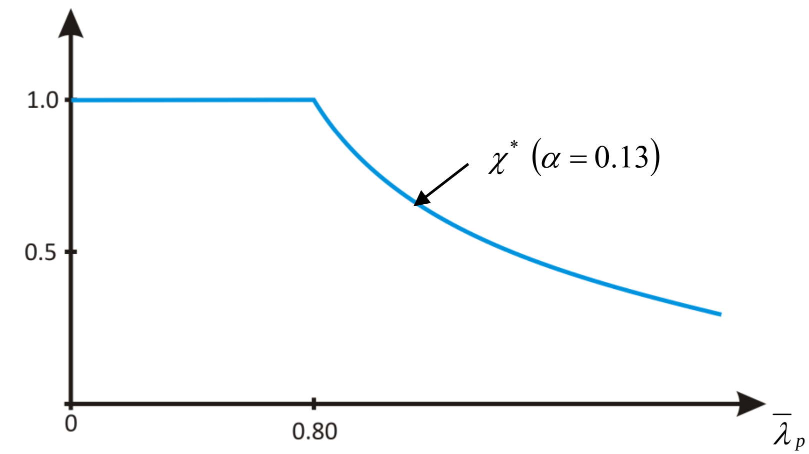
$$Ed\left(\sigma_{x,Ed}, \sigma_{z,Ed}, \tau_{Ed}\right), \alpha_{crit}$$



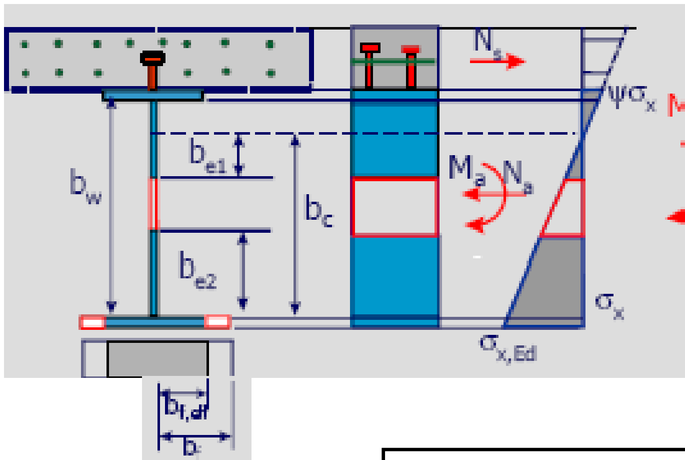
$\bar{\lambda}_{glob}$

6.1 STABILITY RULES

Plate-buckling coefficients

Method 1	Method 2
	
$\bar{\lambda}_{\sigma x} = \sqrt{\frac{\alpha_{ult,\sigma_x}}{\alpha_{crit,\sigma_x}}}$ $\bar{\lambda}_{\sigma z} = \sqrt{\frac{\alpha_{ult,\sigma_z}}{\alpha_{crit,\sigma_z}}}$ $\bar{\lambda}_{\tau} = \sqrt{\frac{\alpha_{ult,\tau}}{\alpha_{crit,\tau_x}}}$	$\bar{\lambda}_{glob} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{crit,global}}}$

Method 1: Effective cross-section for σ_x



Cross-section assessment

$$\eta_1 = \frac{\sigma_{xEd}}{f_{yd}} \leq 1{,}0$$

$$f_{yd} = \frac{f_{yk}}{\gamma_{Rd}} \qquad \gamma_{Rd} = 1{,}1$$

Effective web

$$b_{eff} = \rho\, b_c = \rho \frac{b_w}{1-\psi} \quad (\text{for } \psi < 0)$$

$$b_{eff,1} = 0{,}4\, b_{eff} \qquad b_{eff,2} = 0{,}6\, b_{eff}$$

$$k_\sigma = \frac{16}{\sqrt{(1+\psi)+0{,}112\,(1+\psi)^2} + (1+\psi)}$$

für $1 \geq \psi \geq -1$

Reduction factor

$$\rho = \frac{\bar{\lambda}_p - 0{,}553(3+\psi)}{\bar{\lambda}_p^2} \leq 1{,}0$$

Slenderness

$$\bar{\lambda}_p = \sqrt{\frac{f_{yk}}{\sigma_{x,Pi}}}$$

Critical stress

$$\sigma_{x,Pi} = k_\sigma \sigma_e \qquad \sigma_e = \frac{\pi^2 E_{st} t^2}{12 b^2 (1-\mu^2)}$$

Effective flange

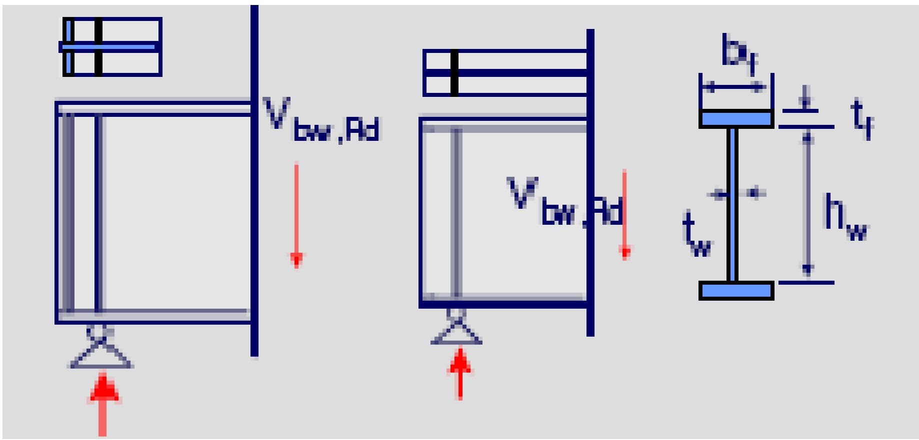
$$b_{t,eff} = \rho b_f$$

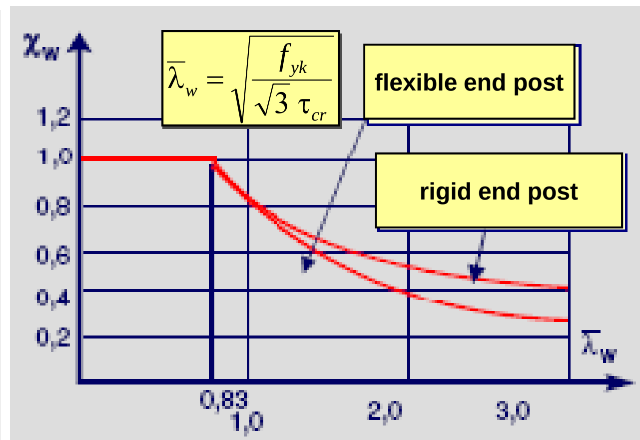
$k_\sigma = 0{,}43$ für $\psi = 1$

Method 1: Resistance to shear τ

rigid end post

flexible end post





reduction factor χ_w		
$\bar{\lambda}_w < 0{,}83$	1.0	1.0
$0{,}83 \le \bar{\lambda}_w < 1{,}08$	$0{,}83 / \bar{\lambda}_w$	$0{,}83 / \bar{\lambda}_w$
$\bar{\lambda}_w \ge 1{,}08$	$1{,}37(0{,}7 + \bar{\lambda}_w)$	$0{,}83 / \bar{\lambda}_w$

$$V_{bw,Rd} = \chi_w \cdot h_w \cdot t_w \frac{f_{yd}}{\sqrt{3}}$$

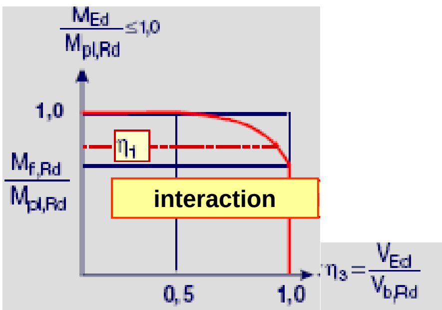
$$\eta_3 = \frac{V_{Ed}}{V_{bw,Rd}}$$

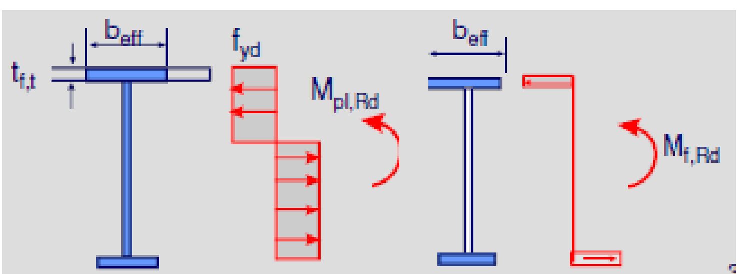
6.1 STABILITY RULES

Assessment for plate buckling

<table>
<tr><th>Method 1</th><th>Method 2</th></tr>
<tr><td>

Interaction





$$\left.\begin{array}{l}\eta_1 = \dfrac{\sigma_{Ed}}{f_y} \le 1 \\ \eta_3 = \dfrac{V_{Ed}}{V_{Rd}} \le 1\end{array}\right\} \eta_1 + \left[1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right]\left[2\eta_3 - 1\right]^2 \le 1$$

</td><td>

$$\frac{\chi_{glob} \cdot \alpha_{ult,k}}{\gamma_M} \ge 1$$

</td></tr>
</table>

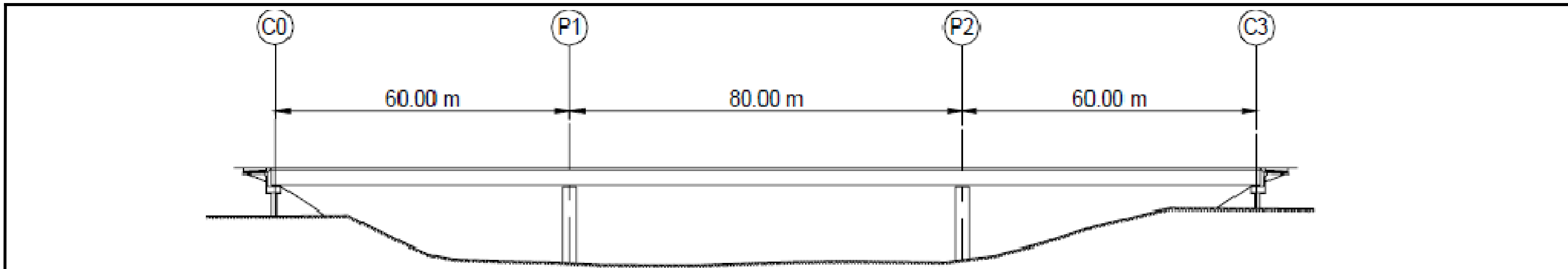
6.1 STABILITY RULES

German National Annex

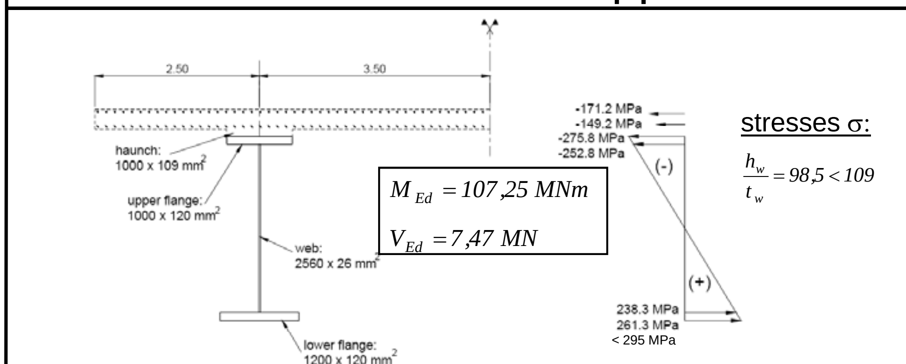
- Method 1 only applicable to girders without longitudinal stiffners

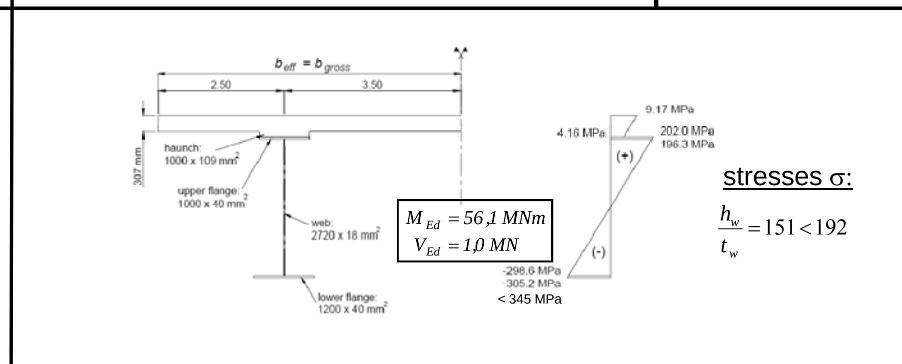
- The use of Method 1 should be supplemented by checking global buckling with Method 2 for characteristic load level E_k and $\gamma_M = 1{,}10$

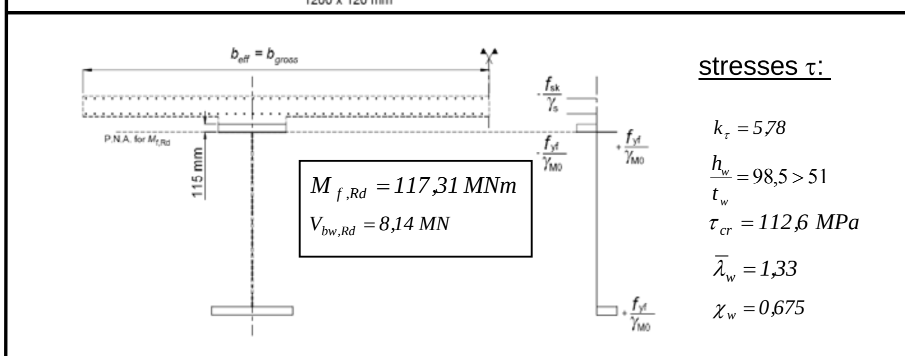
Example: cross-section check for a composite bridge

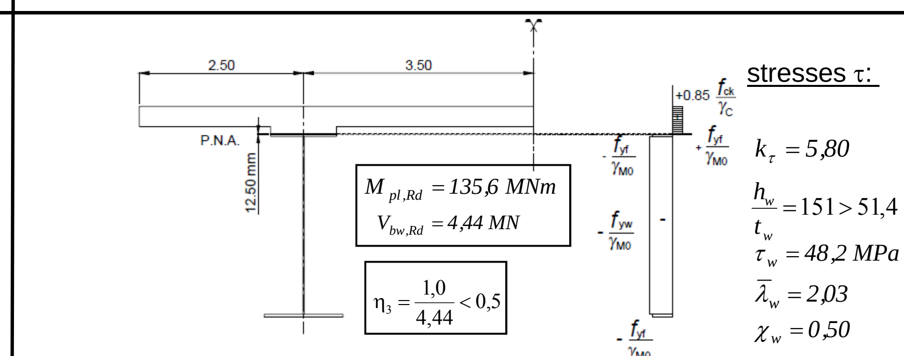


Cross-section at support	Cross-section at midspan



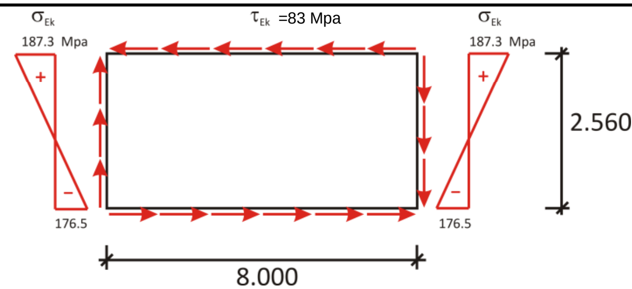






6.1 STABILITY RULES

Panel plate buckling check with method 2



$$\psi = \frac{-176}{+187.3} = -0{,}94 \qquad \alpha = \frac{8000}{2560} = 3{,}13 \qquad \sigma_e = 19.6\ MPa$$

$$k_\sigma = 23 \rightarrow \quad \sigma_{cr} = 23 \cdot 19.6 = 450.8\ MPa \rightarrow \alpha_{crit_\sigma} = 2{,}55$$

$$k_\tau = 6 \rightarrow \quad \tau_{cr} = 6 \cdot 19.6 = 117.6\ MPa \rightarrow \alpha_{crit_\tau} = 1{,}42$$

$$\frac{1}{\alpha_{crit}} = \frac{1+\psi}{4\,\alpha_{cr\sigma}} + \left[\left(\frac{1+\psi}{4\,\alpha_{crit,\sigma}}\right)^2 + \frac{1-\psi}{\alpha^2_{crit,\sigma}} + \frac{1}{\alpha^2_{crit,\tau}}\right]^{1/2} = 0.888$$

$$\alpha_{crit} = 1.127$$

$$\alpha_{ult,k} = \frac{f_y}{\sqrt{\sigma^2_{E_k} + 3\tau_{E_k^2}}} = 1.56$$

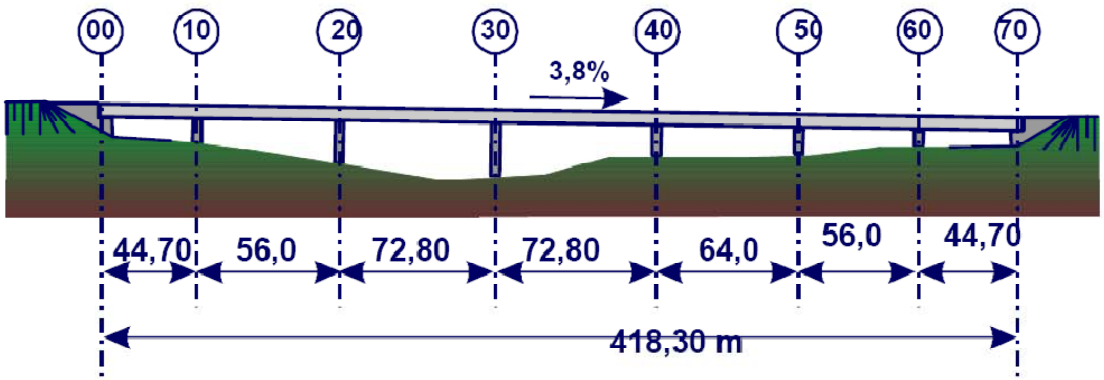
$$\bar{\lambda} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{crit}}} = 1{,}18$$

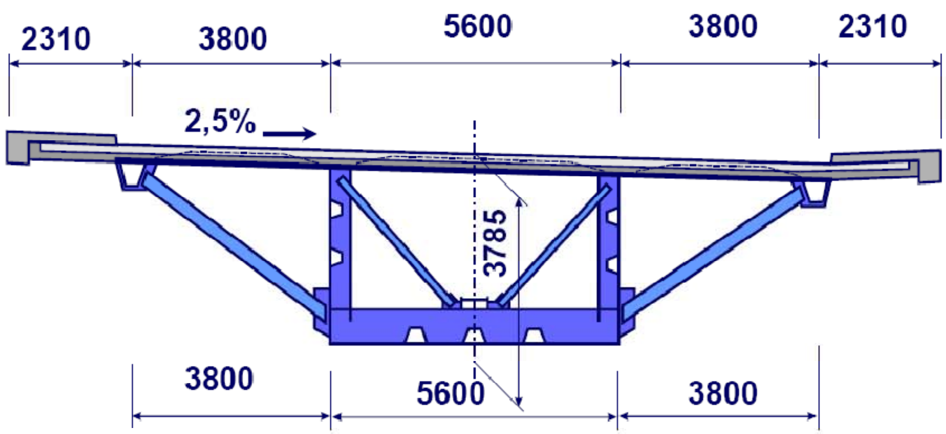
$$\phi = 0.5\left[1 + 0.13\left(\bar{\lambda} - 0.80\right) + \bar{\lambda}\right] = 1.15 \qquad \chi_w = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}}} = 0.73$$

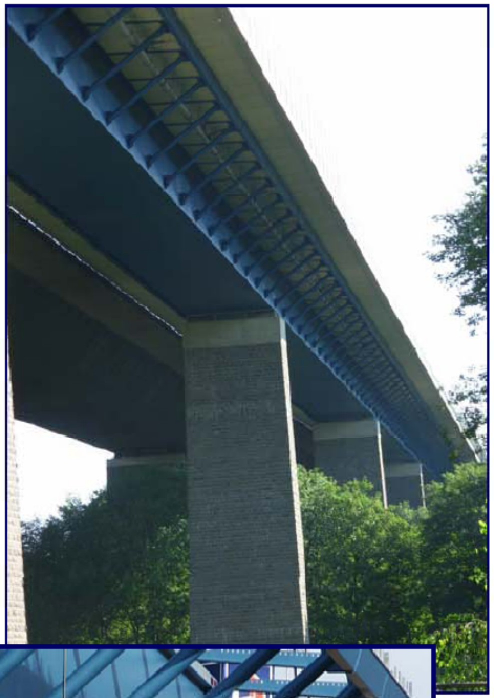
$$\frac{\chi_w \cdot \alpha_{ult,k}}{\gamma_M} = \frac{0.73 \cdot 1.56}{1.10} = 1.03 > 1.00$$

6.1 STABILITY RULES

Verification of stiffened web plate for launching, Bridge Oehde

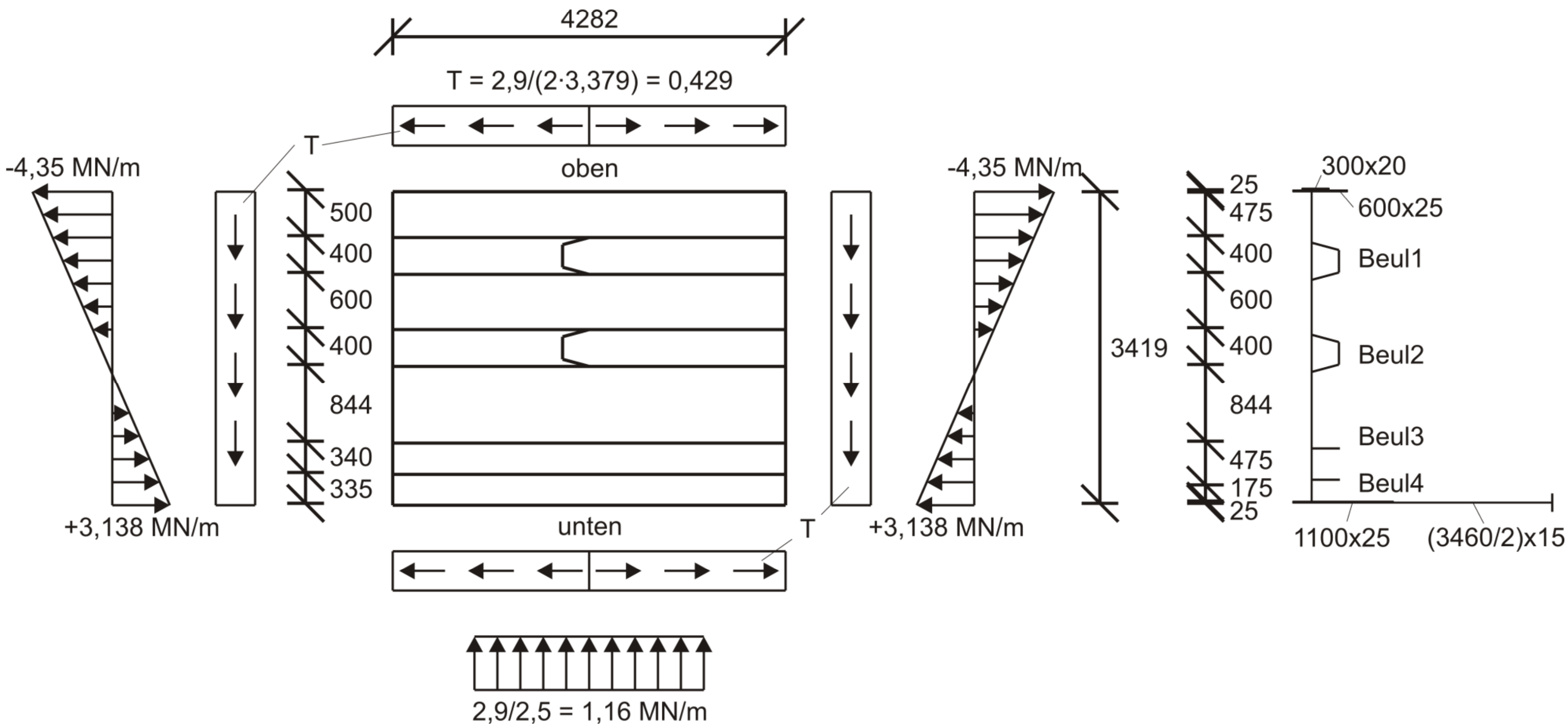






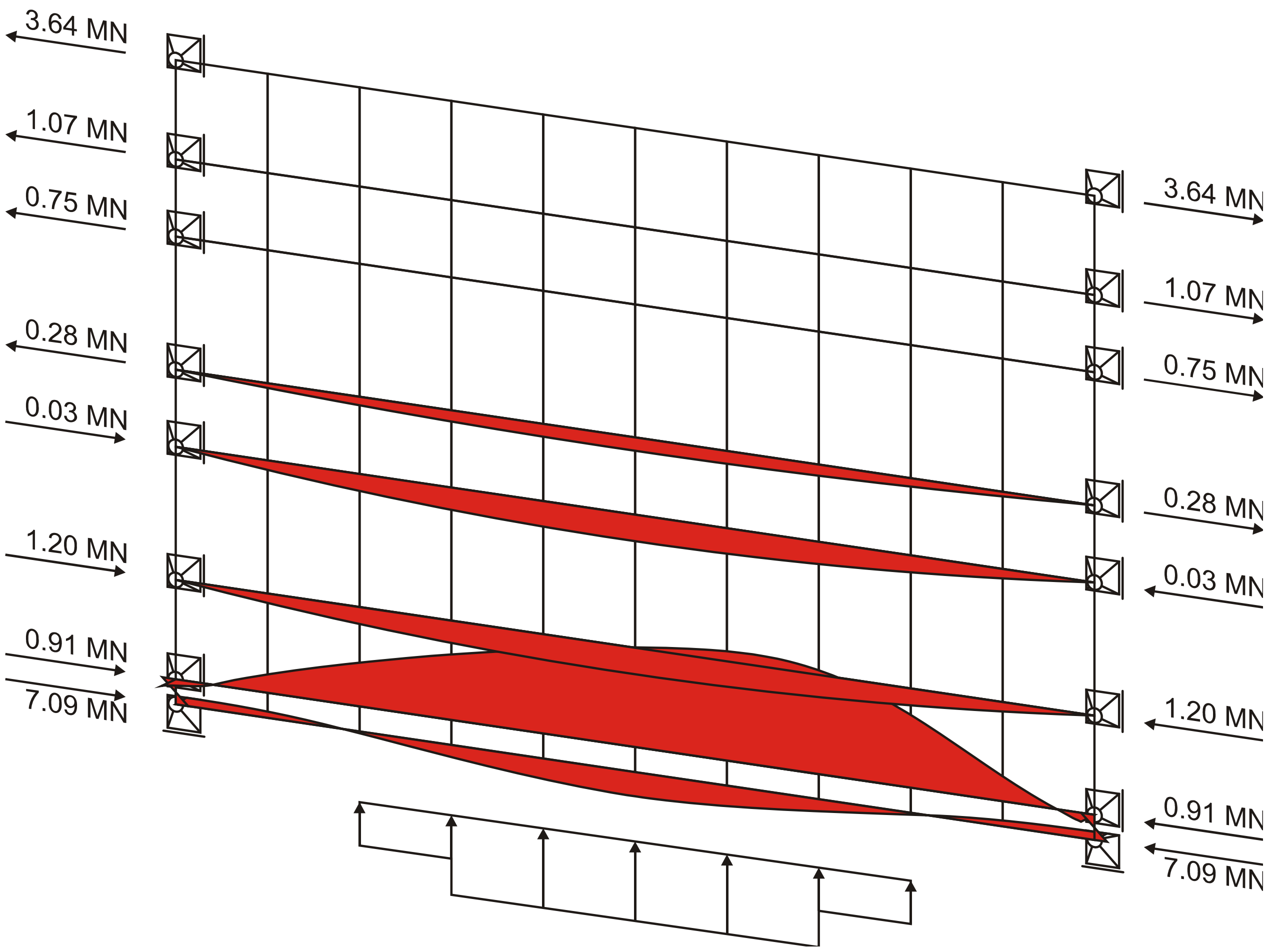
6.1 STABILITY RULES

Stiffened web panel and loading



6.1 STABILITY RULES

Use of method 2 for stress-assessment



Stiffener : $\max M = 44{,}3\ kNm \rightarrow \sigma = -152 - 68 = -220 \leq 240\ MPa$

Webplate: $\max M = 2{,}83\ kNm \rightarrow \sigma = -64 - 176 = 240 = 240\ MPa$

6.1 STABILITY RULES

JRC Scientific and Technical Reports

COMMENTARY AND WORKED EXAMPLES TO EN 1993-1-5 "PLATED STRUCTURAL ELEMENTS"

B. Johansson, R. Maquoi, G. Sedlacek, C. Müller, D. Beg

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EUR 22898 EN - 2007

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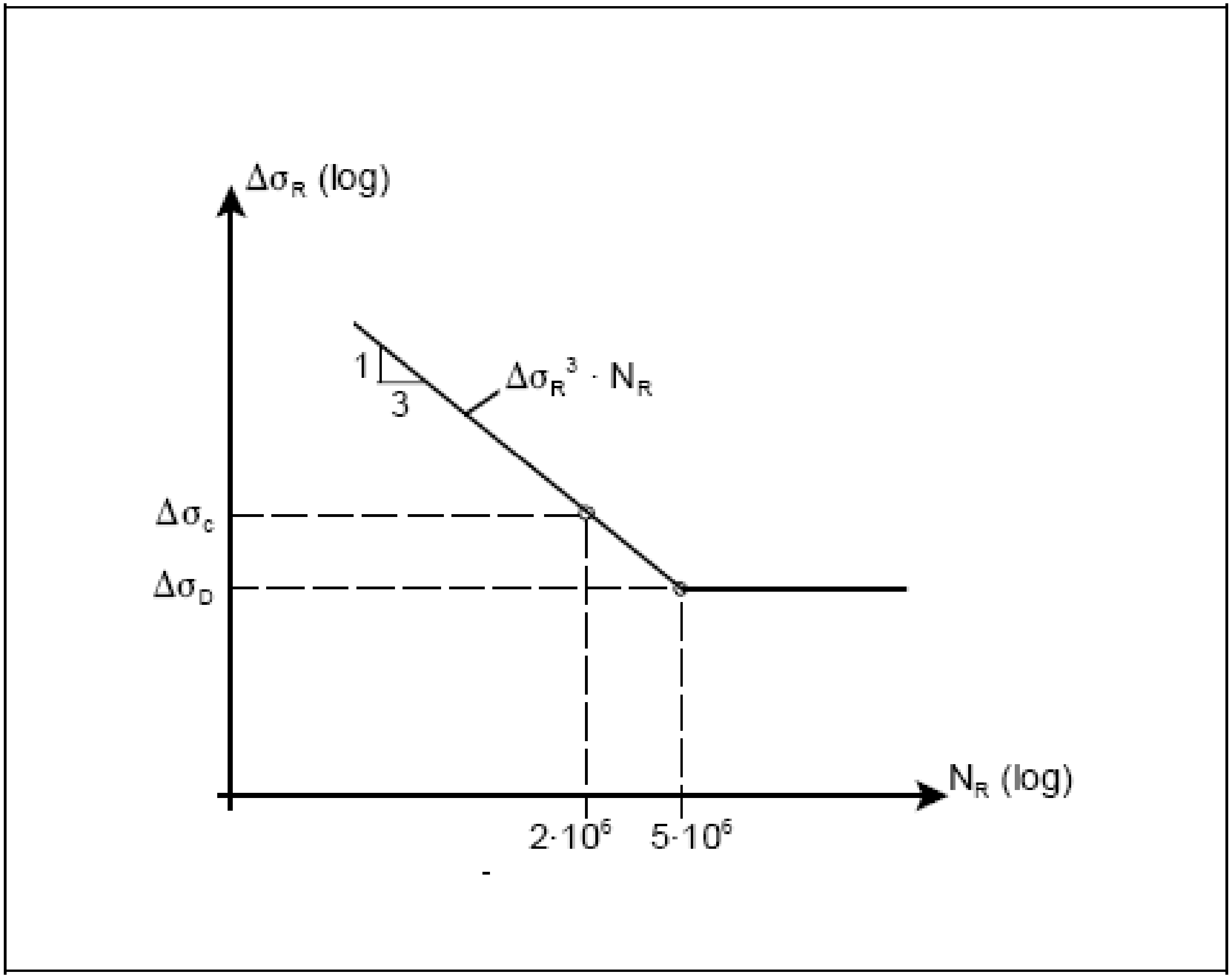
Standardized Wöhler- curve for welded details



6.2 FATIGUE RULES

Damage equivalence

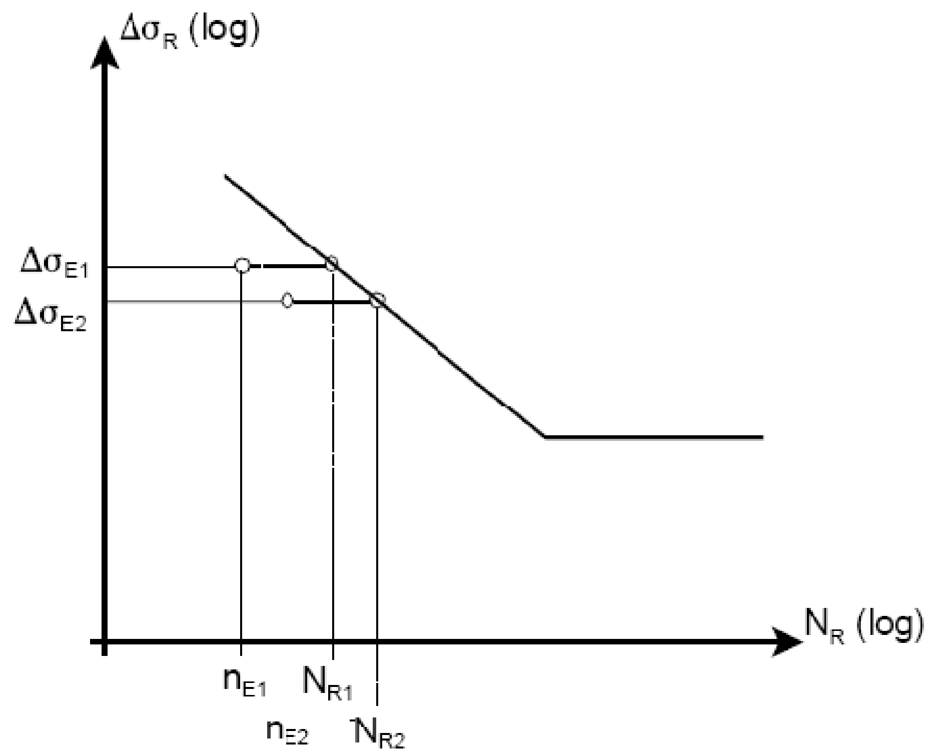
$$D = \sum D_i = \sum \frac{n_{Ei}}{N_{Ri}}$$

$$= \sum \frac{\Delta\sigma_{EI}^3 \; n_{Ei}}{\Delta\sigma_C^3 \cdot 2 \cdot 10^6}$$

Damage equivalence:

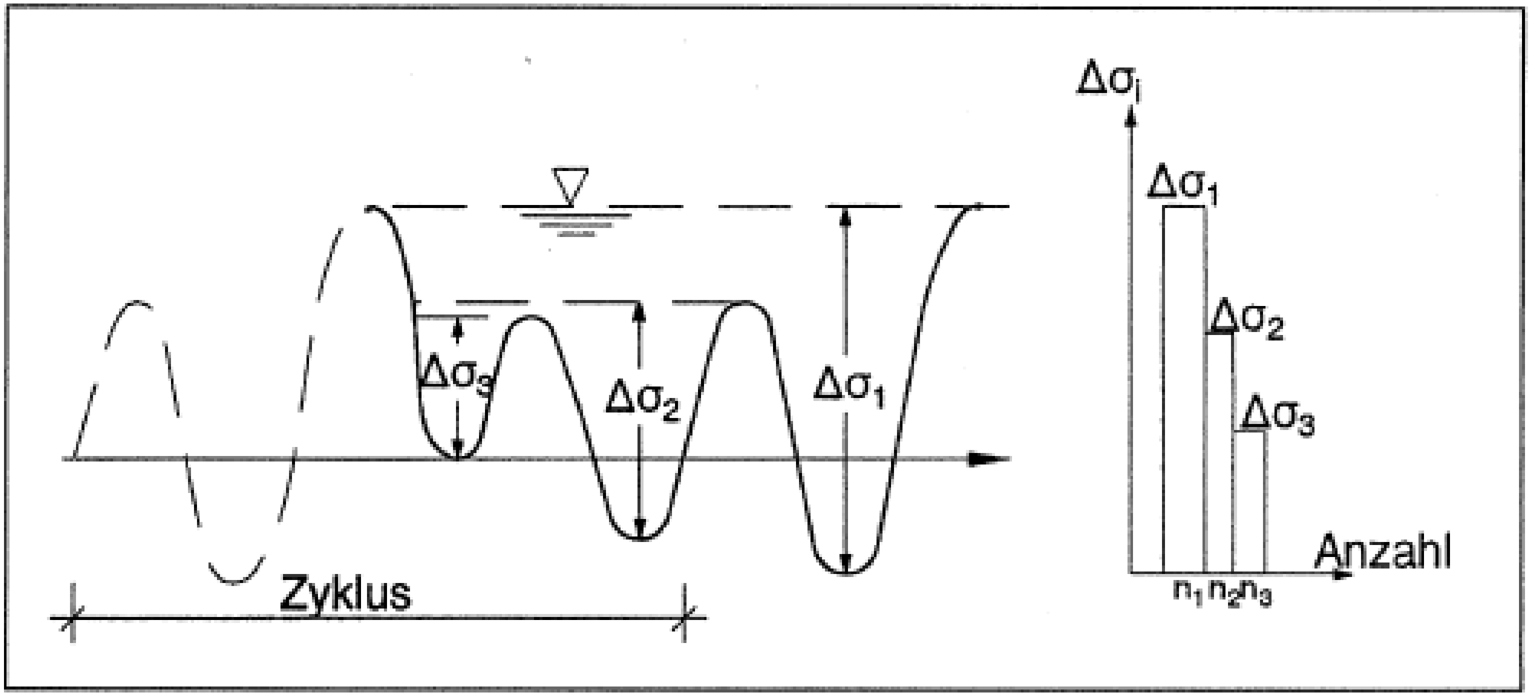
$$\Delta\sigma_e^3 \cdot \sum n_{Ei} = \sum \Delta\sigma_{Ei}^3 \cdot n_{Ei}$$

$$\Delta\sigma_e = \left[\frac{\sum \Delta\sigma_{Ei}^3 \cdot n_{Ei}}{\sum n_{Ei}}\right]^{\frac{1}{3}}$$

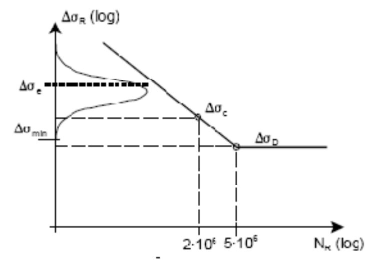
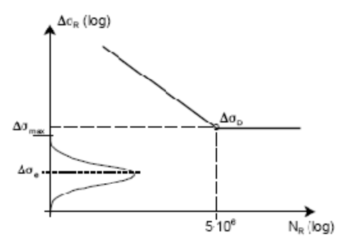
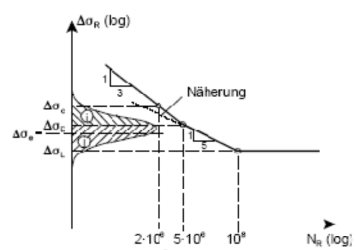


6.2 FATIGUE RULES

Reservoir-counting method

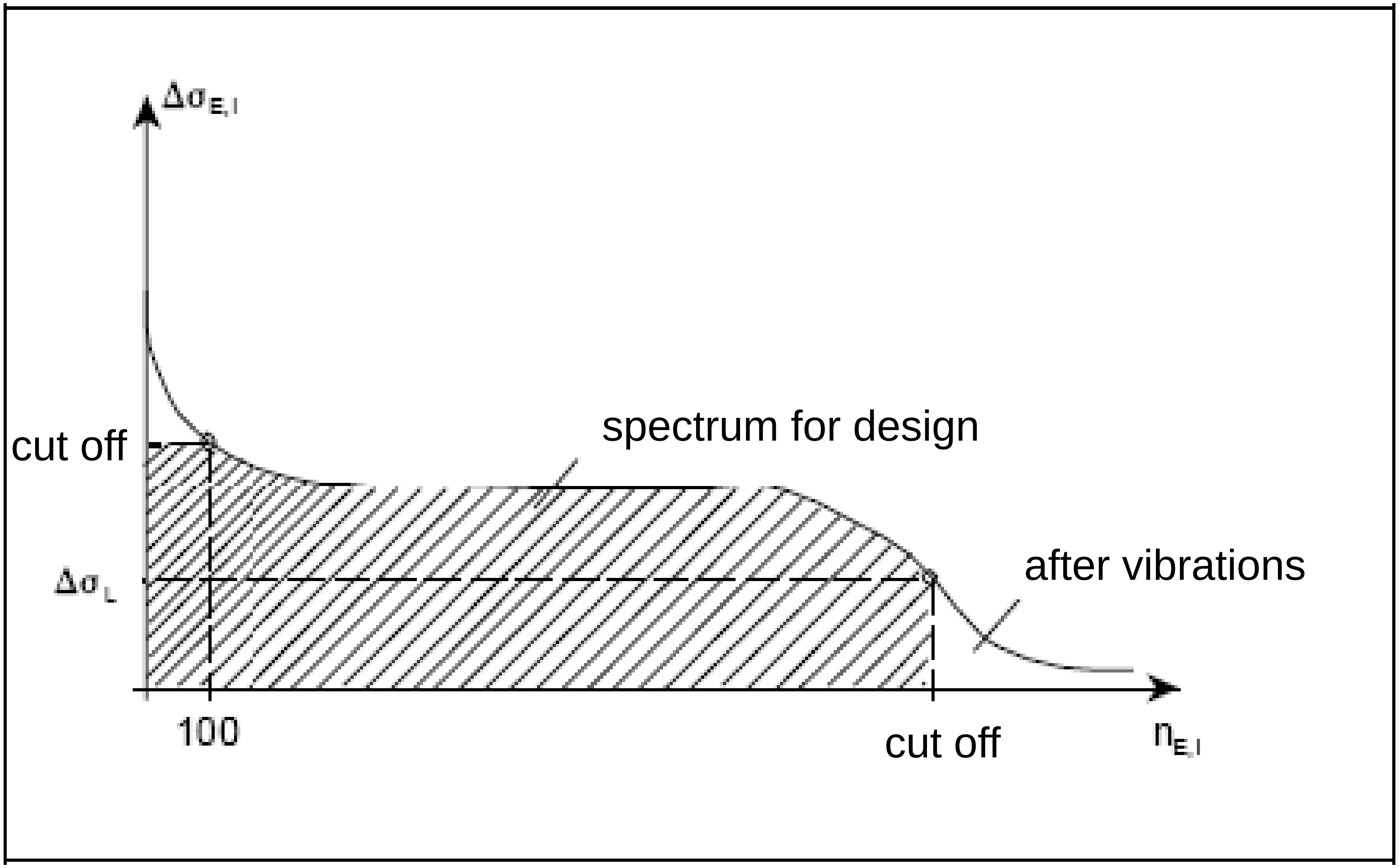


Various design situations

Case 1 $\Delta\sigma_{min} \geq \Delta\sigma_D$		$\Delta\sigma_e^3 \cdot \Sigma n_i \leq \Delta\sigma_c^3 \cdot 2 \cdot 10^6$ $\boxed{\lambda \cdot \Delta\sigma_e \leq \Delta\sigma_c}$ $\lambda = \sqrt[3]{\frac{\Sigma n_i}{2 \cdot 10^6}}$
Case 2 $\Delta\sigma_{max} \leq \Delta\sigma_D$		$\Delta\sigma_{max} \leq \Delta\sigma_D$ $k \cdot \Delta\sigma_e = \Delta\sigma_{max}$ $\boxed{\lambda_{max} \cdot \Delta\sigma_e \leq \Delta\sigma_c}$ $\Rightarrow \lambda_{max} = k \cdot \sqrt[3]{\frac{5}{2}}$
Case 3 $\Delta\sigma_i \geq \Delta\sigma_D$ $\Delta\sigma_j \leq \sigma_D$ Modified Wöhler curve for using the Miner-rule		$\Delta\sigma_e^5 \cdot \Sigma n_j \leq \Delta\sigma_D^5 \cdot 5 \cdot 10^6$ $\boxed{\lambda \cdot \Delta\sigma_e \leq \Delta\sigma_c}$ $\Rightarrow \lambda = \sqrt[3]{\frac{5}{2}} \cdot \sqrt[5]{\frac{\sum n_j}{5 \cdot 10^6}}$

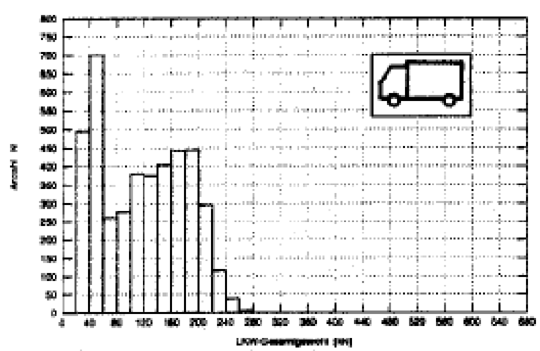
6.2 FATIGUE RULES

Representations of fatigue spectrum

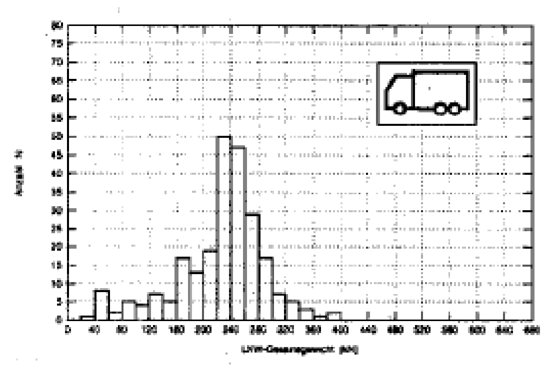


6.2 FATIGUE RULES

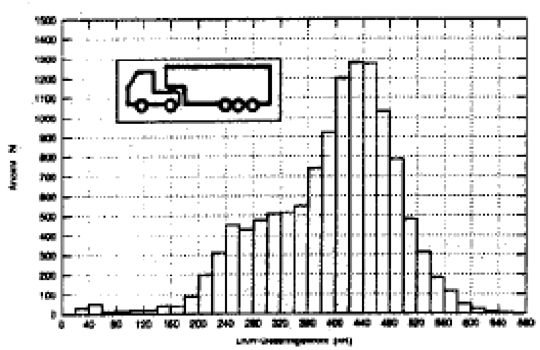
Distribution of weights of heavy vehicles



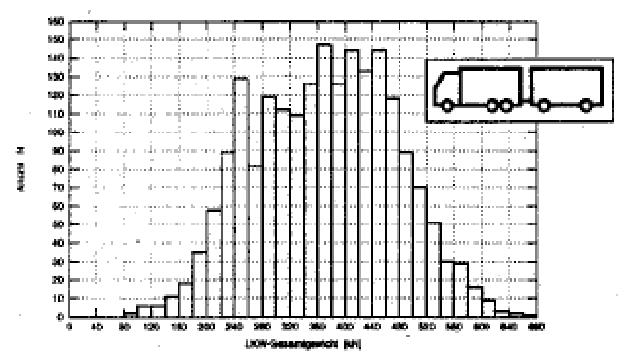
total weight type 1



total weight type 2

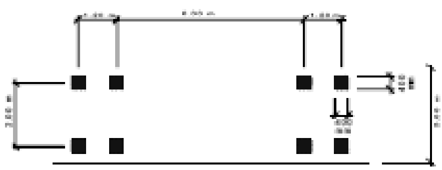
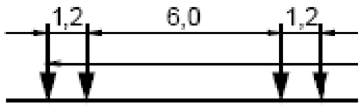
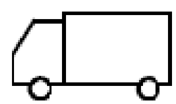
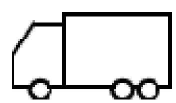
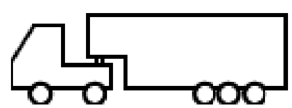
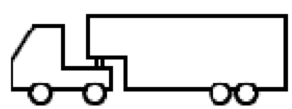
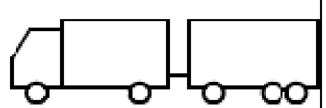


total weight type 3



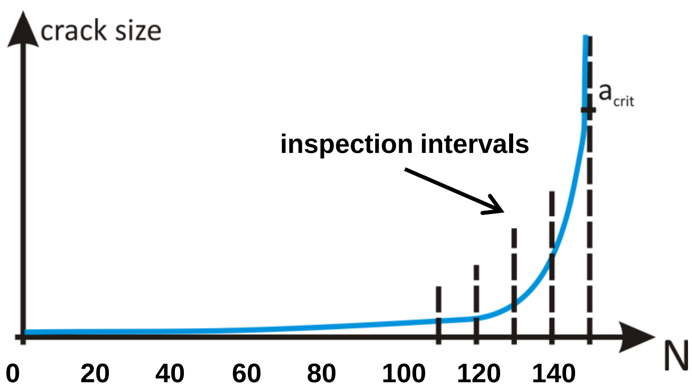
total weight type 4

Load-models for fatigue checks of road bridges

FLM 3 Main structure	Detailed FLM 4		
	LKW-Typen	Achslasten	Anteil Fernverkehr
 4x120 kN = 480 kN 		70-130	20%
		70-120-120	5%
		70-150-90-90-90	40%
		70-140-90-90	25%
		70-130-90-80-80	10%

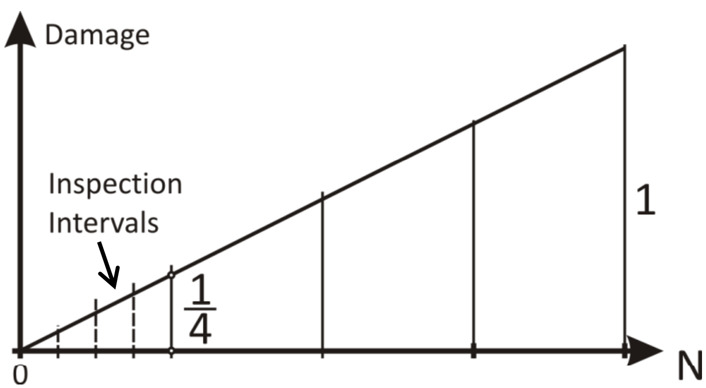
6.2 FATIGUE RULES

Safety-plan for damage tolerant design



$$D=\sum \frac{\left(\gamma_{Ff}\Delta\sigma_{Ei}\right)^3 n_{Ei}}{\left(\frac{\Delta\sigma_c}{\gamma_{Mf}}\right)^3 \cdot 2\cdot 10^6} + \sum \frac{\left(\gamma_{Ff}\Delta\sigma_{Ej}\right)^5 n_{Ej}}{\left(\frac{\Delta\sigma_D}{\gamma_{Mf}}\right)^3 \cdot 5\cdot 10^6} \le \frac{1}{4}$$

$$\left(\frac{1}{\gamma_{Ff}\cdot\gamma_{Mf}}\right)^5 \frac{1}{1+n} = \frac{1}{4} \qquad n = \left(\frac{4}{\left(\gamma_{Ff}\cdot\gamma_{Mf}\right)^5}\right) - 1$$

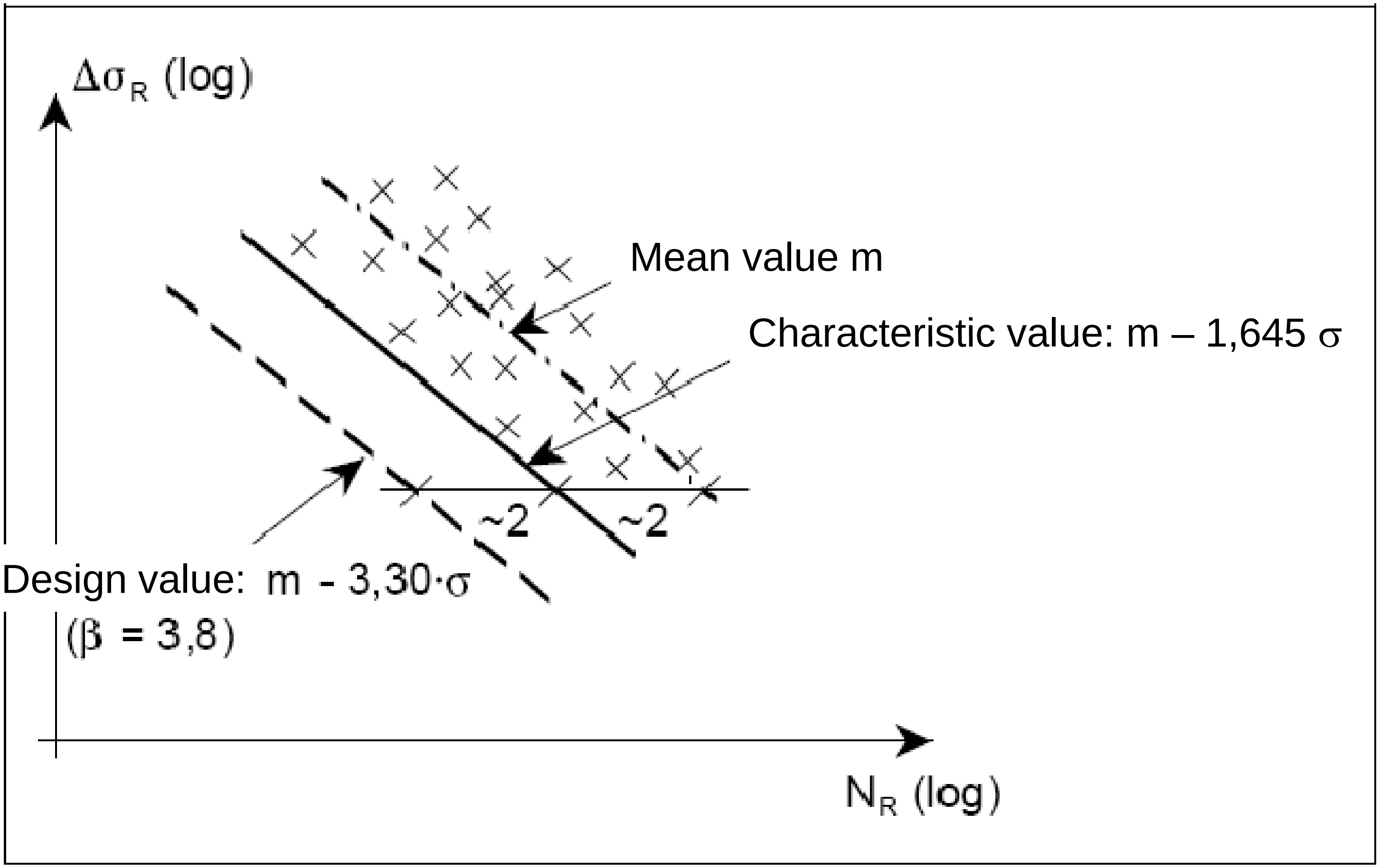


$$\gamma_{Ff}\cdot\gamma_{Mf} = 1.0 \Rightarrow n = 4 - 1 = 3$$

$$\gamma_{Ff}\cdot\gamma_{Mf} = 1.15 \Rightarrow n = \frac{4}{1.15^5} - 1 \approx 1$$

$$\gamma_{Ff}\cdot\gamma_{Mf} = 1.35 \Rightarrow n = \frac{4}{1.35^5} - 1 \approx 0$$

6.2 FATIGUE RULES



Control of actions $\gamma_N = 2 \rightarrow \gamma_{Mf} = \sqrt[5]{2} = 1{,}15$

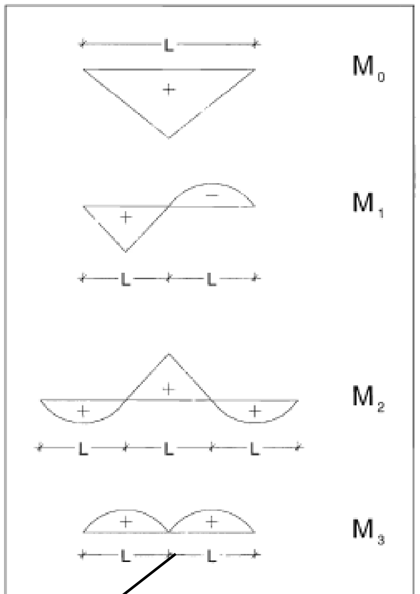
No control of actions $\gamma_N = 4{,}5 \rightarrow \gamma_{Mf} = \sqrt[5]{4{,}50} = 1{,}35$

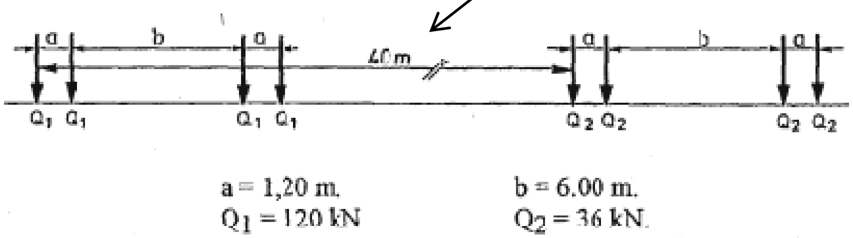
6.2 FATIGUE RULES

Assessment procedures

$$\gamma_{Ff}\Delta\sigma_{E2} \le \frac{\Delta\sigma_c}{\gamma_{Mf}}$$

Crossing of FLM3
↓
stress history
↓
counting method
↓
Miner-rule
↓
$\Delta\sigma_{E2}$





Use of λ-values

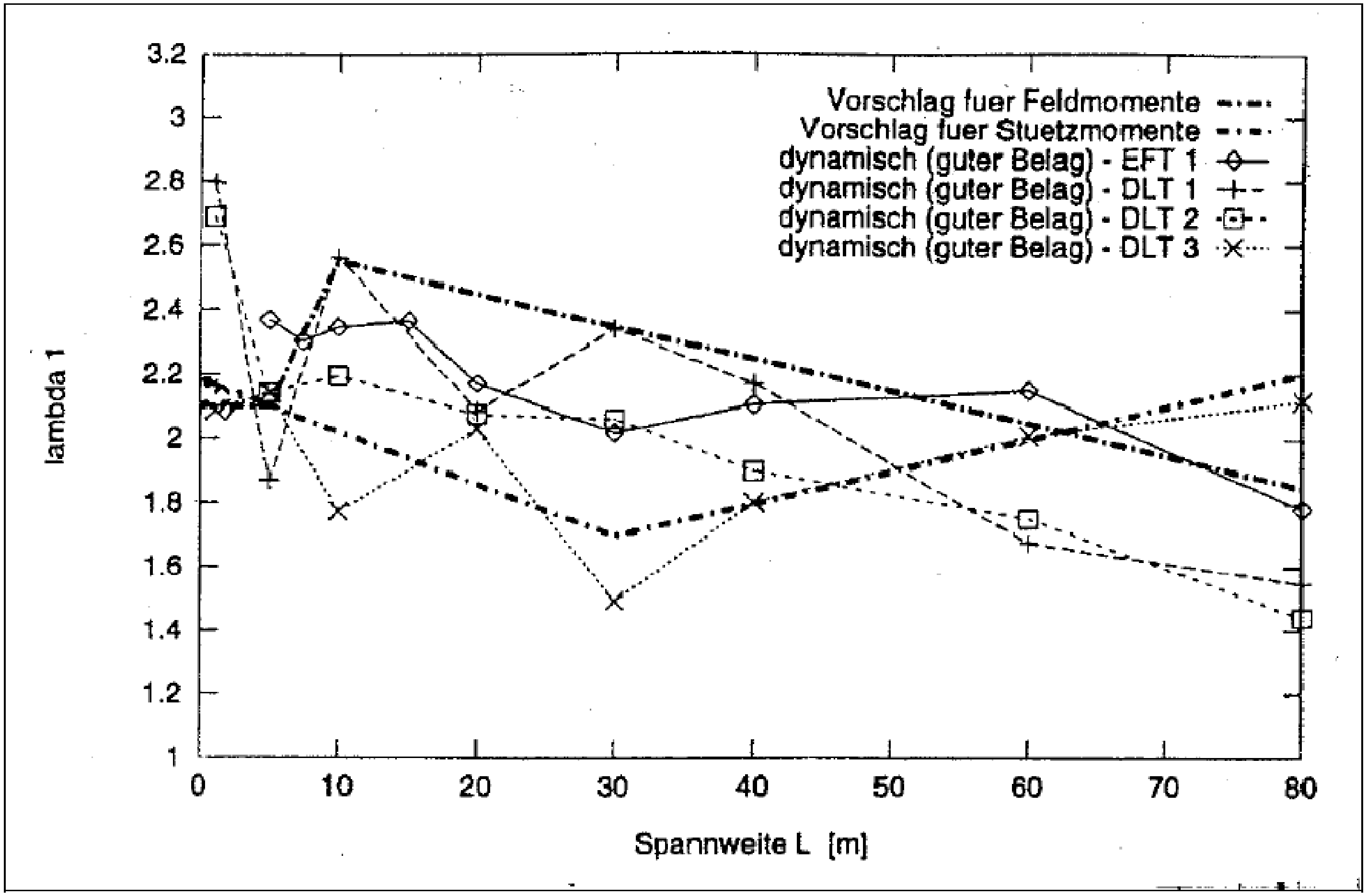
$$\Delta\sigma_{E2} = \lambda \cdot \varphi \cdot (\sigma_{max} - \sigma_{min})$$

$$\lambda = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4$$

- λ_4: effects of other lanes
- λ_3: design life
- λ_2: traffic composition
- λ_1: span length

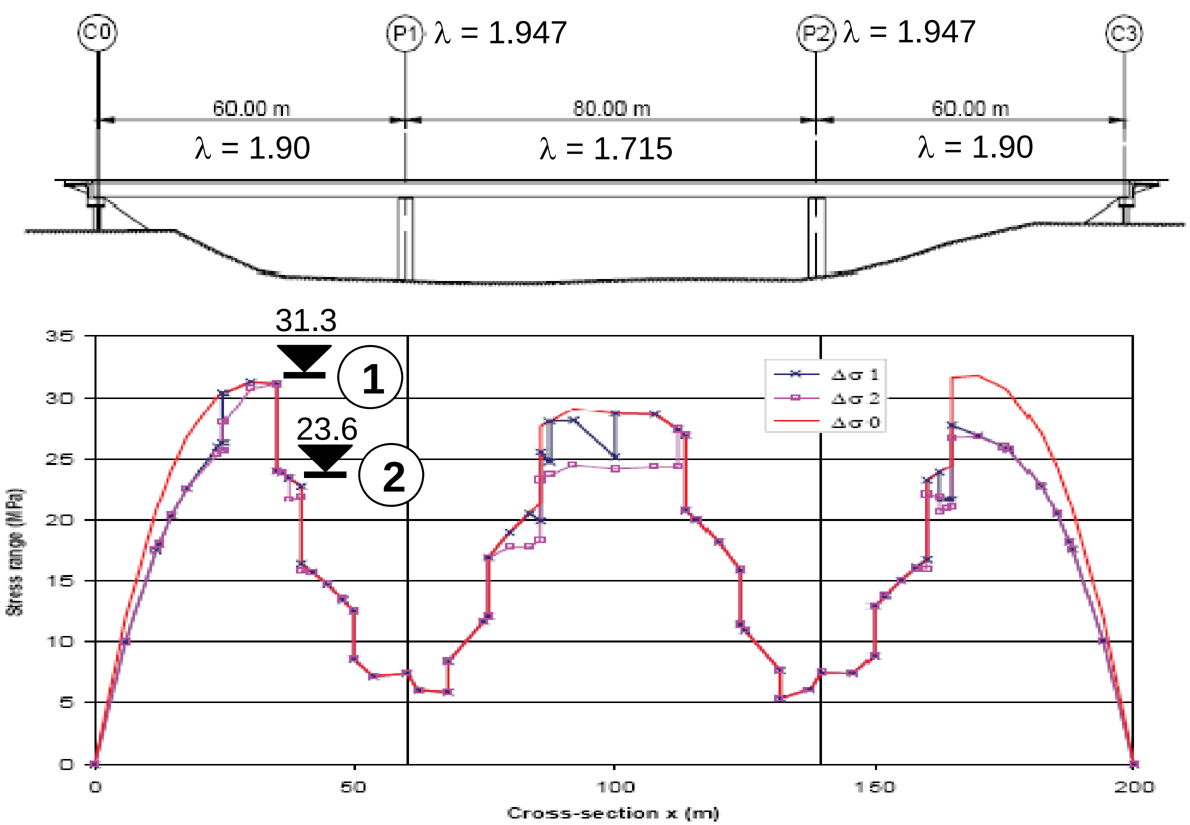
6.2 FATIGUE RULES

λ_1 value from simulations with Auxerre traffic



6.2 FATIGUE RULES

Example: Fatigue assessment for a composite bridge



stress ranges ($\sigma_{max} - \sigma_{min}$) at lower flange

1 Transverse weld from stiffener: $\Delta\sigma_{E2} = 1.9 \cdot 31.3 = 59.5 < 80 MPa$

2 Butt weld of flange: $\Delta\sigma_{E2} = 1.9 \cdot 26.6 = 44.8 < 77 MPa$

6.2 FATIGUE RULES

JRC Scientific and Technical Reports

Commentary to Eurocode 3
EN 1993 - Part 1-9 - Fatigue

G. Sedlacek, A. Hobbacher, A. Nussbaumer, J. Stötzel, D. Tschickardt

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Rope-structures - Stayed cable bridges

Definition

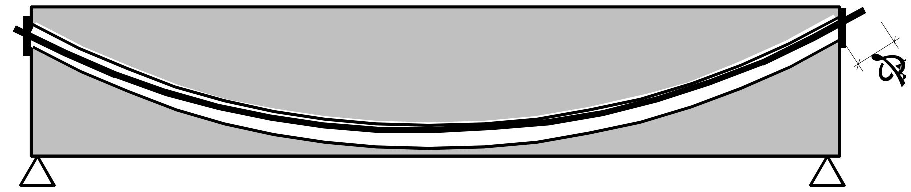
- Any prestress is generated by preloading

- Preloading is a process to impose
  - forces or
  - deformations

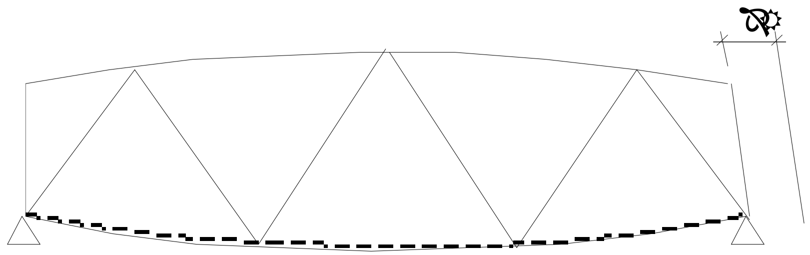
- The effects of preloading may be
  - variations of stresses (prestress)
  - variations of deformations
  - other variations of permanent stage

Examples for preloading processes

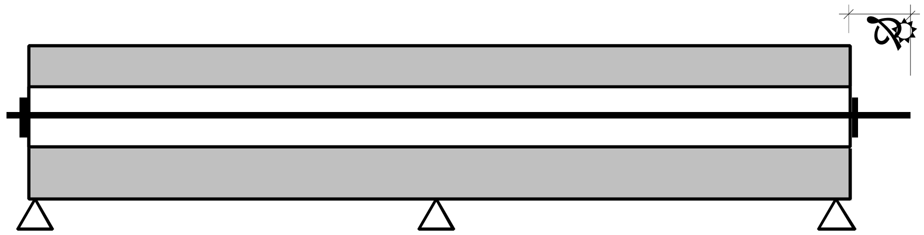
1a) Prestressing by internal tendons



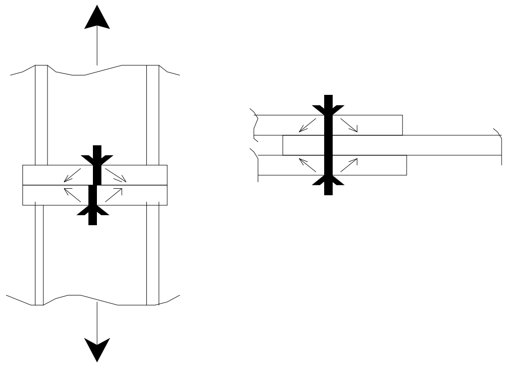
1b) Prestressing of trusses by cables in hollow sections



1c) Prestressing by external tendons



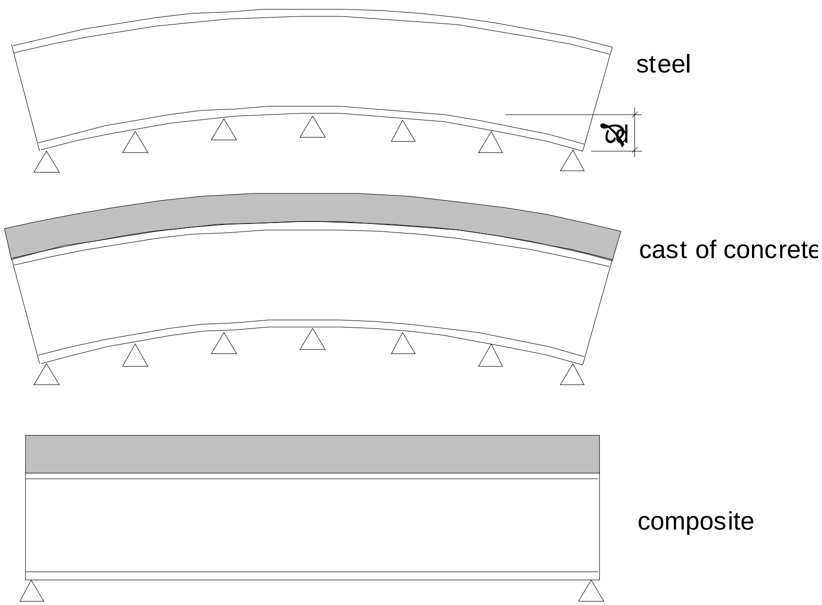
1d) Prestressing of joints subjected to tension or friction



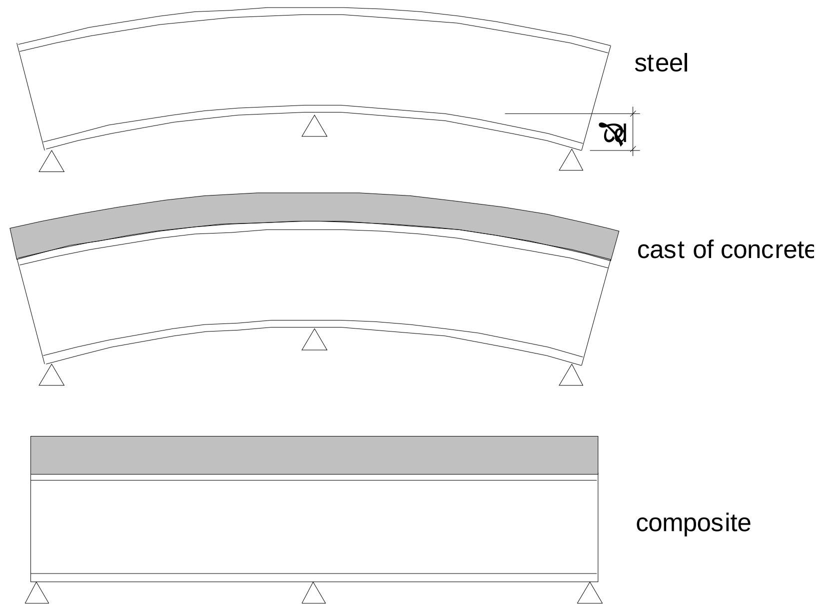
6.3 ROPE STRUCTURES

Examples for preloading processes

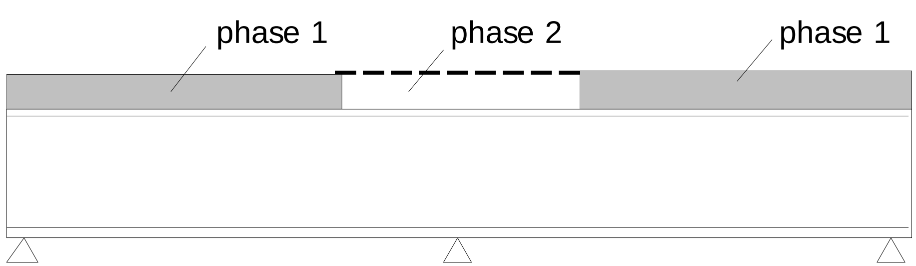
2) Prestressing by propping



4) Prestressing by imposed deformation



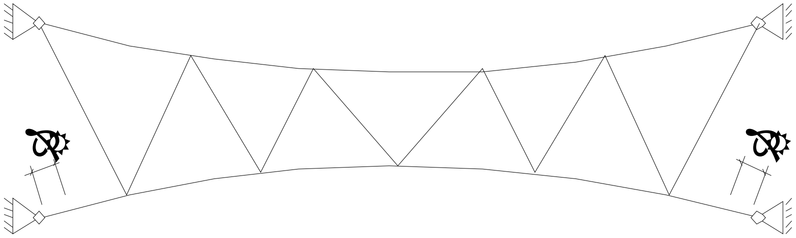
3) Prestressing by sequence of casting concrete



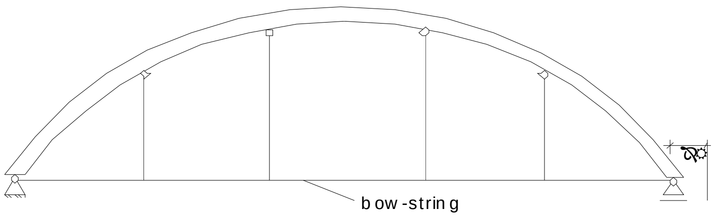
6.3 ROPE STRUCTURES

Examples for preloading processes

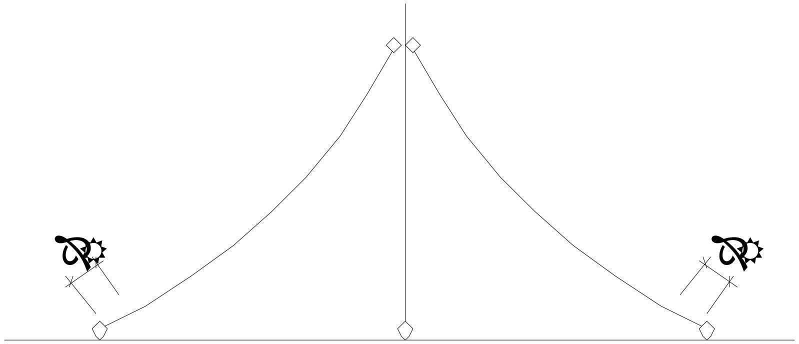
5a) Prestressing of
cable structures



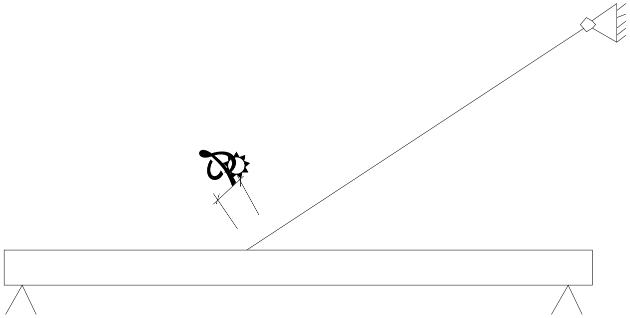
5b) Prestressing of
arches by string-elements



5c) Prestressing of guyed
masts



5d) Prestressing of cable
stayed structures

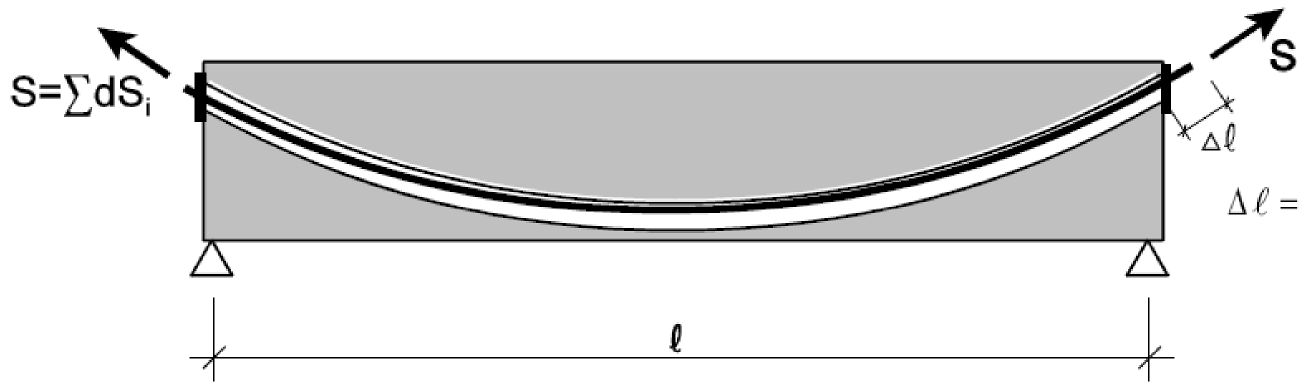


Principles

- It is possible to define the preloading or prestressing process by all necessary steps including controls

- It is not possible to define “prestress” as an effect of prestressing or preloading in a general way, that covers all cases

Example for the applicability of “prestress”



$$\Delta \ell = \frac{\ell_s}{EA} S \left[1 - \sum \frac{ds_i \, \ell_i}{S \, \ell} \right]$$

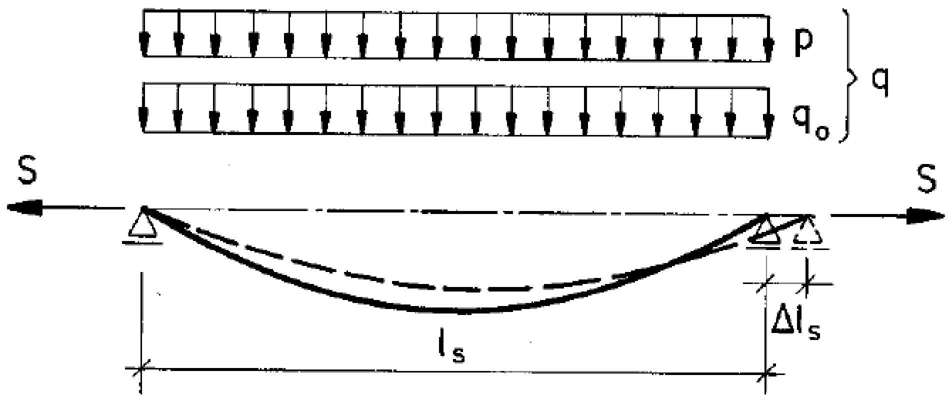
stress before prestresses: $\sigma_{q0,\Delta l=0}$

stress immediately after prestressing: $\sigma_{q0,\Delta l}$

prestress: $\sigma_{q0,\Delta l=0,\Delta l} = \sigma_{q0,\Delta l} - \sigma_{q0,\Delta l=0}$

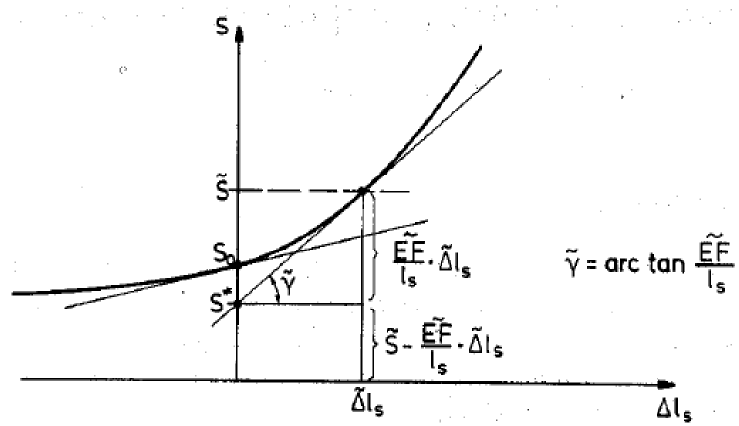
6.3 ROPE STRUCTURES

Example for the non-applicability of “prestress”



$$\Delta l_s = \frac{l_s}{EF}(S - S_0) - \frac{l_s^3}{24}\left(\frac{q^2}{S^2} - \frac{q_0^2}{S_0^2}\right) + \alpha_t (t - t_0)\, l_S$$

strain catanery temperature



Conclusion

“P” in EN 1990

a) preloading or prestressing process leading to a structural shape or behaviour as required

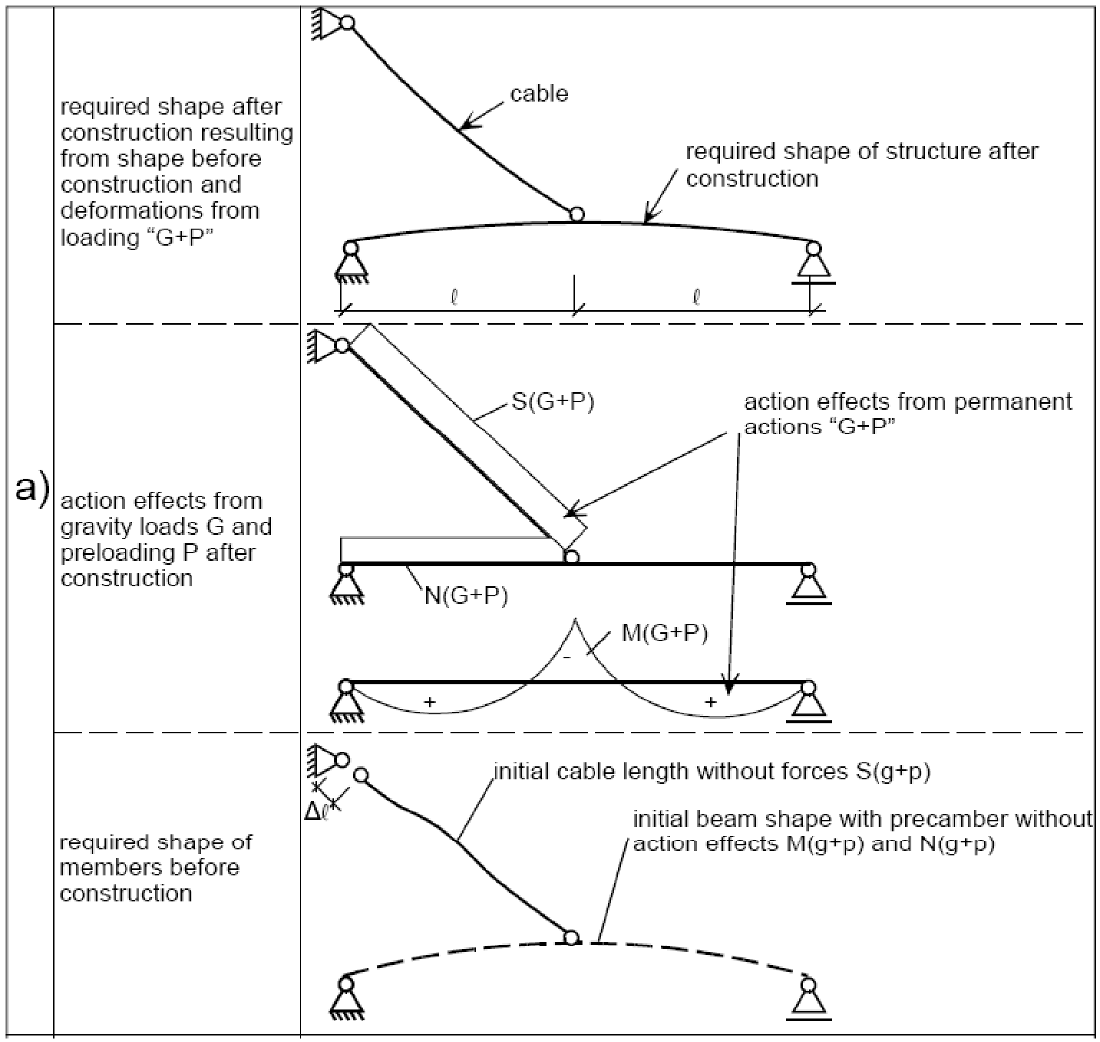
b) prestress in specific cases where defined

Treatment of preloading and prestressing processes in the construction phase

Target: attainment of the required structural form and distribution of effects of (G+P)

Conclusion: calculation with characteristic values, linear material law:
stress limitations and prestressing of cables.

Treatment of preloading and prestressing processes in the construction phase



Treatment of preloading and prestressing processes in the service phase

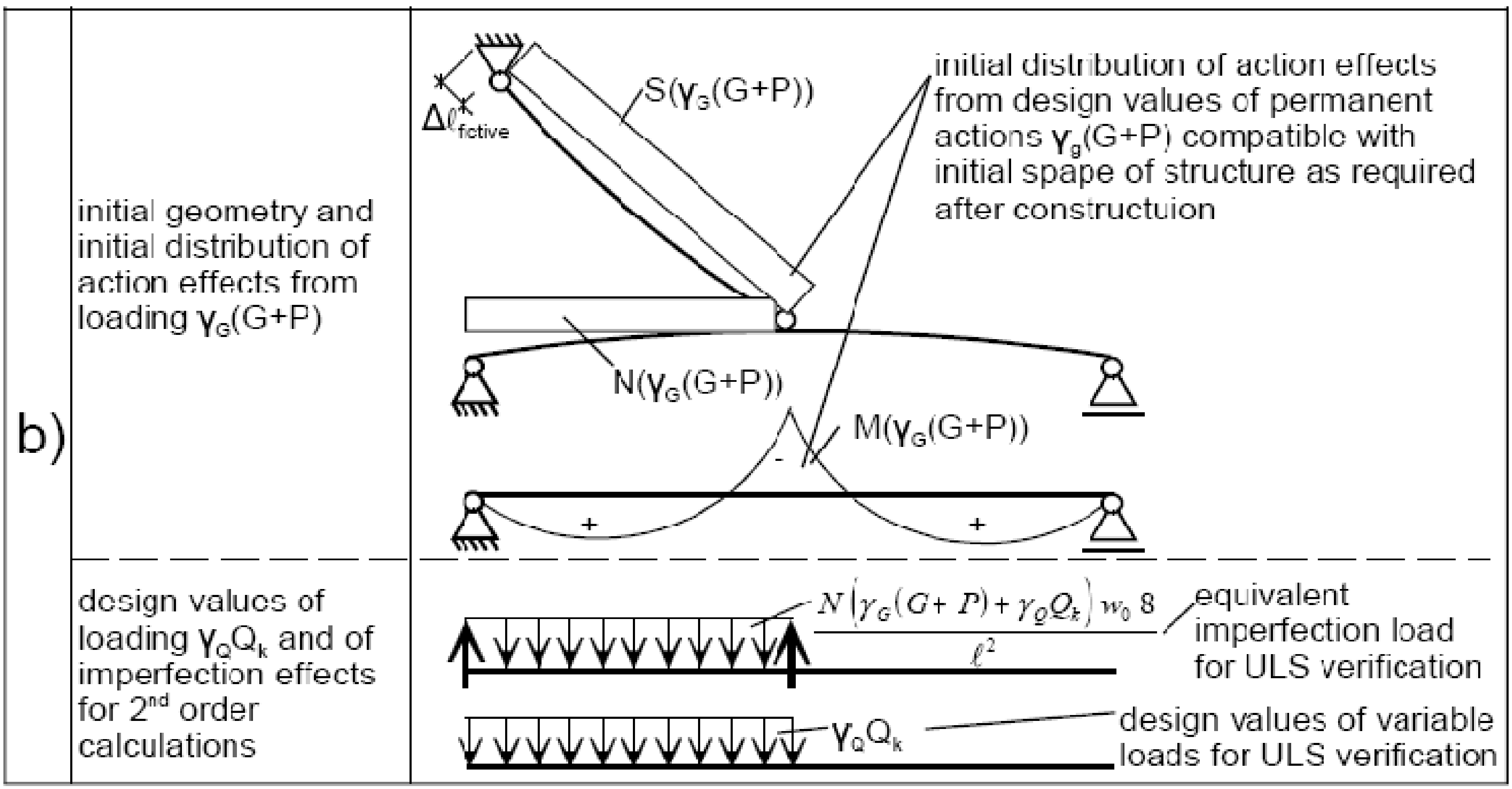
Target: ULS verification on the basis of:

- permanent actions $\gamma_G(G+P)$
- permanent from resulting from (G+P)
- imperfections of the form
- variable actions $\gamma_Q\{Q_{K1} + \psi_0 Q_{Q2}\}$

Conclusion: Calculation with the permanent form associated with the effect from $\gamma_G(G+P)$

6.3 ROPE STRUCTURES

Treatment of preloading and prestressing processes in the service phase



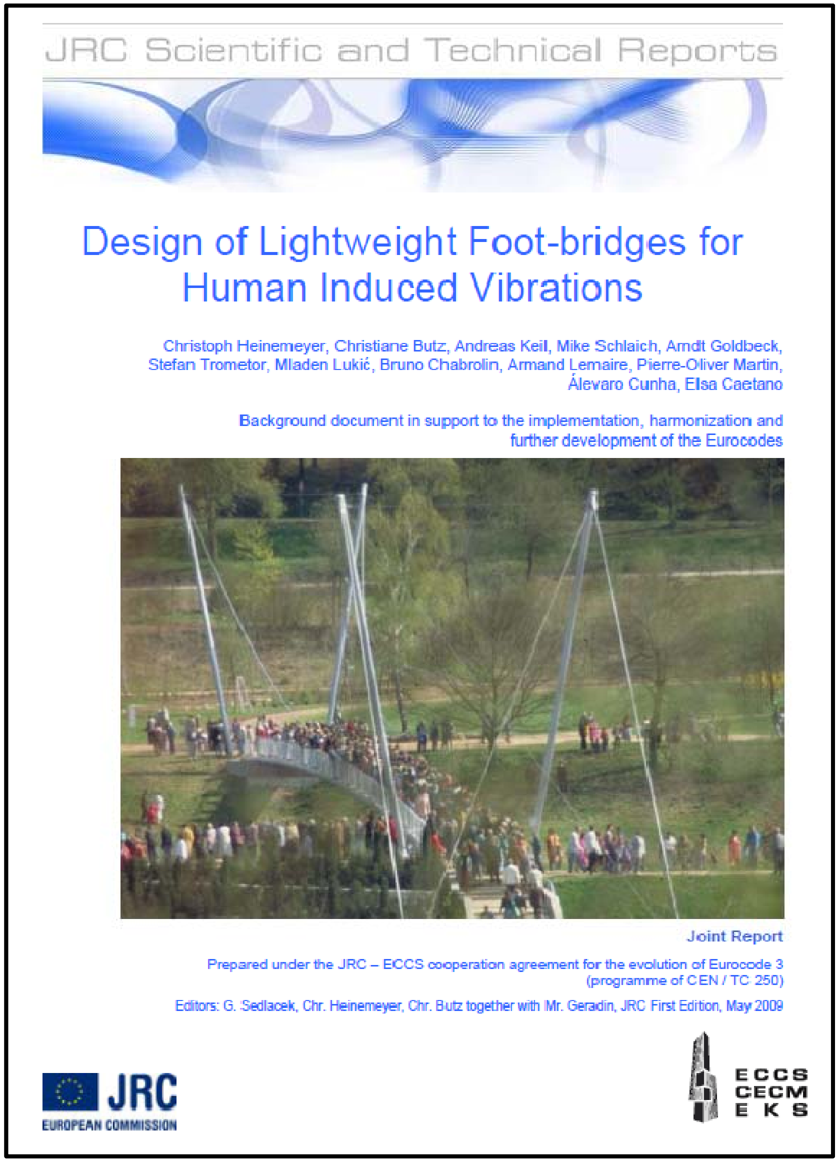
Treatment at counterflexure points

Treatment at counterflexure points, or where the action effects from (G+P) are limited (e.g. by decompression):

$\Delta G = \alpha G$, where $0{,}05 \leq \alpha \leq 0{,}10$

applied to influence surfaces.

6.3 ROPE STRUCTURES



JRC Scientific and Technical Reports

Design of Lightweight Foot-bridges for Human Induced Vibrations

Christoph Heinemeyer, Christiane Butz, Andreas Keil, Mike Schlaich, Arndt Goldbeck, Stefan Trometor, Mladen Lukić, Bruno Chabrolin, Armand Lemaire, Pierre-Oliver Martin, Álevaro Cunha, Elsa Caetano

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Editors: G. Sedlacek, Chr. Heinemeyer, Chr. Butz together with Mr. Geradin, JRC First Edition, May 2009

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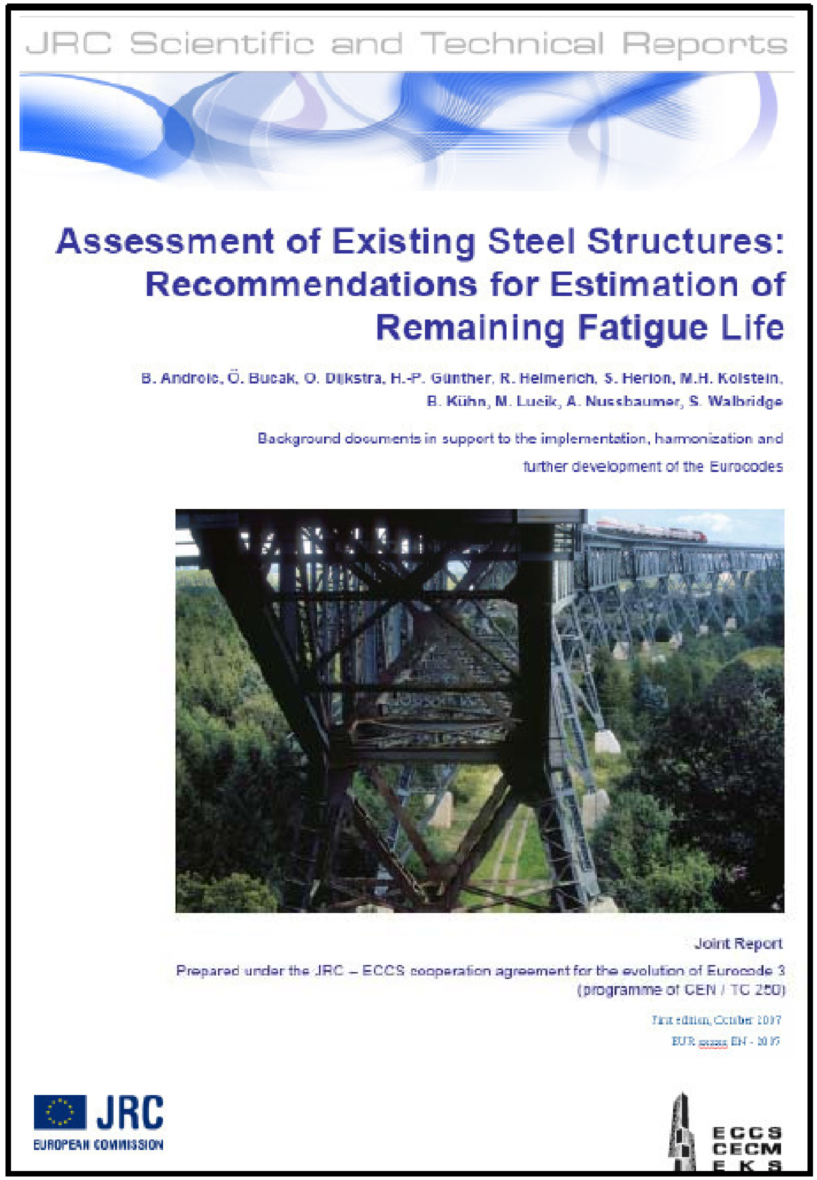
7. ASSESSMENT OF EXISTING STEEL BRIDGES



JRC Scientific and Technical Reports

Assessment of Existing Steel Structures: Recommendations for Estimation of Remaining Fatigue Life

B. Androic, Ö. Bucak, O. Dijkstra, H.-P. Günther, R. Helmerich, S. Herion, M.H. Kolstein, B. Kühn, M. Lucik, A. Nussbaumer, S. Walbridge

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