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DIN 2413:2011-06

Seamless steel tubes for oil- and water-hydraulic systems – Calculation rules for pipes and elbows for dynamic loads, English translation of DIN 2413:2020-04

Nahtlose Stahlrohre für öl- und wasserhydraulische Anlagen –
Berechnungsgrundlage für Rohre und Rohrbögen bei schwellender Beanspruchung,
Englische Übersetzung von DIN 2413:2020-04

Tubes en acier sans soudure pour des systèmes hydrauliques d’huile et d’eau –
Règles de calcul pour tuyaux et coudes de tuyaux sous efforts dynamiques,
Traduction anglaise de DIN 2413:2020-04

Document comprises 34 pages

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In case of doubt, the German-language original shall be considered authoritative.

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A comma is used as the decimal marker.

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Foreword

This document has been prepared by Working Committee NA 082-00-07 AA “Compression Couplings” of DIN-*Normenausschuss Rohrleitungen und Dampfkesselanlagen* (NARD) (DIN Standards Committee Piping and Boiler Plant).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. DIN shall not be held responsible for identifying any or all such patent rights.

With the publication of DIN EN 13480-3, the previously valid editions of DIN 2413-1 and 2413-2 have been withdrawn. The practical application of DIN EN 13480-3 showed that this standard can result in wall thicknesses for hydraulic systems which many years of experience has shown to be overdimensioned. It was therefore necessary to specify a different calculation method. For this reason DIN 2413 was developed with the cooperation of NA 082-00-07 AA and Steel Institute VDEh.

Even if the results of a wall thickness calculation as in 5.2 are not always confirmed in practice, the theoretical approach was retained for the sake of completeness and in the absence of other alternatives.

Amendments

This document differs from DIN 2413:2011-06 as follows:

a) the Scope has been limited to seamless carbon and stainless steel pipes and elbows for oil and water hydraulic systems not covered by the Pressure Equipment Directive 2014/68/EU;

b) Normative references and the Bibliography have been updated;

c) the standard has been editorially revised.

Previous editions

DIN 2413: 1927-01, 1936-09, 1954-05, 1966-06, 1972-06, 2011-06

DIN 2413-1: 1993-10

DIN 2413-2: 1993-10

DIN 2445 Supplement: 1974-11

DIN 2445 Supplement 1: 2000-09

1 Scope

This document contains the principles for the analysis of seamless pipes and elbows made of carbon and stainless steel for oil and water hydraulic systems.

This document is to be applied to piping where each of the three following conditions is met:

1) the piping is intended for installation in machines within the meaning of the Machinery Directive 2006/42/EC;

2) the piping is intended for service

   i) with fluids of group 2 according to the Pressure Equipment Directive 2014/68/EU (PED) with DN $\leq$ 200 at any pressure, and with DN $>$ 200 and at a maximum allowable pressure (PS) $\leq$ 50 MPa (500 bar), or

   ii) with gases of group 2 as in the PED with DN $\leq$ 100 or PS DN $\leq$ 350 MPa (3 500 bar);

3) the piping is intended for service at maximum allowable temperatures (TS) up to 120 °C.

NOTE The exclusion in Article 1, paragraph 2 (f) of the Pressure Equipment Directive applies to piping which fulfils the conditions of point 1 and point 2.

This document is not applicable to piping falling within the scope of the Pressure Equipment Directive.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

DIN EN 10204, *Metallic products — Types of inspection documents*

DIN EN 10216-1, *Seamless steel tubes for pressure purposes — Technical delivery conditions — Part 1: Non-alloy steel tubes with specified room temperature properties*

DIN EN 10216-3, *Seamless steel tubes for pressure purposes — Technical delivery conditions — Part 3: Alloy fine grain steel tubes*

DIN EN 10216-5, *Seamless steel tubes for pressure purposes — Technical delivery conditions — Part 5: Stainless steel tubes*

DIN EN 10305-4, *Steel tubes for precision applications — Technical delivery conditions — Part 4: Seamless cold drawn tubes for hydraulic and pneumatic power systems*

DIN EN 13480 (all parts), *Metallic industrial piping*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in the DIN EN 13480 series of standards apply.

DIN and DKE provide terminology databases for use in standardization at the following addresses:

— DIN-TERMinology Portal: available at https://www.din.de/en/services/din-term

— DKE IEV: available at http://www.dke.de/DKE-IEV

4 Units, symbols and abbreviated terms

4.1 Units

The units used in this document are listed in Table 1.

Table 1 — Units

Quantity	Unit
Dimensions	—
Diameter, wall thickness, radius	mm
Area	mm^2
Length of pipe run	m
Pressure[a]	N/mm^2
Stresses, characteristic strength values, modulus of elasticity	N/mm^2
Mass	kg
Density	kg/m^3
Time	s or h
Velocity	m/s
Temperature	°C
Temperature difference	K

[a] For other pressure units the following applies: 1 N/mm^2 = 1 MPa = 10 bar

4.2 Symbols and abbreviated terms

The symbols used in this standard are listed in Table 2.

Table 2 — Symbols

Symbol	Quantity	Unit
Pipes		
a	Propagation velocity of a pressure wave	m/s
$c = c_1 + c_2$	Allowance to be used in wall thickness calculation	mm
c_1	Allowance for permissible wall thickness undersize	mm
c_1'	Permissible wall thickness undersize	%
c_2	Allowance for corrosion or wear	mm
d_a	Pipe outside diameter	mm
d_i	Pipe inside diameter	mm
l	Length of pipe run	m

Table 2 *(continued)*

Symbol	Quantity	Unit
n	Number of cycles (number of pressure cycles) expected in service	—
n_B	Number of cycles to failure	—
N	Number of cycles at which the fatigue limit is attained	—
p	Design pressure	N/mm^2
p_k	Critical external pressure (causes elastic buckling)	N/mm^2
$\hat{p} - \check{p}$	Stress amplitude of a pressure oscillation	N/mm^2
p'	Test pressure	N/mm^2
Δp	Change in pressure due to a pressure surge	N/mm^2
r	Radius of curvature along the axis of an elbow	mm
s	Required wall thickness, including allowances	mm
s_v	Design wall thickness, not including allowances	mm
$u = d_a/d_i$	Ratio of outside to inside diameter	—
w	Flow rate	m/s
w^{ϑ}	Rate at which temperature changes	k/h
A	Elongation after rupture $\left(L_o = 5{,}65 \cdot \sqrt{S_o}\right)$	%
B_P	Factor to account for the sealing forces in the test presses during the works test	—
B_u	Design factor to account for non-round pipes	—
E	Modulus of elasticity of the steel	N/mm^2
K	Characteristic strength value	N/mm^2
$\check{R}_{eH}$	Upper yield strength (specified minimum value) at 20 °C	N/mm^2
$\check{R}_{p\,0,2}$	0,2 % proof strength (specified minimum value) at 20 °C	—
$\check{R}_{t\,0,5}$	Proof strength at 0,5 % total elongation at 20 °C (specified minimum value)	—
$\check{R}_{p\,1,0}$	1 % proof strength (specified minimum value) at 20 °C	N/mm^2
$\check{R}_{p\,0,2/\vartheta}$	Yield strength at elevated temperature or minimum 0,2% proof strength (specified minimum value) at the design temperature ϑ	N/mm^2
$\check{R}_{p\,1,0/\vartheta}$	1 % proof strength (specified minimum value) at the design temperature ϑ	N/mm^2
R_m	Tensile strength	N/mm^2
$\check{R}_m$	Tensile strength (specified minimum value)	N/mm^2

Table 2 *(continued)*

Symbol	Quantity	Unit
$\overline{R}_{\mathrm{m}/200\,000/\vartheta}$	Creep rupture strength after 200 000 h (mean value) at design temperature ϑ	N/mm^2
$\overline{R}_{\mathrm{m}/100\,000/\vartheta}$	Creep rupture strength after 100 000 h (mean value) at design temperature ϑ	N/mm^2
S	Safety factor	—
S_{L}	Safety factor (for load cycles to failure)	—
S_{K}	Safety factor (to account for buckling)	—
T_{R}	Response time after a pressure surge	s
T_{S}	Closing time of stop valve or control valve	s
U	Out-of-roundness	%
$Y = 1/S$	Degree of utilization	—
Y'	Degree of utilization of the minimum yield strength during internal pressure test (pressure testing at the works)	—
α_{l}	Coefficient of linear thermal expansion	1/K
ϑ	Design temperature	°C
ν	Poisson’s ratio	—
ρ	Density of medium conveyed	kg/m^3
σ_{zul}	Maximum permissible stress under static loading	N/mm^2
$\overline{\sigma}_{\mathrm{zul}}$	Maximum permissible stress under dynamic loading	N/mm^2
σ_{l}	Longitudinal stress	N/mm^2
σ_{r}	Radial stress	N/mm^2
σ_{M}	Mean stress	N/mm^2
$\overset{\vee}{\sigma}_{\mathrm{Sch/D}}$	Minimum fatigue strength at constant stress amplitude	N/mm^2
σ_{Schi}	Equivalent pulsating stress	N/mm^2
$\overset{\vee}{\sigma}_{\mathrm{Sch/n}}$	Minimum fatigue strength at a specified number of cycles	N/mm^2
σ_{u}	Circumferential stress	N/mm^2
σ_{v}	Reference stress	N/mm^2
Δr	Deviation from roundness	mm
Δw	Change in flow rate as a result of a controlling operation (can be positive or negative)	m/s
$\Delta\sigma$	Stress amplitude	N/mm^2
$\Delta\vartheta$	Change in temperature	K

Table 2 *(continued)*

Symbol	Quantity	Unit
Additional symbols for elbows		
$c_{1\ \mathrm{B}}$	Allowance for permissible wall thickness undersize of elbows	mm
d_i, d_a	Inside and outside diameters of elbows	mm
f_u	Reduction factor for fatigue strength of non-round elbows	—
r, R	Radius of curvature of elbow as in Figure 3*)	mm
s_i	Required wall thickness of inside of the elbow with allowances	mm
s_a	Required wall thickness of outside of the elbow with allowances	mm
s_ei	Actual wall thickness of the inside of the elbow with allowances	mm
s_ea	Actual wall thickness of the outside of the elbow with allowances	mm
s_vi	Wall thickness of inside of the elbow without allowances } (design minimum wall thickness)	mm
s_va	Wall thickness of outside of the elbow without allowances	mm
B_I	Design factor for determining the wall thickness of the inside of the elbow	—
B_A	Design factor for determining the wall thickness of the outside of the elbow	—
B	Design factor for same wall thickness on inside and outside of elbow	—
$\overline{\sigma}_\mathrm{I}$	Mean stress at inside of elbow	$\mathrm{N/mm^2}$
$\overline{\sigma}_\mathrm{A}$	Mean stress at outside of elbow	$\mathrm{N/mm^2}$
$\sigma_\mathrm{I,i}$	Stress at elbow inside, wall inner side, see Figure 3*	$\mathrm{N/mm^2}$
$\sigma_\mathrm{A,i}$	Stress at elbow outside, wall inner side, see Figure 3*	$\mathrm{N/mm^2}$
Additional symbols		
$\wedge$	Maximum value (e.g. $\hat{p}$ = maximum pressure)	—
$\vee$	Minimum value (e.g. $\check{p}$ = minimum pressure)	—
$\bar{}$	Mean value (e.g. $\overline{\sigma}$= mean stress)	—
~	Variable (e.g. $\tilde{\sigma}_\mathrm{zul}$ = dynamic loading)	—

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* Translator's note: This should read Figure 1.

5 Calculation of wall thicknesses of straight pipes and elbows to account for internal pressure

5.1 Calculation of wall thicknesses of straight pipes

5.1.1 Load cases

The formulae given for calculating the wall thickness to account for internal pressure apply to pipes with circular cross-sections without cut-outs up to a diameter ratio $u = d_a/d_i = 2{,}0$ for the following load cases:

I Piping for predominantly static loading up to a design temperature of 120 °C[1];

III Piping for predominantly dynamic loading up to a design temperature of 120 °C[2].

The formulae to be applied for calculating the design wall thickness s_v for the individual load cases are given in Table 3, for material characteristics see Table 4.

Table 3 — Determining the design wall thickness s_v and test pressure p'

Load case	Design wall thickness s_v	Characteristic strength value K	Safety factor S and degree of utilization Y for pipes				
				with		without[a]	
				inspection certificate as in DIN EN 10204			
	mm	N/mm²					
$\sigma_{zul} = K/S = Y \cdot K$			A[b]	S	Y	S	Y
I predominantly static loading	$s_v = \frac{d_a \cdot p}{2\sigma_{zul}}$ (1) $= \frac{d_i}{\frac{2\sigma_{zul}}{p} - 2}$ (2)	Yield strength or 0,2 % proof strength or proof strength at 0,5 % total elongation Minimum values at 20 °C[d,e] See 6.3.1 for exception	≥ 25 %	1,5	0,67	1,7	0,59
			= 20 %	1,6	0,63	1,75	0,57
			= 15 %	1,7	0,59	1,8	0,55
			For buried pipes in areas not subjected to significant additional loading, the following applies:				
			≥ 25 %	1,4	0,72	1,7	0,59
			= 20 %	1,5	0,67	1,75	0,57
			= 15 %	1,6	0,63	1,8	0,55

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[1] For wall temperatures below −10 °C special attention is to be paid to the toughness properties of the steels. Preference shall then be given to steels with special cold toughness properties. For low temperature steels see DIN EN 10216-3 and DIN EN 10216-4, for low temperature applications see AD 2000-Merkblatt W 10.

[2] For higher temperatures, see AD 2000-Merkblatt S 2.

Table 3 *(continued)*

Load case	**Design wall thickness s_v** mm	**Characteristic strength value K** N/mm^2	**Safety factor S and degree of utilization Y for pipes**				
				with		without[a]	
				inspection certificate as in DIN EN 10204			
$\sigma_\mathrm{zul} = K/S = Y \cdot K$			A[b]	S	Y	S	Y
III dynamic loading The analysis is to account for deformation and fatigue failure at a specified number of cycles. Therefore, the larger design wall thickness s_v obtained is to be used in the analysis.	a) Analysis to account for deformation: as in Equation (1) and Equation (2)[c] b) Analysis to account for fatigue failure or fatigue failure at constant stress amplitude: $$s_\mathrm{v} = \frac{d_\mathrm{a}}{\frac{2\tilde{\sigma}_\mathrm{zul}}{\hat{p} - \check{p}} - 1} \quad (3)$$ For different amplitudes see 6.3.3.3.	See load case I $\tilde{\sigma}_\mathrm{zul}$ see 6.3.3.1 Cyclic fatigue strength $\check{\sigma}_\mathrm{Sch/n}$	See load case I —	see 6.3.1, 6.3.3 and 7.2.4 S_L = 2 to 10		—	—
		Fatigue strength at constant stress amplitude $\check{\sigma}_\mathrm{Sch/D}$	—	1,5	0,67	—	—
Test pressure p' in the test press N/mm^2	$$p' = B_\mathrm{p} \cdot Y' \cdot \check{R}_\mathrm{eH} \frac{2(s - c_1)}{d_\mathrm{a}} \quad (4)$$ Applies to a single pipe. 6.7 shall be observed.						

[a] Pipes not supplied with an inspection certificate shall only be made of unalloyed materials with a minimum tensile strength of up to 550 N/mm^2 or from austenitic materials with an elongation after rupture $A \geq 40$ %.

[b] Intermediate values of $L_\mathrm{o} = 5{,}65 \cdot \sqrt{S_\mathrm{o}}$ may be obtained by linear interpolation, or, where the strain is less than 15 %, they may be extrapolated.

[c] Equation (2) is the mathematical conversion of Equation (1) and leads to the same result if $d_\mathrm{a} = d_\mathrm{i} + 2s_\mathrm{v}$. The same applies to Equation (4) compared to Equation (3) and Equation (6) compared to Equation (5).

[d] The yield strength shall be taken from the respective standards, regulations, material sheets or specifications; if necessary, interpolation is to be carried out. For design temperatures below 20 °C, the values specified for 20 °C apply (see 6.3.2).

[e] For austenitic steels, under certain conditions, analysis may be performed with $\check{R}_{\mathrm{p}\,1{,}0}$ instead of $\check{R}_{\mathrm{p}\,0{,}2}$ and with $\check{R}_{\mathrm{p}\,1{,}0/\vartheta}$ instead of $\check{R}_{\mathrm{p}\,0{,}2/\vartheta}$ (see 6.3.2).

5.1.2 Design formulae

The required wall thickness is

$$s = s_\mathrm{v} + c_1 + c_2 \tag{5}$$

It is given by the design wall thickness s_v as in Table 3, the allowance c_1 for taking into account the permissible wall thickness undersize (see 6.6.2) and the allowance c_2 for corrosion or wear (see 6.6.3). Where the permissible wall thickness undersize is given as a percentage, c_1', the required wall thickness is

$$s = (s_\mathrm{v} + c_2)\frac{100}{100 - c_1'} \tag{6}$$

5.1.3 Material characteristics

Table 4 — Mechanical characteristics of the relevant materials

Material		**Wall strength**	**Characteristic strength value K**	R_m	$A_{5\ \mathrm{min}}$
Material no. (name)	as in standard	mm	N/mm^2	N/mm^2	%
1.0308+N (E235+N)	DIN EN 10305-4	$d_\mathrm{a} \le 30$ mm, $s \le 3$ mm	$R_\mathrm{eH} = 225$	340	25
		other dimensions	$R_\mathrm{eH} = 235$		
1.0580+N (E355+N)	DIN EN 10305-4	$d_\mathrm{a} \le 30$ mm, $s \le 3$ mm	$R_\mathrm{eH} = 345$	490	22
		other dimensions	$R_\mathrm{eH} = 355$	490	22
1.4571 (X6CrNiMoTi17-12-2)	DIN EN 10216-5	$d_\mathrm{a} \le 50$ mm	$R_\mathrm{eH} = 245$	490	35

5.2 Design of wall thickness of elbows

5.2.1 General

The calculation rule takes into account the fact that under internal pressure an elbow has higher stresses on the inside of the bend and lower stresses on the outside of the bend than a straight pipe of the same wall thickness and diameter.

The notation for the dimensions of an elbow is given in Figure 1.

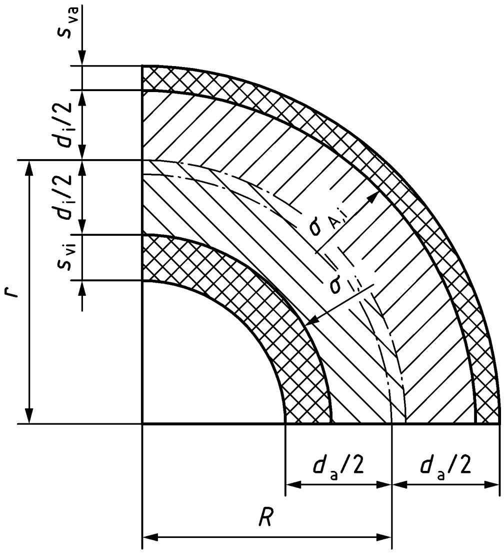

Figure 1 — Schematic representation of an elbow with dimensions (notation)

5.2.2 Required wall thickness

The design minimum wall thickness is:

- for the elbow inside s_{vi}
- for the elbow outside s_{va}

If allowances are to be made for the permissible wall thickness undersize $c_{1\,B}$ and/or corrosion c_2, then the following applies:

- for the elbow inside $s_i = s_{vi} + c_{1\,B} + c_2$ (7)
- for the elbow outside $s_a = s_{va} + c_{1\,B} + c_2$ (8)

For existing elbows with the inside and outside wall thicknesses s_{ei} and s_{ea} , respectively, the following shall be taken:

- for the elbow inside $s_{vi} = s_{ei} - c_{1\,B} - c_2$ (9)
- for the elbow outside $s_a = s_{ea} - c_{1\,B} - c_2$ (10)

Where the transition zone between elbow and pipe is provided with chamfered edges to create a smooth transition or to prevent offset, these need not be taken into account for design purposes.

5.2.3 Design

5.2.3.1 Design of wall thickness

The wall thickness on the inside of the elbow, without allowances, is given by

$$s_{\mathrm{vi}} = s_{\mathrm{v}} \cdot B_{\mathrm{I}} \tag{11}$$

with s_{v} as in Table 3.

The wall thickness on the outside of the elbow, without allowances, is given by

$$s_{\mathrm{va}} = s_{\mathrm{v}} \cdot B_{\mathrm{A}} \tag{12}$$

The formulae for determining the factors B_{I} and B_{A} are given in 5.2.3.2, 5.2.3.3 and 5.2.3.4.

5.2.3.5 specifies simplified formulae for determining the factors B_{I} and B_{A} which for $s_{\mathrm{v}}/d_{\mathrm{a}} \leq 0{,}02$ are sufficiently accurate and err on the safe side for elbows with thicker walls.

5.2.3.2 Design factors B_{I} and B_{A} for a given inside diameter

The design factors B_{I} and B_{A} to be used where the inside diameter of the elbow is known shall be calculated using Equations (13) and (14), respectively.

$$B_{\mathrm{I}} = \frac{s_{\mathrm{vi}}}{s_{\mathrm{v}}} = \frac{r}{s_{\mathrm{v}}} - \frac{d_{\mathrm{i}}}{2s_{\mathrm{v}}} - \sqrt{\left(\frac{r}{s_{\mathrm{v}}} - \frac{d_{\mathrm{i}}}{2s_{\mathrm{v}}}\right)^2 - 2\frac{r}{s_{\mathrm{v}}} + \frac{d_{\mathrm{i}}}{2s_{\mathrm{v}}}} \tag{13}$$

$$B_{\mathrm{A}} = \frac{s_{\mathrm{va}}}{s_{\mathrm{v}}} = -\frac{r}{s_{\mathrm{v}}} - \frac{d_{\mathrm{i}}}{2s_{\mathrm{v}}} + \sqrt{\left(\frac{r}{s_{\mathrm{v}}} + \frac{d_{\mathrm{i}}}{2s_{\mathrm{v}}}\right)^2 + 2\frac{r}{s_{\mathrm{v}}} + \frac{d_{\mathrm{i}}}{2s_{\mathrm{v}}}} \tag{14}$$

Actual values for B_{I} and B_{A}, as a function of r/d_{i}, can be taken from Figure 4.

5.2.3.3 Design factors B_{I} and B_{A} for a known outside diameter

The design factors B_{I} and B_{A} to be used where the outside diameter of the elbow is known shall be calculated using Equations (15) and (16), respectively.

$$B_{\mathrm{I}} = \frac{s_{\mathrm{vi}}}{s_{\mathrm{v}}} = \frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}} + \frac{r}{s_{\mathrm{v}}} - \left(\frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}} + \frac{r}{s_{\mathrm{v}}} - 1\right) \cdot \sqrt{\frac{\left(\frac{r}{s_{\mathrm{v}}}\right)^2 - \left(\frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}}\right)^2}{\left(\frac{r}{s_{\mathrm{v}}}\right)^2 - \frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}} \cdot \left(\frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}} - 1\right)}} \tag{15}$$

Since the radius of curvature R is normally also known where d_{a} is known, then

$$\frac{r}{s_{\mathrm{v}}} = \sqrt{\frac{1}{2} \cdot \left[\left(\frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}}\right)^2 + \left(\frac{R}{s_{\mathrm{v}}}\right)^2\right] + \sqrt{\frac{1}{4} \cdot \left[\left(\frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}}\right)^2 + \left(\frac{R}{s_{\mathrm{v}}}\right)^2\right]^2 - \frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}} \cdot \left(\frac{d_{\mathrm{a}}}{2s_{\mathrm{v}}} - 1\right) \cdot \left(\frac{R}{s_{\mathrm{v}}}\right)^2}} \tag{16}$$

is to be used.

The same results will be obtained with Equations (13) and (15) only if

$$d_\mathrm{a} = d_\mathrm{i} + s_\mathrm{vi} + s_\mathrm{va} \tag{17}$$

and

$$R = r - \frac{1}{2} \cdot (s_\mathrm{vi} - s_\mathrm{va}) \tag{18}$$

$$B_\mathrm{A} = \frac{s_\mathrm{va}}{s_\mathrm{v}} = \frac{d_\mathrm{a}}{2s_\mathrm{v}} - \frac{r}{s_\mathrm{v}} - \left(\frac{d_\mathrm{a}}{2s_\mathrm{v}} - \frac{r}{s_\mathrm{v}} - 1\right) \cdot \sqrt{\frac{\left(\frac{r}{s_\mathrm{v}}\right)^2 - \left(\frac{d_\mathrm{a}}{2s_\mathrm{v}}\right)^2}{\left(\frac{r}{s_\mathrm{v}}\right)^2 - \frac{d_\mathrm{a}}{2s_\mathrm{v}} \cdot \left(\frac{d_\mathrm{a}}{2s_\mathrm{v}} - 1\right)}} \tag{19}$$

Where R is known, r/s_v shall be determined using Equation (16).

Actual values for B_I and B_A, as a function of R/d_a, can be taken from Figure 4.

The same results will be obtained with Equations (14) and (19) only if the relationship between d_i, d_a, r and R is as expressed by Equations (17) and (18).

5.2.3.4 Design factors B_I and B_A for elbows where $s_\mathrm{vi} = s_\mathrm{va}$

Where the wall thicknesses on the inside and outside of the elbow are the same, the required wall thickness can be calculated as follows

$$s_\mathrm{vi} = s_\mathrm{va} = s_\mathrm{v} \cdot B \tag{20}$$

1) for elbows with a known inside diameter:

with the factor $B = B_\mathrm{I}$ as in Equation (13)

2) for elbows with a known outside diameter:

$$B = \frac{s_\mathrm{vi}}{s_\mathrm{v}} = \frac{s_\mathrm{va}}{s_\mathrm{v}} = \frac{d_\mathrm{a}}{2s_\mathrm{v}} - \frac{R}{s_\mathrm{v}} + \sqrt{\left(\frac{d_\mathrm{a}}{2s_\mathrm{v}} - \frac{R}{s_\mathrm{v}}\right)^2 + 2\frac{R}{s_\mathrm{v}} - \frac{d_\mathrm{a}}{2s_\mathrm{v}}} \tag{21}$$

Actual values for B, as a function of R/d_a, can be taken from Figure 5.

Equation (13), when used in combination with Equation (20), will only provide the same results as Equation (21) if the following criteria are satisfied:

$$d_\mathrm{a} = d_\mathrm{i} + 2s_\mathrm{vi} \tag{22}$$

and

$$R = r \tag{23}$$

5.2.3.5 Simplified calculation of factors B_I and B_A

For the elbow inside the following applies:

$$B_\mathrm{I} = \frac{2R/d_\mathrm{a} - 0{,}5}{2R/d_\mathrm{a} - 1} \tag{24}$$

For the elbow outside the following applies:

$$B_\mathrm{A} = \frac{2R/d_\mathrm{a} + 0{,}5}{2R/d_\mathrm{a} + 1} \tag{25}$$

For Equations (24) and (25) the curves in Figure 4 with $s_\mathrm{v}/d_\mathrm{a} = 0$ apply.

5.2.4 Stress analysis for elbows of known dimensions

In Table 5 Equations (26) to (33) for determining reference stresses in elbows are given for load cases I and III. These stresses are calculated according to the maximum shear theory.

Under otherwise identical conditions, Equations (30), (32), (31) and (33) result in slightly higher stresses for load case III than when Equations (11) to (21) are applied; this difference is permissible.

Table 5 — Analysis of stress (reference stresses based on the maximum shear theory)

Load case	d_i, r	d_a, R
I predominantly static loading	$\overline{\sigma}_\mathrm{I} = \frac{p \cdot d_\mathrm{i}}{2s_\mathrm{vi}} \cdot \frac{2r - 0{,}5d_\mathrm{i}}{2r - d_\mathrm{i} - s_\mathrm{vi}} + p$ (26) $\overline{\sigma}_\mathrm{A} = \frac{p \cdot d_\mathrm{i}}{2s_\mathrm{va}} \cdot \frac{2r + 0{,}5d_\mathrm{i}}{2r + d_\mathrm{i} + s_\mathrm{va}} + p$ (28)	$\overline{\sigma}_\mathrm{I} = \frac{p(d_\mathrm{a} - s_\mathrm{vi} - s_\mathrm{va})}{2s_\mathrm{vi}} \cdot \frac{2R - 0{,}5d_\mathrm{a} + 1{,}5s_\mathrm{vi} - 0{,}5s_\mathrm{va}}{2R - d_\mathrm{a} + s_\mathrm{vi}} + p$ (27) $\overline{\sigma}_\mathrm{A} = \frac{p(d_\mathrm{a} - s_\mathrm{vi} - s_\mathrm{va})}{2s_\mathrm{va}} \cdot \frac{2R + 0{,}5d_\mathrm{a} + 0{,}5s_\mathrm{vi} - 1{,}5s_\mathrm{va}}{2R + d_\mathrm{a} - s_\mathrm{va}} + p$ (29)
III	$\sigma_\mathrm{I,i} = \frac{p \cdot (d_\mathrm{i} + s_\mathrm{vi})}{2s_\mathrm{vi}} \cdot \frac{2r - 0{,}5d_\mathrm{i}}{2r - d_\mathrm{i} - s_\mathrm{vi}} + p$ (30) $\sigma_\mathrm{A,i} = \frac{p(d_\mathrm{i} + s_\mathrm{va})}{2s_\mathrm{va}} \cdot \frac{2r + 0{,}5d_\mathrm{i}}{2r + d_\mathrm{i} + s_\mathrm{va}} + p$ (32)	$\sigma_\mathrm{I,i} = \frac{p(d_\mathrm{a} - s_\mathrm{va})}{2s_\mathrm{vi}} \cdot \frac{2R - 0{,}5d_\mathrm{a} + 1{,}5s_\mathrm{vi} - 0{,}5s_\mathrm{va}}{2R - d_\mathrm{a} + s_\mathrm{vi}} + p$ (31) $\sigma_\mathrm{A,i} = \frac{p(d_\mathrm{a} - s_\mathrm{vi})}{2s_\mathrm{va}} \cdot \frac{2R + 0{,}5d_\mathrm{a} + 0{,}5s_\mathrm{vi} - 1{,}5s_\mathrm{va}}{2R + d_\mathrm{a} - s_\mathrm{va}} + p$ (33)

5.2.5 Accounting for out-of-roundness under pulsating fatigue loading

The fatigue strength of elbows with an out-of-roundness U in %

$$U = \frac{2\left(\hat{d}_{\mathrm{a}} - \overset{\vee}{d}_{\mathrm{a}}\right)}{\hat{d}_{\mathrm{a}} + \overset{\vee}{d}_{\mathrm{a}}} \cdot 100 \qquad (34)$$

will decrease in direct proportion to their degree of out-of-roundess as in Figure 2.

The wall thickness s_{v} as in Table 3 for load case III shall be determined using the characteristic strength value K multipled by the factor f_{u}.

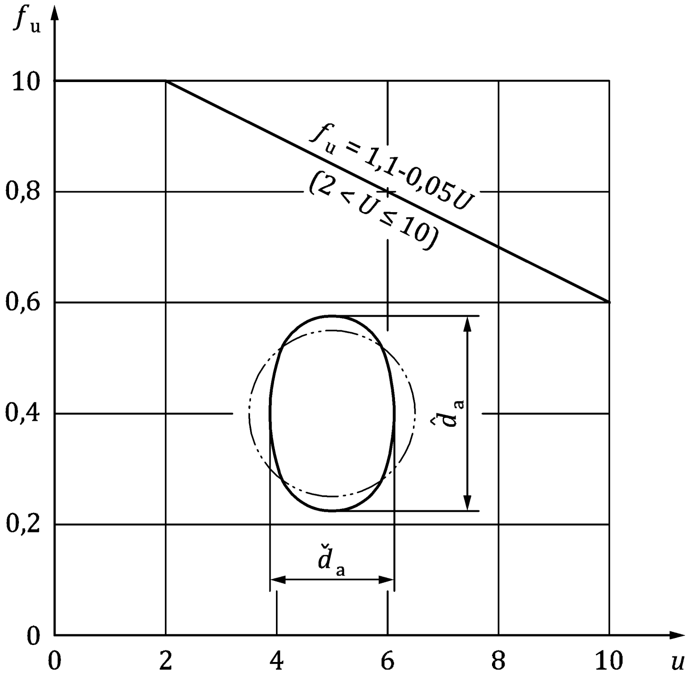

Figure 2 — Decreased fatigue strength of elbows with non-round cross-section

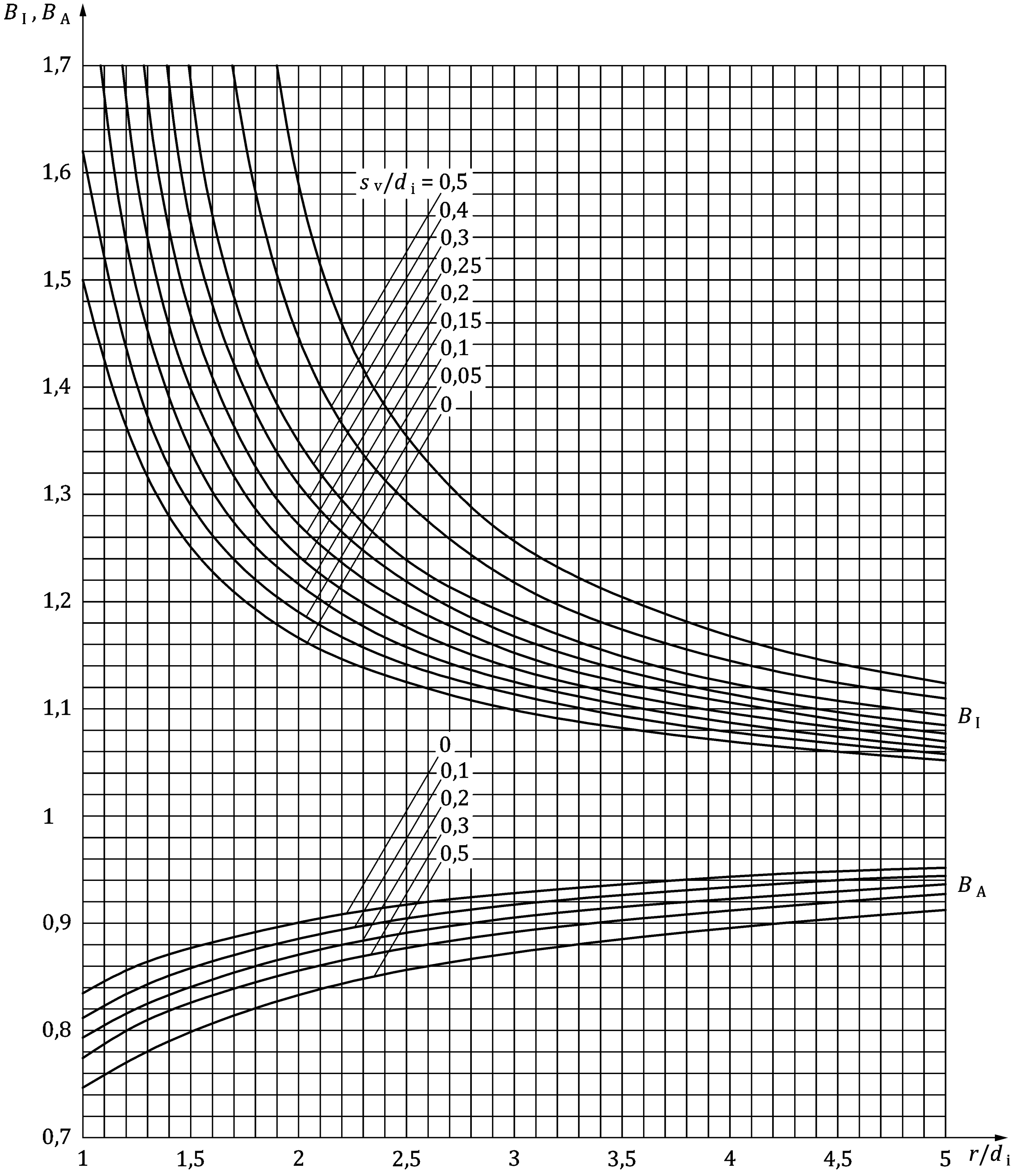

Figure 3 — B_I and B_A for a known inside diameter

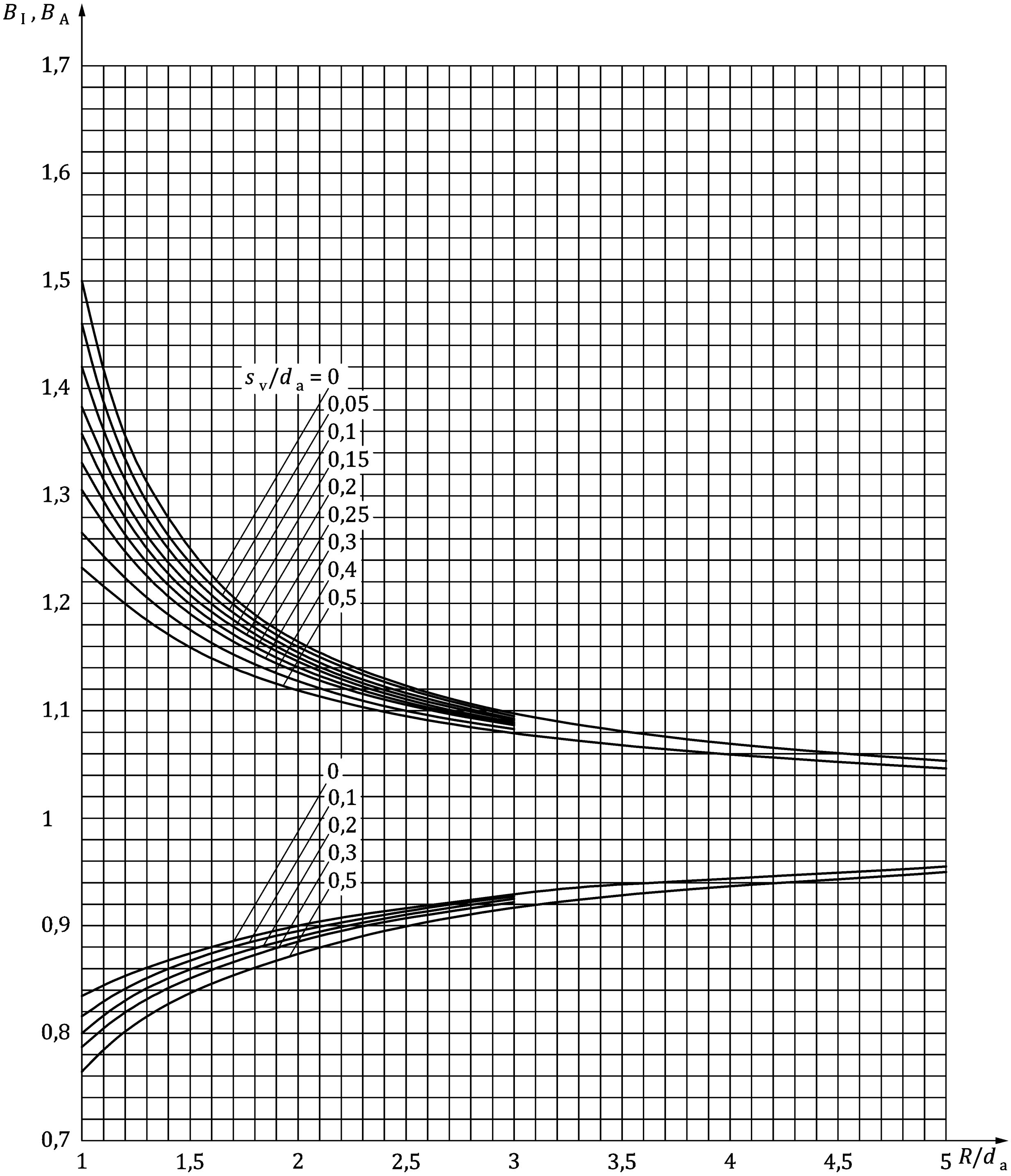

Figure 4 — B_I and B_A for a known outside diameter

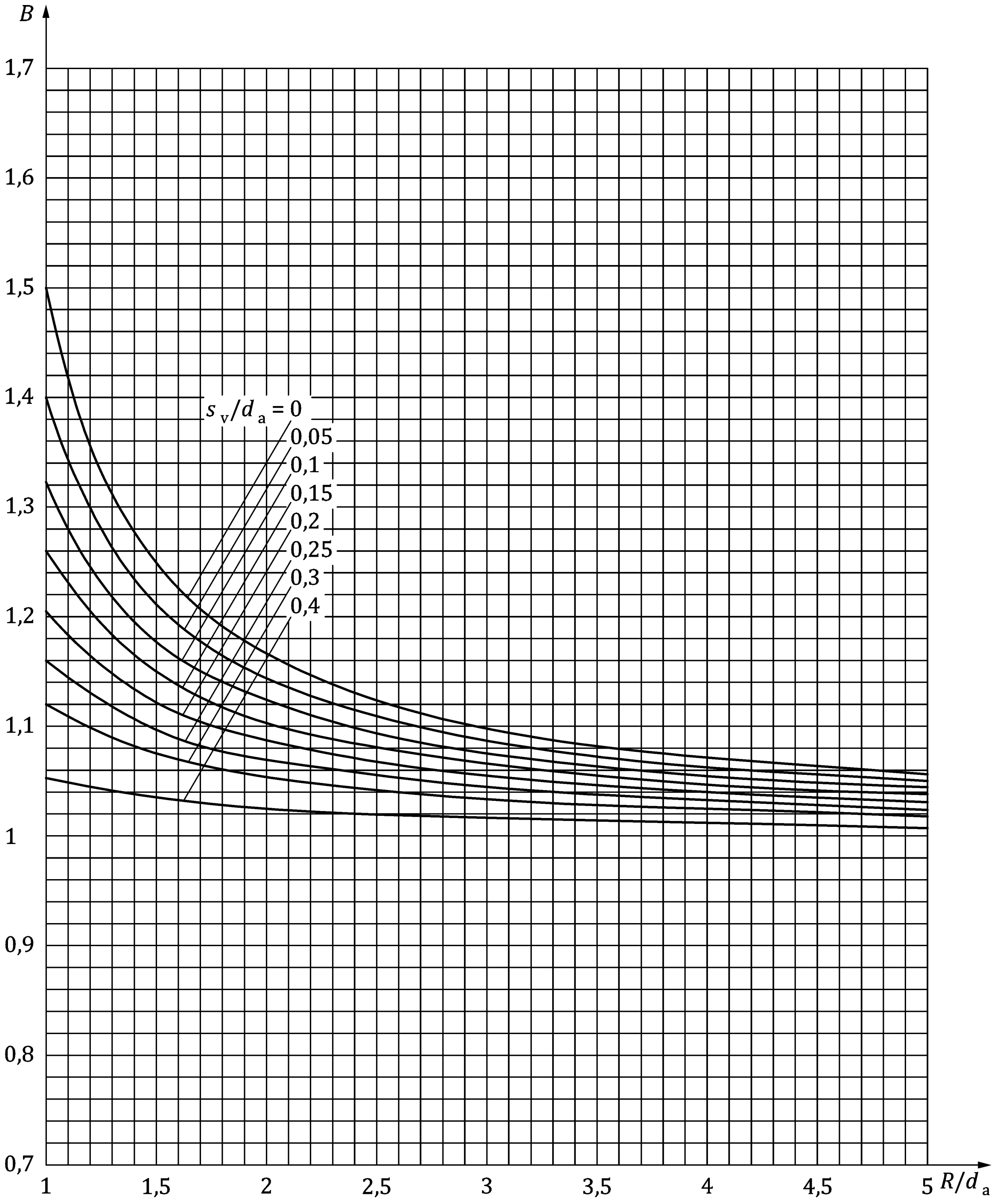

Figure 5 — Design factor *B* for elbows where the wall thickness $s_{vi} = s_{va}$ with outside diameter = nominal diameter

6 Information on design of pipes as in Table 3

6.1 General

The design analysis applies for pipes under internal pressure. Equations (1), (2) and (3) given in Table 3 are based on the maximum shear theory which only accounts for the maximum and minimum values of primary stresses, i.e. when the pipe is subjected to internal pressure the stresses σ_u and σ_r are normally taken into account. Provided the value of longitudinal stress σ_l as a result of internal pressure and additional stresses (see subclause 7.2) lies between the values of σ_u and σ_r , i.e. as long as

- for Equations (1) and (2): $$-p \leq \sigma_\mathrm{l} \leq \frac{p \cdot d_\mathrm{i}}{2s}$$
- for Equation (3): $$-p \leq \sigma_\mathrm{l} \leq \frac{p \cdot (d_\mathrm{i} + s)}{2s}$$

apply, the result of the analysis will not be affected.

Where the stresses exceed the above values, subclause 7.2 shall be taken into account.

6.2 Design pressure

The design pressure, p, is understood to be the internal pressure to which a pipe run is subjected, account being taken of all service conditions involved.

The design pressure p shall be taken as the greater of the values described under 1) and 2) below.

1) The maximum pressure at the safety device, plus the pressure resulting from the difference in height between this device and the lowest point of the pipework.

2) The following components of peak pressure $\hat{p}$ (maximum possible inside pressure) under expected service conditions (including increases in pressure) as a result of difference in height, loss in pressure and dynamic events (e.g. pressure surges), are given as:

   $p = 1{,}00\,\hat{p}$, when the duration of peak pressure exceeds 10 % of the intended total operating time.

   $p = 0{,}83\,\hat{p}$, when the duration of peak pressure does not exceed 1 % of the intended total operating time.

   Intermediate values shall be obtained by linear interpolation.

   The reduced peak pressures in 2) resulting from pressure surges shall only be allowed for in the case of predominantly static loading (load case I). In the case of dynamic loading (load case III) and when limiting the dynamic loading as in 6.3, the actual peak pressures as a result of pressure surges shall be used.

   Dynamic pressure changes (pressure surges) shall be given due consideration especially where fluids are conveyed.

6.3 Maximum permissible stress

6.3.1 General

The maximum permissible stress is $\sigma_\mathrm{zul} = K/S = Y \cdot K$ (see Table 6 and Table 7). The use of $Y \cdot K$ has been taken from international codes of practice for pipe design. The factor Y represents the degree of utilization which can be assigned to the characteristic strength value K under the given loading conditions. Values for the safety factor S and the degree of utilization Y are given in Table 3.

For dynamic loading, design for predominantly static loading (load case I) is sufficient when, during service, the number of load cycles determined for different tensile strengths in Table 6 and Table 7 and with the safety factor $S_\mathrm{L} = 10$ are not exceeded for the respective specified permissible loads σ_zul on which the calculation is based. When determining the safety factor, only those pressure changes having a large amplitude, such as those occurring during start-up and shut-down of a pipeline, shall be taken into account. Where higher numbers of cycles are expected, analysis shall also be based on load case III.

Table 6 — Maximum number of load cycles for seamless steel pipes with an outside diameter > 114,3 mm (determined with $S_{\mathrm{L}} = 10$ as in Figure 6)

σ_{zul} N/mm²	$\overset{\vee}{R}_{\mathrm{m}}$ N/mm²				
	350 to 450	500	550	600	650
160	100 000	> 100 000	> 100 000	> 100 000	> 100 000
180	50 000	90 000	> 100 000	> 100 000	> 100 000
200	30 000	50 000	80 000	> 100 000	> 100 000
250	—	17 000	26 000	40 000	56 000
300	—	—	—	16 000	22 000
350	—	—	—	—	10 000

Table 7 — Maximum number of load cycles for seamless steel pipes with an outside diameter ≤ 114,3 mm, quality characteristics as in DIN EN 10216-1 or comparable standards and codes of practice (determined with $S_{\mathrm{L}} = 10$ as in Figure 7)

σ_{zul} N/mm²	$\overset{\vee}{R}_{\mathrm{m}}$ N/mm²			
	350	400	450	500
160	> 100 000	> 100 000	> 100 000	> 100 000
180	70 000	> 100 000	> 100 000	> 100 000
200	—	—	> 100 000	> 100 000
250	—	—	—	70 000

6.3.2 Load case I, predominantly static loading rated up to 120 °C

The characteristic strength value K shall be deemed to be the specified minimum yield strength at 20 °C. However, in the case of fine grain steel pipes in accordance with DIN EN 10216-3 and of austenitic steel pipes used at operating temperatures exceeding 50 °C, K shall be the yield strength at the relevant operating temperature.

Where the operating temperature is below 20 °C, K shall be the yield strength at 20 °C.

However, in the case of special steels having a high ratio of minimum yield strength to tensile strength, the following maximum values of K shall be applied:

- $0{,}7\overset{\vee}{R}_{\mathrm{m}}$ in the case of non-tempered steel;
- $0{,}8\overset{\vee}{R}_{\mathrm{m}}$ in the case of tempered steel and of microalloyed, controlled rolled steel with a low carbon equivalent.

It may be permitted to deviate from these limit values where these materials have been proven in use, or where written proof of their suitability has been provided.

"Proven in use" shall be demonstrated on pipes or piping made of the appropriate steel grades (for the intended application) with $\check{R}_{\mathrm{p}\,0,2}/\check{R}_{\mathrm{m}} > 0{,}80$ (or $> 0{,}7\check{R}_{\mathrm{m}}$)[3]. Such pipes shall have both a theoretical and an actual utilization in a range of $K > 0{,}8\check{R}_{\mathrm{m}}$ (or $> 0{,}7\check{R}_{\mathrm{m}}$) under the intended service conditions.

In the case of pipes made from "new" steels or of pipes which cannot be sufficiently demonstrated to be proven in use, other proof of suitability shall be provided which indicates that they have a characteristic strength of $K > 0{,}8\check{R}_{\mathrm{m}}$ (or $> 0{,}7\check{R}_{\mathrm{m}}$).

The steel used shall be sufficiently ductile; the lower limit for ductility is an elongation after rupture value of $A = 14\,\%\ \left(L_{\mathrm{o}} = 5{,}65 \cdot \sqrt{S_{\mathrm{o}}}\right)$ as determined on longitudinal test pieces at 20 °C.

In the case of austenitic steel with a ratio of 0,2 % proof strength to tensile strength of $\check{R}_{\mathrm{p}\,0,2}/\check{R}_{\mathrm{m}} \leq 0{,}5$ at 20 °C, the pipes may be designed for a 1% yield strength $\check{R}_{\mathrm{p}\,1,0}$.

The safety factors given in Table 3 are minimum values. They shall be determined as a function of the elongation after rupture of the material as determined on longitudinal test pieces[4] at 20 °C.

Intermediate values may be obtained by linear interpolation, or, where the strain is less than 15 %, they may be extrapolated.

Pipes which have not undergone acceptance inspection shall only be made from unalloyed steel with a minimum tensile strength up to 550 $\mathrm{N/mm}^2$ or from austenitic steel with an elongation after rupture of $A \geq 40\,\%\left(L_{\mathrm{o}} = 5{,}65 \cdot \sqrt{S_{\mathrm{o}}}\right)$.

6.3.3 Load case III, dynamic loading up to 120 °C

6.3.3.1 General

In the case of pipes subjected to dynamic loading, analysis as for load case I shall be carried out, along with an analysis for fatigue failure taking into account the number of cycles n or for fatigue failure at constant stress amplitude. The larger design wall thickness obtained is to be used in the analysis.

a) Analysis for unallowed deformation

   The analysis shall be carried out for load case I, as in 6.3.2.

b) Test for fatigue failure at a specified number of cycles or fatigue failure at constant stress amplitude

   Depending on the frequency and amplitude of the pressure fluctuations occurring in a pipeline section (number of load cycles), the test for fatigue failure at a specified number of cycles or analysis for fatigue failure at constant stress amplitude shall be carried out.

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[3] Instead of $\check{R}_{\mathrm{p}\,0,2}$ also $\check{R}_{\mathrm{eH}}$ or $\check{R}_{\mathrm{t}\,0,5}$

[4] Where the relevant material specifications express the elongation after rupture as determined on transverse test pieces, the values to be used to determine the factors of safety can be increased by two units.

Limit curves for the fatigue strength or fatigue strength at constant stress amplitude of seamless steel pipes are based on internal pressure fatigue tests with a constant stress amplitude and are given in Figure 6 and Figure 7.

In these Wöhler curves, the influence of the surface, the shape and the material is already included, so that these influencing variables do not have to be taken into special consideration again.

For seamless pipes, the fatigue strength values in Figure 6 apply. For seamless tubes with an outside diameter $d_{\mathrm{a}} \leq 114{,}3$ mm with particularly high quality characteristics as in DIN EN 10216-1 or comparable delivery conditions, the more stringent fatigue strength values in Figure 7 may be used.

Seamless pipes can be manufactured in different ways. A basic distinction is made between hot-rolled and cold-drawn pipes, which have different properties in terms of material characteristics and surface condition. This also results in different characteristics in terms of resistance to internal pressure. Figure 6 and Figure 7 show typical fatigue strengths of seamless pipes. In hydraulics, the proportion of cold-drawn seamless pipes has increased as compared to hot-rolled pipes. Seamless cold-drawn pipes for precision applications enable higher fatigue strengths due to the manufacturing process.

For steel pipes for precision applications made of E235+N (as in DIN EN 10305-4), a fatigue strength at constant stress amplitude of $\sigma_{\mathrm{Sch/D}} = 225\ \mathrm{N/mm^2}$ may be used in the analysis.

Fatigue strength does not increase proportionally with tensile strength. Higher fatigue strength values of precision steel tubes made of E355+N (as in DIN EN 10305-4) as compared to those of E235+N are currently being investigated.

The information generally refers to straight pipes with form deviations lying within the permissible tolerances.

It should also be noted that the fatigue strength drops considerably if the inner surface of the pipes is heavily corroded.

Service life considerations from other influencing variables, e.g. surface damage, should likewise be noted.

6.3.3.2 Cycles of constant stress amplitude

Analysis shall be carried out using Equation (3) for fatigue failure for a specified number of cycles. The permissible stress $\tilde{\sigma}_{\mathrm{zul}}$ of the pipes against fatigue failure shall be taken from Figure 1 and Figure 2 for the number of cycles to failure $n_{\mathrm{B}} = S_{\mathrm{L}} \cdot n$. Here n means the number of load cycles to be expected in the course of the entire intended operating time, while the safety factor for load cycles to failure is represented by S_{L}.

If operating load collectives are known, a safety factor of $S_{\mathrm{L}} = 5$ is sufficient. A higher safety factor is recommended where special corrosion conditions or other surface defects are to be expected.

For the purpose of analysis for fatigue failure at constant amplitude, the permissible stress is

$$\tilde{\sigma}_{\mathrm{zul}} = \frac{\overset{\vee}{\sigma}_{\mathrm{Sch/D}}}{S} \qquad (35)$$

The safety factor shall be $S = 1{,}5$.

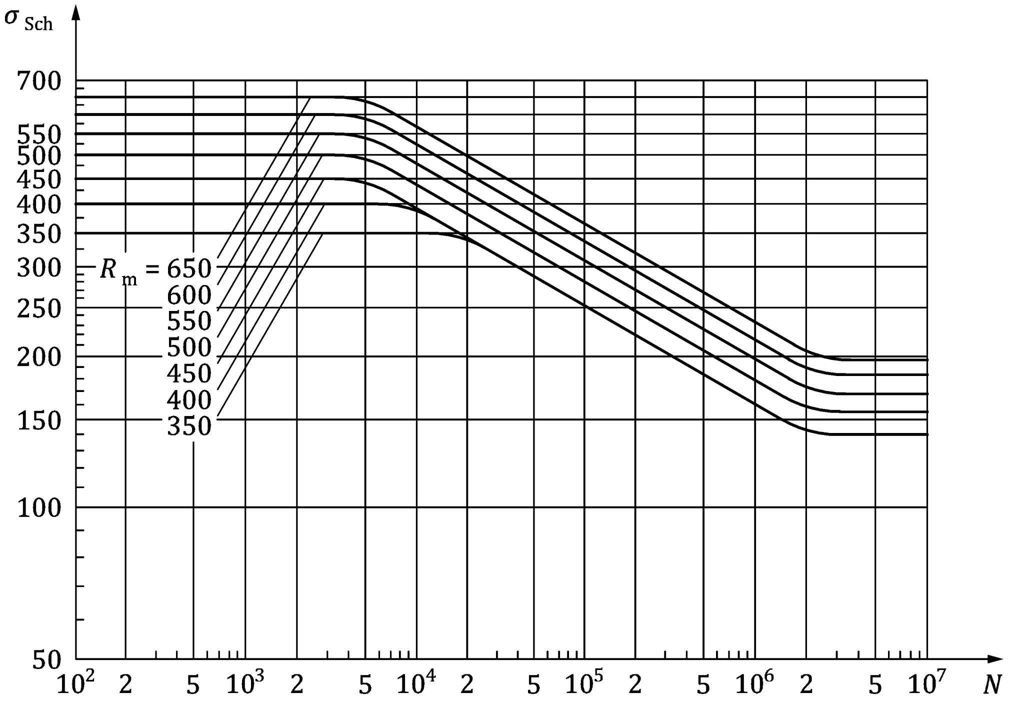

Figure 6 — Fatigue strength of seamless steel pipes with an outside diameter $d_a > 114{,}3$ mm

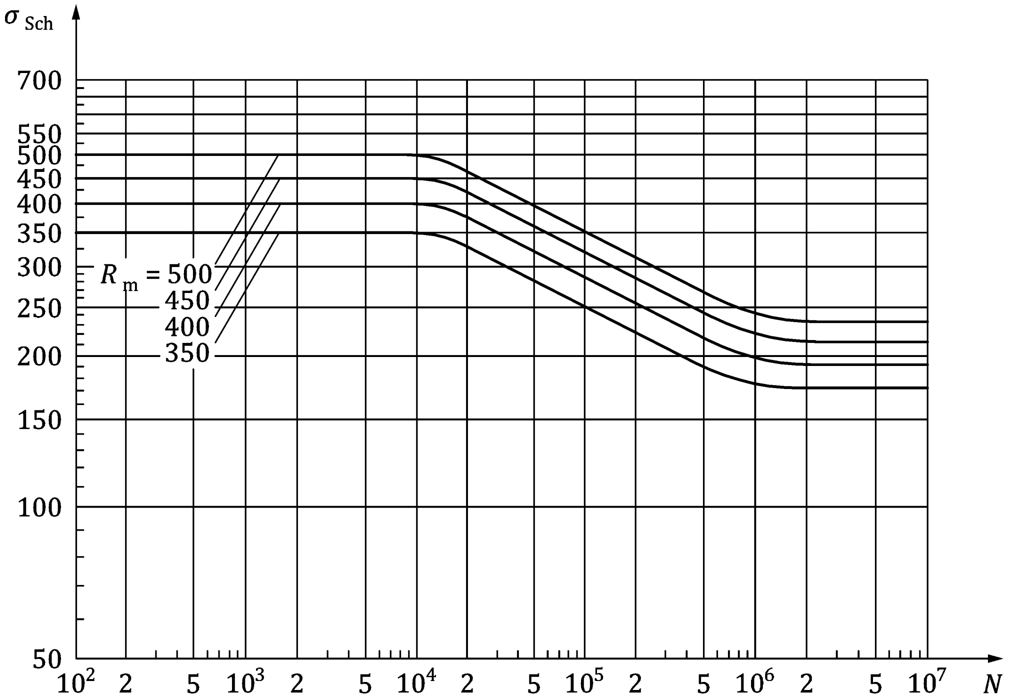

Figure 7 — Fatigue strength of seamless steel pipes with an outside diameter $d_a \leq 114{,}3$ mm**, quality characteristics as in DIN EN 10216-1 or comparable standards and codes of practice**

6.3.3.3 Cycles of varying stress amplitude

Where pipes are subjected to fluctuating internal pressures, the wall thickness s_v cannot be determined by a direct method. The investigation will then extend to a review of the damage likely to be suffered in the course of operation.

This can be carried out on the basis of the linear damage accumulation theory (Miner's rule). To this end, the most unfavourable combination of pressures shall be used for the various amplitudes involved,

$$\Delta p_\mathrm{i} = \hat{p}_\mathrm{i} - \overset{\vee}{p}_\mathrm{i} \tag{36}$$

which are determined from the stress amplitudes obtained with Equation (3)

$$\sigma_\mathrm{Schi} = 0{,}5 \cdot \Delta p_\mathrm{i} \cdot (1 + d_\mathrm{a}/s_\mathrm{v}) \tag{37}$$

taking the associated N_i from the relevant Figure 6 or Figure 7.

Stress amplitudes with a mean stress greater than $\sigma_\mathrm{M} \geq \frac{\Delta\sigma}{2}$ shall be corrected as follows:

$$\sigma_\mathrm{Schi} = \frac{2{R_m}^2}{\Delta\sigma}\left[\sqrt{\left(1-\left(\frac{\sigma_M}{R_m}\right)^2\right)^2 + \left(\frac{\Delta\sigma}{R_m}\right)^2} + \left(\frac{\sigma_M}{R_m}\right)^2 - 1\right] \tag{38}$$

With the given operating load cycles n_i, the following condition is then given for the damage *D:*

$$D = \sum_{i=1}^{m} \frac{n_\mathrm{i}}{N_\mathrm{i}} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \ \ldots\ + \frac{n_\mathrm{m}}{N_\mathrm{m}} \leq \frac{1}{S_\mathrm{L}} \ \text{mit}\, S_\mathrm{L} \geq 5 \tag{39}$$

If no operating load collectives are known, but only information on the pressure changes to be expected during start-up and shut-down is available, a load cycle safety factor $S_\mathrm{L} \geq 10$ shall be expected.

6.4 Design temperature

The design temperature is considered to be the pipe wall temperature that is used to determine characteristic strength values.

In the case of pipes that will not be heated, the design temperature shall be the highest temperature that the medium conveyed can be expected to reach under any given service conditions.

Where determination of wall thickness is based on values of creep rupture strength, the design temperature shall be 5 K (measurement tolerance) higher than the temperature of the medium conveyed.

NOTE Information regarding design temperatures for heated pipes is given in AD 2000-Merkblatt B 0.

6.5 Accounting for pressure surges

Dynamic changes in pressure ("pressure surges", for short) shall be added to the normal, static service pressure. In the case of pipework designed to account for creep rupture strength at elevated temperatures, increases in pressure need only be accounted for when verifying their elevated temperature yield strength.

Pressure surges occur when the flow rate of the medium conveyed changes, e. g. when stop valves or control valves are opened or closed, or when pumps, turbines, compressors, etc. are turned on or off.

Water hammers are the result of a negative pressure surge and occur after the water column has been broken off due to negative pressure by the subsequent, undamped reappearance of the returning water column on the shut-off device.

The most significant factors which affect the severity of a pressure surge Δp are the length of the relevant pipe run, l, the closing or actuating time, T_S, of the control valve, the flow rate, w , of the medium conveyed, and the propagation velocity, a, of the pressure wave in the medium conveyed. Disregarding the frictional influences in the fluid, a sudden change in the flow rate

$$\Delta w = w_1 - w_2$$

is the maximum change in pressure:

$$\Delta p = \frac{\rho \cdot a \cdot \Delta w}{10^6} \tag{40}$$

The maximum pressure surge (Joukowsky surge) is calculated according to Equation (40) if the flow rate is reduced suddenly from $w_1$to $w_2 = 0$, i.e. in a very short closing time

$$T_\mathrm{s}\left(T_\mathrm{s} < T_\mathrm{R}\ \text{with response time}\ T_\mathrm{R} = 2\frac{l}{a}\right)$$

In the case of control valves with a linear change in flow rate, a noticeable reduction of the pressure surge can be achieved by extending the closing time to several reflection times with

$$\Delta p = \frac{\rho \cdot a \cdot \Delta w}{10^6} \cdot \frac{T_\mathrm{R}}{T_\mathrm{S}} \tag{41}$$

In the case of hydraulic, relatively thick-walled pipes conveying water and for low-viscosity oil, an approximate mean value of $a \approx 1\,300$ m/s applies.

The above equations can only be used for approximate calculation of the pressure surge. Therefore, in the case of piping likely to be subjected to pressure surges, which includes piping conveying highly compressed gases, a more accurate analysis is recommended in order to account for as many influencing factors as possible and to determine whether and which protective (e.g. constructive) measures are necessary.

6.6 Allowance c

6.6.1 General

This allowance comprises the individual allowances for permissible wall thickness undersize c_1 and for corrosion and wear c_2.

6.6.2 Allowance c_1 to account for permissible wall thickness undersize

For all three load cases the permissible wall thickness undersize in the production of seamless pipes is to be added as a value c_1 to the design wall thickness s_v. The value c_1 or c_1' is specified in the technical delivery conditions for seamless pipes. If the permissible wall thickness undersize c_1' is expressed in %, then the absolute allowance c_1 in mm is calculated as follows:

$$c_1 = (s_\mathrm{v} + c_2)\ \frac{c_1'}{100 - c_1'} \tag{42}$$

When designing pipes within the scope of this document, only those wall thickness undersizes that are permissible over the entire length of the pipe shall be taken into account, in accordance with the technical delivery conditions. Any limited undersize beyond this, which only applies to a small range of lengths and which is also specified in the technical delivery conditions, need not be taken into account when calculating the allowance c_1.

6.6.3 Allowance c_2 to account for corrosion and wear

The factor c_2 is intended to account for a possible reduction in wall thickness due to corrosion and/or wear; it is to be specified as a function of the medium conveyed and the environment in which the piping is laid. Such an allowance c_2 is not intended to account for a reduction in fatigue strength due to corrosion.

In the case of ferritic steels, 1 mm is generally deemed to be a sufficient value for c_2 . In the case of austenitic steels, allowance for corrosion generally need not be made.

The allowance can also be dispensed with in cases where suitable measures have been taken to prevent corrosion, or where wear is not likely. The influence of stress corrosion cracking or similar phenomena on the material shall be given special consideration and cannot be covered by an allowance c_2.

6.7 Test pressure for a single pipe

The level of the test pressure for the internal pressure test carried out in the manufacturer's works on straight pipes is generally specified in the technical delivery conditions or can be agreed between the customer and manufacturer.

In order to avoid exceeding the yield strength at the inner fibre of the pipe, using the shape change energy hypothesis, the test pressure shall not exceed

$$p' = B_\mathrm{p} \cdot Y' \cdot \overset{\vee}{R}_\mathrm{eH} \frac{2 \cdot (s - c_1)}{d_\mathrm{a}} \qquad (43)$$

The factor B_p, which takes into account the longitudinal relief occurring during testing in the press and the pressure acting on the pipe ends to maintain the seal is for pipes

$$\text{where } s/d_\mathrm{a} \leq 0{,}1 \qquad B_\mathrm{p} = 0{,}96 \qquad (44)$$

$$\text{where } s/d_\mathrm{a} > 0{,}1 \qquad B_\mathrm{p} = 1{,}02 - 0{,}6\, s/d_\mathrm{a}$$

The degree of utilization of the yield strength $\overset{\vee}{R}_\mathrm{eH}$ or $\overset{\vee}{R}_\mathrm{p\,0,2}$ is generally $Y' \leq 0{,}95$; this accounts for fluctuations that occur as the upper yield strength is approached, as well as the permanent strain on the pipe that occurs at 0,2 % proof strength.

If a higher test pressure than that according to Equation (43) is agreed between the customer and the manufacturer by choosing Y' up to 1,0, a one-sided flow at the point of lowest wall thickness and an increase in the diameter tolerance field of the individual pipe is to be expected.

7 Design principles for pipes

7.1 General

In general, the wall thickness design to take account of predominantly static loading from internal pressure according to load case I is sufficient, as can be seen in Table 6 and Table 7. If the limit load cycles specified there are exceeded, such pipes shall be designed or inspected in accordance with load case III. Any additional stresses that may occur, including alternating additional stresses, shall also be taken into account.

In relation to the total alternating stress $\tilde{\sigma}_\mathrm{v}$ (see 7.4.4), at least a load cycle safety factor $S_\mathrm{L} = 5$ of the fatigue strength under consideration or 1,1 times the safety factor to take account of fatigue strength at constant stress amplitude should be required.

7.2 Additional stresses

7.2.1 General

The most important additional stresses on pipes in pipelines result from the criteria listed in 7.2.2 to 7.2.6.

7.2.2 Bending moments from loading as a result of the self-weight of the piping (including coating, lining, insulation, and medium conveyed), wind and snow loads, fitted elements, etc.

In the case of above-ground pipework, bending moments from loads along the pipe run result in axial stresses which shall be accounted for in the general analysis. The same applies to stresses at pipe supports.

7.2.3 Bending moments from an elastic curvature of the pipe axis during installation

The stress in longitudinal direction resulting from an elastic curvature of the axis with radius r is

$$\sigma_\mathrm{l} = \pm \frac{E \cdot d_\mathrm{a}}{2r} \tag{45}$$

7.2.4 Forces and moments due to obstructed thermal expansion of the piping and the resultant longitudinal stresses

Forces and moments due to obstructed thermal expansion result in longitudinal stresses in the case of straight pipes laid in one plane and, in the case of pipework arranged in other configurations, in torsional stresses.

Increasing the wall thickness to prevent obstructed thermal expansion does not improve the construction, but rather increases the constraints involved.

The stresses that result from obstructed thermal expansion can be favourably influenced in above-ground pipelines by the selection of appropriate types of pipe support and fixing points and by the provision of expansion compensators. The forces that act on the piping in service can also be reduced by prestressing the pipeline during assembly.

7.2.5 Non-uniform temperature distribution across the pipe wall

The thermal stresses in the pipe wall, in both the circumferential and longitudinal directions, that result from a difference in temperature, $\Delta\vartheta$, between the inside and outside of the pipe wall, can be approximated using the following equation for $u = d_\mathrm{a}/d_\mathrm{i} = 1{,}2$

$$\sigma_\mathrm{uw} = \sigma_\mathrm{lw} \approx \pm \frac{1}{2} \cdot \frac{E}{1 - v} \cdot \alpha_\mathrm{l} \cdot \Delta\vartheta \tag{46}$$

where tensile stresses occur on the colder side. This equation can be used for more precise analyses, particularly for thick-walled pipes.

The thermal stresses σ_w that occur in unalloyed and low-alloy steel pipes at a given rate of temperature change w_ϑ when the valves are opened or closed may be approximated using the following equation:

$$\sigma_\mathrm{uw} = \sigma_\mathrm{lw} \approx \pm \frac{2}{10^{10}} \cdot E \cdot w_\vartheta \cdot s^2 \tag{47}$$

or, in the case of austenitic steel pipes:

$$\sigma_\mathrm{uw} = \sigma_\mathrm{lw} \approx \pm \frac{5}{10^{10}} \cdot E \cdot w_\vartheta \cdot s^2 \tag{48}$$

Considerable thermal stresses can result from sudden warming or cooling (thermal shock).

7.2.6 Circumferential bending stresses as a result of out-of-roundness

If non-round pipes are placed under internal pressure, bending stresses in the circumferential direction occur in the wall, as the internal overpressure tries to force the non-round pipe cross-section into a circular shape. Assuming the pipe has an approximately elliptical shape, with a given deviation of the radius from the circular form, Δr, the maximum circumferential bending stresses will occur in the vertices of the ellipses. Their value is calculated as

$$\hat{\sigma}_{\mathrm{u,b}} = \pm \frac{p \cdot d_{\mathrm{i}}}{2 \cdot s_{\mathrm{v}}} \cdot \frac{6 \Delta r}{s_{\mathrm{v}}} \cdot \frac{1}{B_{\mathrm{u}}} \tag{49}$$

with the design factor,

$$B_{\mathrm{u}} = 1 + \frac{1 - v^2}{2} \cdot \frac{p}{E} \cdot \left(\frac{d_{\mathrm{a}} - s_{\mathrm{v}}}{s_{\mathrm{v}}} \right)^3 \tag{50}$$

In general, pipes subjected to predominantly static internal loading need not be analyzed for stresses as a result of out-of-roundness.

For pipes subjected to internal pressure fatigue loading, the strength values specified in Figure 6 and Figure 7 account for permissible out-of-roundness as covered in the relevant standards (e.g. DIN EN 10216-1 and DIN EN 10305-4). Where the out-of-roundness of pipes exceeds the values specified therein, the actual stresses as a result of internal pressure and any additional stresses shall be added to the bending stress as determined in accordance with Equation (49). Reference values shall be taken from Figure 6 and Figure 7, and the safety factors from Table 3 for load case III.

7.3 External pressure

Pipes subjected to external pressure or to an internal vacuum shall be analyzed for their resistance to buckling. Where external pressure and internal vacuum are concurrent, their values shall be added.

The critical external pressure which causes a circular pipe to buckle is

$$p_{\mathrm{k}} = \frac{2E}{1 - v^2} \cdot \left(\frac{s}{d_{\mathrm{a}}} \right)^3 \tag{51}$$

Any deviations of form will considerably increase the tendency of pipes to buckle. With regard to possible out-of-roundness of the pipes, a safety factor of at least $S_{\mathrm{K}} = 3$ to account for the existing external pressure shall generally be required.

If only vacuum occurs, or if the external pressure plus any vacuum does not exceed 0,1 $\mathrm{N/mm^2}$ (= 1 bar), then analysis for resistance to buckling is only necessary for pipes with a wall thickness-diameter ratio of $s/d_{\mathrm{a}} < 0{,}01$.

7.4 Classification and assessment of stresses

7.4.1 General

The stresses can be divided up according to their cause and effect. They may be evaluated according to the stress categorization method or with the aid of the component plastic theory. Both methods provide approximately the same safety statements.

7.4.2 Stress categories

A distinction is made between the following stress categories, as a function of the cause and effect of the particular type of stress on the component:

- primary stresses;
- secondary stresses;
- peak stresses.

Because of their different safety relevance, they may be approved at different levels.

This classification system can be used for both static and fatigue loading conditions and assumes an ideal elastic behaviour of the material, but is not suitable for stability analysis.

7.4.2.1 Primary stresses

Primary stresses are considered to be uniformly distributed stresses or stress components which contribute to the establishment of equilibrium between the pipe and the external loads involved. Such loads continue to act even after permanent deformation of the pipe (i. e. they do not diminish). This includes the following loads, for example:

- internal and external pressure;
- self-weight, and snow and wind loads in the case of pipes laid outdoors.

7.4.2.2 Secondary stresses

Secondary stresses are uniformly distributed stresses or stress components which occur as a result of obstructed thermal expansion or geometrical imperfections when subjected to external loading. This includes, for example stresses due to

- obstructed thermal expansion,
- non-uniform temperature distribution across the pipe wall,
- differing expansion behaviour in zones of transition to other components, particularly to those of other geometric shapes (e. g. pipes of different wall thickness, rings used, penetrations through floors, etc.),
- out-of-roundness in the case of internal pressure.

Where loading is excessive, secondary stresses can be diminished where the pipework is able to permanently deform. In other words, pipes subjected to predominantly static loading will not fail as a direct result of secondary stresses but, where deformation occurs frequently, they can lead to fatigue fracture.

7.4.2.3 Peak stresses

Peak stresses are not uniformly distributed and represent a combination of primary and secondary stresses which occur, briefly, at the same time. They cause localized strain, but not significant deformation of the pipework as a whole, and in combination with primary and secondary stresses are only relevant with regard to the fatigue behaviour of the component.

Peak stresses are, for example:

- notch effects;
- bearing stresses
- stresses resulting from thermal shock when the valves are opened or closed.

7.4.3 Plastic theory

When analyzing a component using the plastic theory, the component is considered in its entirety. In the case of components subjected to inhomogeneous loading, this theory accounts for the fact that, where localized hyperelastic loading occurs, the zones that had not previously been subjected to loading will have to accommodate more of the load. This leads to a more efficient use of the component. This method can only be applied for pipes subjected to predominantly static loading.

It may also be used for the assessment of branches, elbows and pipes subjected to localized loading.

7.4.4 Reference stresses

To assess a multi-axial stress pattern, the maximum shear theory or the deformability energy hypothesis can be used. Reference stresses are to be calculated as follows

a) according to the maximum shear theory

$$\sigma_{\mathrm{vSH}} = \sigma_{\mathrm{max}} - \sigma_{\mathrm{min}} \tag{52}$$

b) according to the deformability energy hypothesis

$$\sigma_{\mathrm{vGE}} = \frac{1}{\sqrt{2}} \cdot \sqrt{(\sigma_{\mathrm{u}} - \sigma_{\mathrm{l}})^2 + (\sigma_{\mathrm{l}} - \sigma_{\mathrm{r}})^2 + (\sigma_{\mathrm{r}} - \sigma_{\mathrm{u}})^2} \tag{53}$$

Both equations assume that the stresses concerned are primary stresses.

Depending on the type of stress involved, either the values of the stresses themselves or of the stress amplitudes shall be used in the above equations.

The formulae in Table 3 are based on the maximum shear theory, see also Clause 6.

NOTE Equations (51) and (52) apply regardless of whether the stresses are categorized according to the classification system or assessed according to plastic theory.

7.4.5 Limitation of stresses

The specification of permissible stresses depends on the analysis method used and the safety requirements with which the pipes are expected to comply. Information on this is found in AD 2000-Merkblatt S 2.

Bibliography

DIN 2445-1, *Seamless steel tubes for dynamic loads — Part 1: Hot finished tubes in fluid systems, 100 to 500 bar*

DIN 2445-2, *Seamless steel tubes for dynamic loads — Part 2: Steel tubes for precision application in fluid systems, 100 bar to 500 bar*

DIN EN 764-1, *Pressure equipment — Part 1: Vocabulary*

DIN EN 764-2, *Pressure equipment — Part 2: Quantities, symbols and units*

DIN EN 1333, *Flanges and their joints — Pipework components — Definition and selection of PN*

DIN EN 10216-2, *Seamless steel tubes for pressure purposes — Technical delivery conditions — Part 2: Non-alloy and alloy steel tubes with specified elevated temperature properties*

DIN EN 10216-4, *Seamless steel tubes for pressure purposes — Technical delivery conditions — Part 4: Non-alloy and alloy steel tubes with specified low temperature properties*

DIN EN ISO 3183, *Petroleum and natural gas industries — Steel pipe for pipeline transportation systems*

DIN ISO 10763, *Hydraulic fluid power — Plain-end, seamless and welded precision steel tubes — Dimensions and nominal working pressures*

AD 2000-Merkblatt B 0[5], *Design of pressure vessels*

AD 2000-Merkblatt S 2[5], *Analysis for cyclic loading*

AD 2000-Merkblatt W 10[5], *Materials for low temperatures — Ferrous materials*

Directive 2006/42/EC of the European Parliament and the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC[6]

Directive 2014/68/EU of the European Parliament and of the Council of 15 May 2014 on the harmonisation of the laws of the Member States concerning the making available on the market of pressure equipment[6]

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[5] Obtainable from: Beuth Verlag GmbH, 10277 Berlin

[6] Available at: https://eur-lex.europa.eu/