5

Wall thickness calculation for ductile iron pipes

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5 Wall thickness calculation for ductile iron pipes

When laying underground pipelines consisting of ductile iron pipes to standard EN 545 [5.1], for the most part the pipes are assembled using push-in joints as standardised in DIN 28603 [5.2]. For calculating the wall thickness of ductile iron pipes, a distinction is made between

- non-restrained flexible push-in joints and
- restrained flexible push-in joints.

5.1 Stresses in pressure pipelines

With a pressure pipeline consisting of pipes assembled with restrained joints, e.g. by welding, the internal pressure generates stresses in the pipe wall, which may be circumferential or tangential stresses σ_t and longitudinal or axial stresses σ_a, as shown in Fig. 5.1.

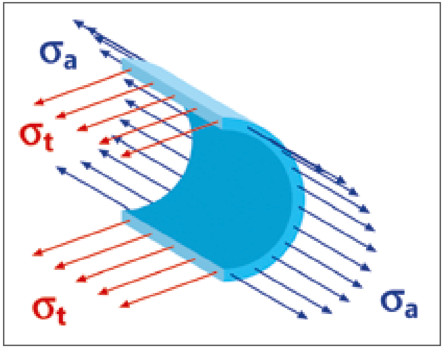

Fig. 5.1:
Stresses produced by internal pressure in a wall of pressure pipes assembled with restrained joints

The two types of stress are calculated as follows:

$$\sigma_t = \frac{p \cdot D}{2 \cdot e} \quad [\text{N/mm}^2] \qquad (5.1)$$

$$\sigma_a = \frac{p \cdot D}{4 \cdot e} \quad [\text{N/mm}^2] \qquad (5.2)$$

p	internal pressure [bar]
D	mean diameter $(D = (DE + Di) / 2 = DE - e)$ [mm]
DE	external diameter [mm]
Di	internal diameter [mm]
e	wall thickness [mm]
σ_t	tangential stress in the pressure pipe wall [N/mm²]
σ_a	axial stress in the pressure pipe wall [N/mm²]

Conversion factor:
1 bar corresponds to 0.1 N/mm²

5.2 Calculating the wall thickness of pipes with non-restrained flexible push-in joints

5.2.1 Calculating the wall thickness of pipes according to pressure classes (C-classes)

For calculating the pipe wall thickness of ductile iron pipes with non-restrained flexible push-in joints, the simple Barlow's formula is used in which the tangential stresses produced by internal pressure, the tensile strength of the pipe material, the thickness of the pipe wall and the diameter of the pipe correlate with each other.

Non-restrained flexible push-in joints do not transmit any axial forces. If the pressure of the medium produces axial forces on dead ends, branches, reducers or changes of direction, these must be transferred into the ground by appropriate means, such as concrete thrust blocks.

Over the last six decades, non-restrained flexible push-in joints have had a considerable influence in shaping the image of the cast iron pipe; they are inexpensive and simple to assemble. Non-restrained push-in joints do not transmit any axial forces, meaning that the stresses shown in Fig. 5.1 in the axial direction σ_a are equal zero. As can be seen in Fig. 5.2, the stresses in the wall of such a socket pipe only run in the circumferential direction as tangential stress σ_t.

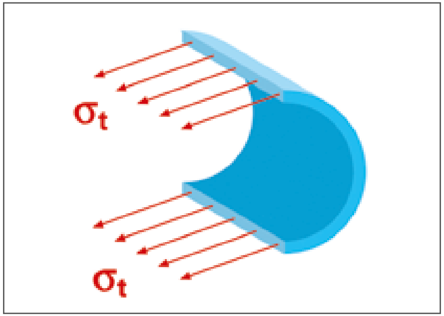

Fig. 5.2:
Tangential stress σ_t in the circumferential direction in a pipe with a non-restrained flexible push-in joint

In principle, they are calculated according to equation 5.1 (Barlow's formula):

$$\sigma_t = \frac{p \cdot D}{2 \cdot e} \qquad [\mathrm{N/mm^2}] \qquad (5.1)$$

σ_t tangential stress in the pressure pipe wall [N/mm²]
p internal pressure [bar]
D mean diameter (D = (DE + Di) / 2 = DE – e) [mm]
e wall thickness [mm]

This produces the following equation for internal pressure p:

$$p = \frac{2 \cdot E \cdot \sigma_t}{D} \qquad [\mathrm{N/mm^2}] \qquad (5.2)$$

Once the minimum pipe wall thickness and a safety factor have been introduced, we arrive at equation 5.3 incorporated in product standard EN 545 [5.2], with which the allowable operating pressure PFA is calculated for the component:

$$\mathrm{PFA} = \frac{20 \cdot e_{min} \cdot R_m}{D \cdot S_F} \qquad [\mathrm{bar}] \qquad (5.3)$$

Where:

$PFA = p =$ allowable operating pressure for the component

e_{min} = minimum pipe wall thickness

$R_m = \sigma_t$ = minimum tensile strength = 420 MPa

S_F = safety factor

Conversion factors:

1 N/mm² = 1 MPa = 10 bar

With a minimum tensile strength R_m = 420 MPa for ductile cast iron and the safety factor $S_F = 3$ we arrive at the following constant 5.4:

$$\frac{20 \cdot R_m}{S_F} = 2.800 \qquad [\mathrm{MPa}] \qquad (5.4)$$

The allowable operating pressure PFA for the component can be calculated with equation 5.5 from the external pipe wall diameter DE and pipe wall thickness e_{min} :

$$PFA = 2.800 \cdot \frac{e_{min}}{DE - e_{min}} \qquad [\mathrm{MPa}] \qquad (5.5)$$

Minimum wall thicknesses e_{min} for ductile iron pipes								
		Pressure class (C-classes) = PFA [bar]						
		20	25	30	40	50	64	100
DN	DE [mm]	e_{min} [mm]						
40	56				**3.0**	**3.5**	4.0	**4.7**
50	66				**3.0**	**3.5**	4.0	**4.7**
60	77				**3.0**	**3.5**	4.0	**4.7**
65	82				**3.0**	**3.5**	4.0	**4.7**
80	98				**3.0**	**3.5**	4.0	**4.7**
100	118				**3.0**	**3.5**	4.0	**4.7**
125	144				**3.0**	**3.5**	4.0	**5.0**
150	170				**3.0**	**3.5**	4.0	**5.9**
200	222				**3.1**	**3.9**	5.0	**7.7**
250	274				**3.9**	**4.8**	6.1	**9.5**
300	326				**4.6**	**5.7**	7.3	**11.2**
350	378			**4.7**	5.3	**6.6**	8.5	**13.0**
400	429			**4.8**	6.0	**7.5**	9.6	**14.8**
450	480			**5.1**	6.8	**8.4**	10.7	**16.6**
500	532			**5.6**	7.5	**9.3**	11.9	**18.3**
600	635			**6.7**	8.9	**11.1**	14.2	**21.9**
700	738		**6.8**	7.8	10.4	**13.0**	16.5	
800	842		**7.5**	8.9	11.9	**14.8**	18.8	
900	945		**8.4**	10.0	13.3	**16.6**		
1000	1048		**9.3**	11.1	14.8	**18.4**		
1100	1152	8.2	**10.2**	12.2	16.2	**20.2**		
1200	1255	8.9	**11.1**	13.3	17.7	**22.0**		
1400	1462	10.4	**12.9**	15.5				
1500	1565	11.1	**13.9**	16.6				
1600	1668	11.8	**14.8**	17.7				
1800	1875	13.3	**16.6**	19.9				
2000	2082	14.8	**18.4**	22.1				
Note: the figures in bold represent the standard range								

Table 5.1: Minimum wall thicknesses e_{min} for ductile iron pipes as per EN 545 [5.1] depending on nominal size DN and pressure class (C-class)

Using equation 5.5 it is possible to calculate the minimum wall thickness e_{min} for an allowable operating pressure PFA with a given nominal size:

$$e_{min} = \frac{DE \cdot PFA}{2.800 + PFA} \quad [mm] \qquad (5.6)$$

Table 5.1 shows the minimum wall thicknesses e_{min} according to EN 545 [5.1] for the seven pressure classes (C-classes) which are assigned to operating pressures PFA 20; 25; 30; 40; 50; 64 and 100. The lower limit for the minimum wall thicknesses has been reduced to e_{min} = 3,0 mm.

5.2.2 Calculating wall thicknesses according K-classes

Since the introduction of ductile cast iron around 60 years ago, the minimum wall thickness e_{min} has undergone a considerable evolution which is due to the impressive development and optimisation of centrifugal casting production technology. The primary beneficiaries of this are the small nominal sizes from DN 80 to DN 250 which account for an extremely high proportion in urban distribution networks.

When the first ductile iron pipes were produced in the middle of the nineteen fifties, safety standards were initially still based on the characteristics of thick-walled grey cast iron pipes. At the time, casting machines were still being manually controlled, meaning that the minimum wall thickness was only observed with large “allowances”. For a coherent representation of wall thicknesses over the entire range of nominal sizes, these were divided into K-classes which were in existence for more than four decades. Nominal wall thicknesses e were determined taking account of the permissible circumferential stresses in the pipe wall using the formula

$$e = 5 + 0.01 \cdot DN \quad [mm] \qquad (5.7)$$

in wall thickness class K 10. Wall thicknesses which deviated from this could be represented in their own K-classes

$$e = K \cdot (5 + 0.001 \cdot DN) \quad [mm] \qquad (5.8)$$

whereby the proportionality factor K was part of a series of whole numbers … 8, 9, 10, 11, 12 …

For drinking water supply, type K values were 10 to begin with, then later on 8 and 9. In order for wall thicknesses of the smaller nominal sizes to remain practically feasible at all, the lower limit for nominal wall thicknesses was reduced to e = 6 mm. The following determination applies to the minimum wall thickness e_{min} for measurement purposes:

$$e_{min} = e - \Delta e \quad [mm] \qquad (5.9)$$

Δe permissible dimensional deviation (minus tolerance)

The following applies for e > 6 mm:

$$\Delta e = -(1.3 + 0.001 \cdot \mathrm{DN})\ [\mathrm{mm}] \qquad (5.10)$$

The following applies for e ≤ 6 mm:

$$\Delta e = -1.3 \qquad [\mathrm{mm}] \qquad (5.11)$$

Hence the lowest minimum pipe wall thickness was 4.7 mm.

5.3 Development of minimum pipe wall thicknesses

The accurate production of smaller pipe wall thicknesses in the centrifugal casting process has matured due to improved machine control and continuous process optimisation in the six decades since the emergence of ductile iron pipes. So it was only logical that the cast iron pipe industry would continue the trend by adapting water supply components to the prevailing pressures – a development which manifested itself in EN 14801 [5.3]. Back in 2002, in the edition current at the time, EN 545 introduced pressure class C 40 in addition to the wall thickness classes (K-classes) still in existence.

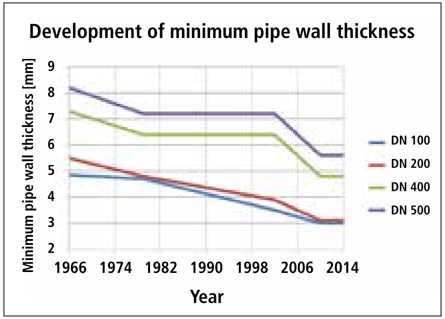

Fig. 5.3:
Development of minimum pipe wall thickness e_{min} from 1966 to 2014

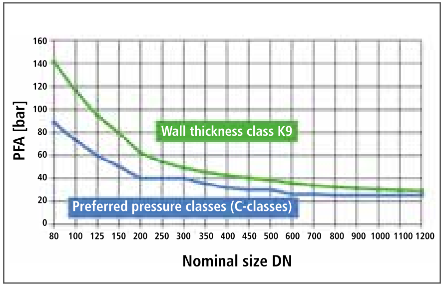

Fig. 5.4:
Comparison of wall thickness class K 9 with the preferred pressure classes (C-classes) as regards allowable operating pressure PFA

As from 2010, EN 545 [5.1] now only contains the pressure (C) classes.

The development of minimum pipe wall thicknesses over the last decades in Fig. 5.3 shows that, since the introduction of ductile iron pipes, in terms of production technology it has been possible to reduce minimum wall thicknesses by almost half.

5.4 Comparison of wall thickness classes (K-classes) and pressure classes (C-classes) for non-restrained flexible pipes

For non-restrained pipes up to nominal size DN 300, calculated according to internal pressure, the introduction of pressure classes (C-classes) has led to some very major changes as compared with the wall thickness classes (K-classes), as can be seen in the diagram alongside (Fig. 5.4). As from DN 400 the differences tend to be negligible.

Minimum wall thicknesses e_{min} for ductile iron pipes																		
DN	DE [mm]	Pressure classes (C-classes) = PFA							Wall thickness classes (K-classes)									
		20	25	30	40	50	64	100	7		8		9		10		11	
		e_{min} [mm]							e_{min} [mm]	PFA [bar]	e_{min} [mm]	PFA [bar]	e_{min} [mm]	PFA [bar]	e_{min} [mm]	PFA [bar]	e_{min} [mm]	PFA [bar]
40	56				3.0	3.5	4.0	4.7										
50	66				3.0	3.5	4.0	4.7										
60	77				3.0	3.5	4.0	4.7										
65	82				3.0	3.5	4.0	4.7										
80	98				3.0	3.5	4.0	4.7	4.7	141.1	4.7	141.1	4.7	141.1	4.7	141.1	5.0	150.5
100	118				3.0	3.5	4.0	4.7	4.7	116.2	4.7	116.2	4.7	116.2	4.7	116.2	5.2	129.1
125	144				3.0	3.5	4.0	5.0	4.7	94.5	4.7	94.5	4.7	94.5	4.8	97.1	5.5	110.1
150	170				3.0	3.5	4.0	5.9	4.7	79.6	4.7	79.6	4.7	79.6	5.1	85.7	5.7	97.1
200	222				3.1	3.9	5.0	7.7	4.7	60.6	4.7	60.6	4.8	61.9	5.5	71.1	6.2	80.4
250	274				3.9	4.8	6.1	9.5	4.7	48.9	4.7	48.9	5.2	54.2	6.0	62.2	6.7	70.2
300	326				4.6	5.7	7.3	11.2	4.7	41.0	4.8	41.8	5.6	48.9	6.4	56.1	7.2	63.2
350	378			4.7	5.3	6.6	8.5	13.0	4.7	34.9	5.2	38.7	6.0	45.2	6.9	51.7	7.7	58.2
400	429			4.8	6.0	7.5	9.6	14.8	4.7	31.0	5.5	36.4	6.4	42.4	7.3	48.5	8.2	54.6
450	480			5.1	6.8	8.4	10.7	16.6	4.9	28.9	5.9	34.5	6.8	40.2	7.8	46.0	8.7	51.7
500	532			5.6	7.5	9.3	11.9	18.3	5.2	27.6	6.2	33.0	7.2	38.4	8.2	43.8	9.2	49.3
600	635			6.7	8.9	11.1	14.2	21.9	5.8	25.8	6.9	30.8	8.0	35.7	9.1	40.7	10.2	45.7
700	738		6.8	7.8	10.4	13.0	16.5		6.4	24.5	7.6	29.1	8.8	33.8	10.0	38.5	11.2	43.1
800	842		7.5	8.9	11.9	14.8	18.8		7.0	23.5	8.3	27.9	9.6	32.3	10.9	36.7	12.2	41.2
900	945		8.4	10.0	13.3	16.6			7.6	22.7	9.0	26.9	10.4	31.2	11.8	35.4	13.2	39.7
1000	1048		9.3	11.1	14.8	18.4			8.2	22.1	9.7	26.2	11.2	30.2	12.7	34.3	14.2	38.5
1100	1152	8.2	10.2	12.2	16.2	20.2			8.8	21.6	10.4	25.5	12.0	29.5	13.6	33.5	15.2	37.4
1200	1255	8.9	11.1	13.3	17.7	22.0			9.4	21.1	11.1	25.0	12.8	28.9	14.5	32.7	16.2	36.6
1400	1462	10.4	12.9	15.5					10.6	20.4	12.5	24.1	14.4	27.9	16.3	31.6	18.2	35.3
1500	1565	11.1	13.9	16.6					11.2	20.2	13.2	23.8	15.2	27.5	17.2	31.1	19.2	34.8
1600	1668	11.8	14.8	17.7					11.8	19.9	13.9	23.5	16.0	27.1	18.1	30.7	20.2	34.3
1800	1875	13.3	16.6	19.9					13.0	19.5	15.3	23.0	17.6	26.5	19.9	30.0	22.2	33.5
2000	2082	14.8	18.4	22.1					14.2	19.2	16.7	22.6	19.2	26.1	21.7	29.5	24.2	32.9

Table 5.2: Comparison of pressure classes (C-classes according to EN 545:2011 [5.1] (left) with the wall thickness classes (K-classes) in EN 545:2007 [5.4] (right)

This effect is based solely on the fact that, with the introduction of pressure classes (C-classes), the limit value for minimum wall thickness has been reduced by roughly one third, from 4.7 mm to 3.0 mm. The equation applicable for calculating wall thicknesses (5.6) remains the same as before.

Table 5.2 illustrates the relationship between the previous K-classes and the new pressure classes (C-classes) for each nominal size. The wall thickness measured in millimetres represents the common comparison parameter for C-classes and for K-classes. The table shows the areas with similar wall thicknesses and the areas corresponding to pressure classes for the allowable operating pressure PFA in the same colours.

This table offers the possibility of comparing the earlier K-classes (wall thickness classes) with the new pressure classes (C-classes), because the actual minimum wall thickness e_{min} is the common reference parameter.

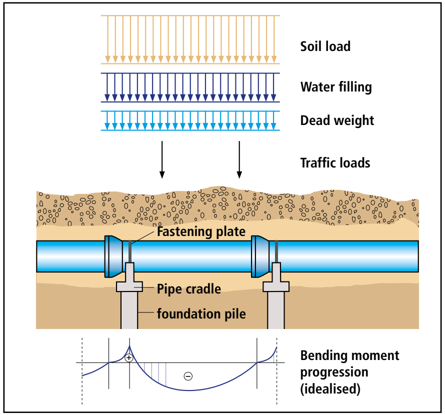

Fig. 5.5:
Bending moments for a buried pipeline on piles

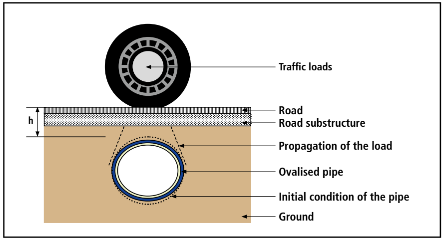

Fig. 5.6:
Ovalisation due to soil loads and traffic loads

5.5 The effect of longitudinal bending strength and ring stiffness on the calculation of pipe wall thickness dimensions

Classification according to pressure classes (C-classes) is only applicable for non-restrained systems in which only tangential stresses σ_t produced by internal pressure are decisive when it comes to calculating pipe wall thickness (Fig. 5.2).

However, such influencing factors should also be taken into account when calculating non-restrained systems as they cause a significant proportion of axial stresses σ_a in the system to be calculated. These may be axial stresses due to bending moments in the longitudinal direction (Fig. 5.5) or to uneven loads in the circumferential direction (Fig. 5.6).

		Permissible bending moments M(x) [kNm]									
		Class 40		Class 50		Class 64		K 9		K 10	
DN	DE [mm]	e_{min} [mm]	M (x)[kNm]	e_{min} [mm]	M (x)[kNm]	e_{min} [mm]	M (x)[kNm]	e_{min} [mm]	M (x)[kNm]	e_{min} [mm]	M (x)[kNm]
80	98	3.0	5.3	3.5	6.1	4.0	6.9	4.7	8.0	4.7	8.0
100	118	3.0	7.8	3.5	9.0	4.0	10.2	4.7	11.8	4.7	11.8
125	144	3.0	11.7	3.5	13.6	4.0	15.4	4.7	17.9	4.8	18.2
150	170	3.0	16.4	3.5	19.0	4.0	21.6	4.7	25.2	5.1	26.7
200	222	3.1	29.2	3.9	36.4	5.0	46.2	4.8	44.4	5.5	50.6
These bending moments, expressed in kilonewton metres [kNm], relate to a load with the same value, expressed in kilonewtons [kN], acting in the central point of a 4 m span.											
Key:		M(x) ≤ 9.9 kNm		10.0 kNm ≤ M(x) ≤ 19.9 kNm		20.0 kNm ≤ M(x) ≤ 29.9 kNm		M(x) ≥ 30.0 kNm			

Table 5.3: Permissible bending moments M(x) for DN 80 to DN 200 pipes for pressure classes (C-classes) and wall thickness classes (K-Classes)

		Minimum ring stiffness S [kN/m^2]									
		Class 25		Class 30		Class 40		K 9		K 10	
DN	DE [mm]	e_{st} [mm]	S [kN/m^2]	e_{st} [mm]	S [kN/m^2]	e_{st} [mm]	S [kN/m^2]	e_{st} [mm]	S [kN/m^2]	e_{st} [mm]	S [kN/m^2]
300	326					5.4	68	6.4	110	8	160
350	378			5.5	46	6.1	67	6.8	89	8.5	120
400	429			5.7	34	6.9	63	7.2	72	9.1	100
450	480			6	28			7.7	61	9.6	86
500	532			6.5	27			8.1	52	10.1	74
600	635			7.7	26			9	41	11.2	58
700	738	7.8	17					9.8	34	12.2	49
800	842	8.6	15					10.7	30	13.2	42
900	945	9.5	15					11.5	26	14.3	37
1000	1048	10.5	14.5					12.3	24	15.4	34
The values for calculated wall thickness e_{st} have been calculated as follows: $e_{st} = e_{min} + 0.5 (1.3 + 0.001 DN)$ [mm]											
Key:		S ≤ 29.9 kN/m^2		30.0 kN/m^2 ≤ S ≤ 49.9 kN/m^2		50.0 kN/m^2 ≤ S ≤ 99.9 kN/m^2		M(x) ≥ 30.0 kNm			

Table 5.4: Summary of minimum ring stiffness values S for nominal sizes DN 300 to DN 1000 for pressure classes (C-classes) and wall thickness classes (K-classes)

5.5.1 Permissible bending moments

The bending moments recordable without damage for pressure classes (C-classes) and wall thickness classes (C-classes) are shown in Table 5.3. It can be seen that, in soils liable to subsidence or where trenchless pipe laying techniques are used, pipes with a higher permissible bending moment are required than those resulting from calculation by means of pressure classes.

5.5.2 Minimum ring stiffness

Stresses due to soil and traffic loads can cause ovalisation, which might be as high as 4%. The minimum ring stiffness values relating to this are stated in both versions of EN 545 and also, dependent on pressure class, in EN 545:2011 [5.1] plus, dependent on wall thickness class, in EN 545:2007 [5.4]. Table 5.4 gives a summary of the values. As is to be expected, the higher ring stiffness areas are once again to be found with the higher wall thicknesses. Here again, the wall thickness is often decisive as opposed to pressure class.

> **4.2 Pressure classes**
>
> According to 3.21, the pressure class of a component is determined by a combination of construction-related functional capability and the functional capability of the non-restrained flexible joint.
>
> Restrained joints can lower the PFA; in this case the PFA is to be specified by the manufacturer.

Fig. 5.7:
Quote from EN 545 [5.1]

5.6 Ductile iron pipes with restrained flexible joints

5.6.1 Identification of the allowable operating pressure

Section 4.2 (Fig. 5.5) of EN 545 [5.1] states that, with restrained joints, the allowable operating pressure PFA may be reduced.

> **4.7.1 Pipes and fittings**
>
> All pipes and fittings must be legibly and durably marked and shall bear at least the following information:
>
> - the manufacturer’s name or mark
> - an indication of the year of manufacture
> - the identification as ductile cast iron
> - the DN
> - the PN rating of flanges for flange components
> - the reference to this European standard, i.e. EN 545
> - the pressure class designation of centrifugally cast pipes
>
> The first five indications must be cast-on or cold-stamped. The other indications may be applied by any other process, e.g. painted onto the casting.

Fig. 5.8:
Quote from EN 545 [5.1]

As seen in Fig. 5.1, restrained pipe joints produce a multiaxial stress state in the pipe wall whereby, with the allowable operating pressure PFA being lower when compared with the non-restrained joint, the pressure class is therefore lower.

The multiaxial stress state in a pipe wall which, in addition to the tangential stress σ_t produced by internal pressure, must also take up axial stresses σ_a, results in a distinct reduction in the allowable operating pressure PFA as compared with the non-restrained design. Therefore the specification of pressure class C as a synonym for the allowable operating pressure PFA is no longer sufficient for restrained-joint pipelines. This has consequences for the identification of the pipes. Fig. 5.8 shows the identification requirements of EN 545 [5.1], Section 4.7.1.

According to EN 545 [5.1], Section 4.2, manufacturers must state the lower values for the PFA of their restrained push-in joints. However, there is no clear and unambiguous determination of the identification of pipes with restrained joints to be found in EN 545 [5.1]. EADIPS®/FGR® has responded to this situation by publishing its own identification standard, EADIPS®/FGR®-NORM 75 [5.5],(Chapter 3, Figs. 3.35 and 3.36).

5.6.2 Positive locking push-in joints

A further requirement has come more and more into the foreground in the last decade: the increasing frequency with which restrained push-in joints are being used with the trenchless laying techniques and the associated requirement for the maximum permissible tensile strength values in the Technical Rules of DVGW Worksheet GW 320-1 [5.6] etc. (see also Chapter 22 on trenchless pipe laying and replacement techniques). In these sets of rules, the permissible tensile strength of, above all, positive locking push-in joints with a welding bead on the spigot end (Fig. 9.5) plays a decisive role for the pulling-in length of a pipe string. Hence it is a determining factor for excavation distances and therefore for the efficiency of a pipe material for a specific trenchless technique. Trenchless pipe laying techniques are mainly performed with positive locking restrained push-in joints. These joints must have a welding bead on the spigot end. A minimum wall thickness of approximately 5 mm for a high-quality weld penetration is considered as a precondition for compliance with the required permissible tensile strength. Also, with trenchless pushing-in techniques, a minimum wall thickness is required for transferring the compressive forces, so that the permissible compression stresses in the connection joint are not exceeded.

Depending on the application case, a number of load types due to internal pressure, vertical load and bending stress, as well as those due to the maximum permissible tensile and compressive forces associated with trenchless laying techniques must therefore be calculated and the optimum pipe determined. The effects on practical planning are described in articles in EADIPS®/FGR® Annual Journals 45 [5.7] and 46 [5.8].

5.7 References

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[Ductile iron pipes and fittings –
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[5.3] EN 14801
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Issue 45 (2011), p. 19 ff]

[5.8] Rammelsberg, J.:
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[5.9] EN 1092-2
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[Flansche und ihre Verbindungen –
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