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DESIGNING LINERS FOR FULLY DETERIORATED SEWERS

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ABSTRACT: In the German design code ATV-M 127-2, *three* host pipe states are differentiated: State I for leaky sewers without cracks, state II for sewers with longitudinal cracks but a stable soil pipe system, and state III for cracked pipes with larger deformations and considerable risk of collapse in the near future. State II sewers that are close to the traffic surface must be calculated as a state III situation. On the other hand, the US Standard ASTM F 1216 defines *two* states: structurally safe and fully deteriorated sewers.

This paper examines the common aspects and differences between the two codes. A simple non-linear numerical approach is presented to evaluate the actual safety of the host pipe-soil system based on the following parameters:

1. the pipe material (e. g. age, corrosion depth, state of the contact zones),
2. the measured or estimated pipe deformations,
3. the soil group, stiffness, and possible voids occurring next to the springlines of the pipe,
4. the loading to be applied on the deteriorated pipe-soil system.

Using stability and ultimate stress criteria, the safety of the system can be defined in a rational way. Missing parameters have to be introduced into the algorithm conservatively.

Case studies are presented to demonstrate safe estimations for the host pipe state. The consequences on the required wall thickness of a lining and the application of non-circular linings are shown. The wall thicknesses resulting from a design for the fully deteriorated state as defined by the design codes in both the USA and Germany are compared and discussed.

1. INTRODUCTION

The models used to describe a lining in a deteriorated sewer are as follows:

1. leaky sewers: rigid boundary with an initial shape, e. g. circular shape;
2. broken longitudinally but structurally safe: rigid boundary of four displaced host pipe quarters, e. g. oval shape;

3. broken and structurally unsafe: flexible boundary of four displaced host pipe quarters, e. g. oval shape, transmission of pressure between the cracked zones:
4. flexible boundary of granular material without capability to transfer pressure forces between cracked zones—in the case of a very weak host pipe material:.

In Germany the models 1–3 are called host pipe states I–III, case 4 belongs to state III. In the USA the models 1–2 are called partially deteriorated and 3–4 fully deteriorated.

Numerical models have been defined and are used for the liner design of cases 1–2

– in Germany: elastic ring embedded in a rigid surrounding structure,
  in USA: free ring in liquid, stability limit enhanced by a factor K = 7 with respect to the structurally safe host pipe

and for the cases 3–4

– in Germany: elastic ring embedded in a cavity that can move (ovalize) because of live loads when the soil cover is small, changes of a water table, changes of overburden etc.
  in USA: elastic ring embedded in granular material that substitutes for the fully deteriorated host pipe

Table 1. Parameters used in the design codes ASTM F 1216 and ATV-M 127-2

ASTM F 1216	ATV-M 127-2	unit	Explanation of variable	ASTM F 1216	ATV-M 127-2	Index used for
q_t	q_v	kN/m²	Total external pressure on pipe	Index C	S	Crown
P	p_a	kN/m²	Water pressure	S	K	Springline
W_s	pV	kN/m²	Live load	I	So	Invert
q	ω_v	%	Ovality	s	B	Soil
C	κ	-	Reduction for ovality	-	v	Imperfection
N	γ	-	Safety factor	-	s	Annular gap
E_s’	E_2	N/mm²	Modulus of soil reaction	-	d	Design load
E_L	E_L	N/mm²	Long-term modulus of elasticity	t	v	Total load
t	s_L	mm	Thickness of the liner wall			
H	h	m	Height of soil above top of pipe			
w	γ_B	kN/m³	Soil unit weight			
H_w		m	Height of water above top of pipe			
	h_w	m	Height of water above the invert			

2. FULLY DETERIORATED GRAVITY PIPE – SOIL AND TRAFFIC LOAD

In the code ASTM F 1216-05 Eq. X1.3 is proposed for fully deteriorated sewers

$$q_t = \frac{C}{N}\cdot\left[32\cdot R_w\cdot B'\cdot E_s'\cdot\left(E_L I/D^3\right)\right]^{1/2} \qquad [1a]$$

where $q_t = 0.00981H_w + wHR_w/1000 + W_s$, see table 1 [1b]

$R_w = 1 - 0.33(H_w/H) \geq 0.67$ = water buoyancy factor (= 1 for $H_w = 0$)

$B' = 1/\left(1+4e^{-0.213H}\right)$ = coefficient of elastic support with H in meters

E_s’ = modulus of soil reaction

D = mean inside diameter of original pipe

Multiplying by the safety factor, setting $R_w = 1$ and using the expression $E_L I/D^3 = S_L/8$ for the ring stiffness of the liner yields the critical pressure on pipe

$$\text{crit}\, q_t = C\cdot 4\cdot\sqrt{2\cdot B'\cdot E_s'\cdot S_L\ /8} \qquad [2a]$$

Assuming B’ to be equal to 0.6 yields

$$\text{crit}\, q_t = C\cdot 2\cdot\sqrt{0.6\cdot E_s'\cdot S_L} \qquad [2b]$$

For pipes without ovality (C = 1) and using the relation $S_{Bh} = 0.6 \cdot E_s'$, the standard expression of the critical pressure for the elastic ring supported elastically from both directions results in

$$\text{crit } q_t = \kappa_v \cdot 2 \cdot \sqrt{S_{Bh} \cdot S_L} \quad \text{(valid for } V_{ps} = S_L/S_{Bh} \leq 0.1) \qquad [3a]$$

The number of waves corresponding to Eq. 3a is defined by $n = \sqrt{1+\sqrt{V_{ps}^{-1}}}$ [3b]

E.g. for V_{ps} = 0.1 follows n = 2 and for V_{ps} = 0.1 n ≅ 6 (Hain & Falter, 1977).

Eq. 3a is used in the German design code ATV-A 127 for newly laid pipelines. Its application in practice is relevant here:

1. The reduction factor C for oval deformations in Eq. 2b has proved to be less significant as the radius of deformed, flexible pipes decreases in the springline where the hoop stress N_S is at a maximum. In the flat region of the crown and springlines, the normal forces N_C and N_I are smaller. A finite element analysis shows clearly that the buckling will start in the springlines, cf. Figures 1 and 2.
2. The critical pressure tends towards infinity when the soil stiffness S_{Bh} or E_s', respectively, becomes large. If the host pipe were modelled by a stiff soil support for a thin liner, the tendency of Eqs. 2b and 3 to become infinite does not correspond with practical experience. Thus, a factor κ_v reducing the critical load in case of stiff soil support was introduced into the design code ATV-A 127, cf. Figure 3.
3. In the code A 127 the total load q_t on the pipe (Eq. 1b) is the soil weight and the live load only, the water pressure is evaluated by a separate equation as the ultimate load is significantly lower for liquid pressure.

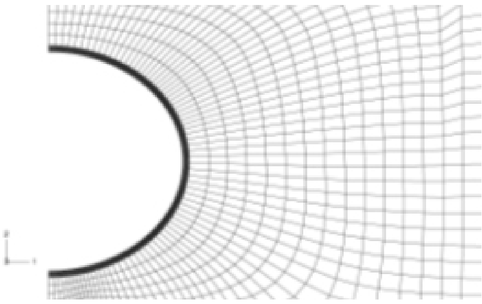

Fig. 1. Buckling mode of pipe in soft soil, pipe-soil stiffness V_{ps} = 0.1, $V_{ps} = S_L/S_{Bh}$

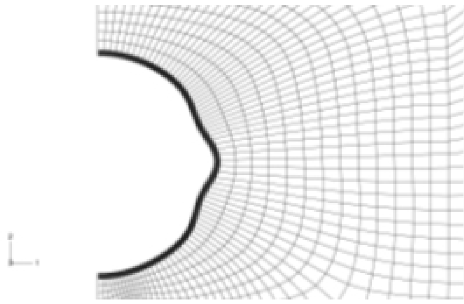

Fig. 2. Buckling mode of pipe in stiff soil, pipe-soil stiffness V_{ps} = 0.001

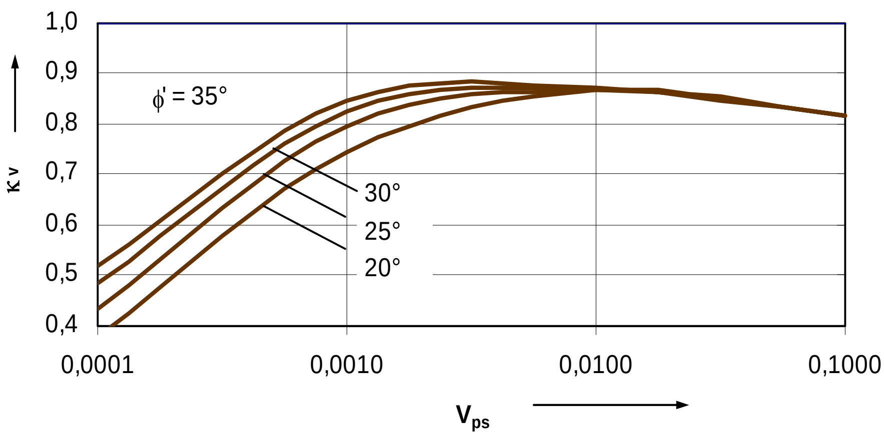

Fig. 3. Reduction factor for critical pressure crit p_t for soil and traffic load (without water pressure)

In addition, the minimum wall thickness is given by $E / (12 \cdot SDR^3) \geq 0.00064$ N/mm², [4]
where E is the initial modulus of elasticity of the liner.

3. FULLY DETERIORATED GRAVITY PIPE – WATER TABLE

If a water table is present, the necessary wall thickness is defined by the pressure on the liner from the outside as well, cf. clause X1.2.2.2 in code F 1216. The acceptable pressure according to Eq. X1.1 is as follows

$$P = \frac{2K \cdot E_L}{1-\nu^2} \cdot \frac{1}{(SDR-1)^3} \cdot \frac{C}{N} \quad [5]$$

where K = 7 = enhancement factor considering the support of the lining by the host pipe
ν = Poisson's ratio (0.3 average)
SDR = OD / t $\leq$ 100 = standard dimension ratio
N = 2 = factor of safety

$$C = \left[\frac{1-q/100}{(1+q/100)^2}\right]^3 \text{ = reduction factor for ovality } q = \frac{\text{mean ID - min ID}}{\text{mean ID}} \cdot 100 \quad [6]$$

Multiplication by the safety factor and use of $R_w = 1$, $s_L = t$ and $r_L = D/2$ for the circular liner geometry yields the critical pressure:

$$\text{crit}\,P = C \cdot 1.75 \cdot \frac{E_L}{1-\nu^2}\left(\frac{s_L}{r_L}\right)^3 \quad [7]$$

As an example, take C = 1, E_L / (1-ν^2) = 1000 N/mm², s_L/r_L = 20 and the result is crit P = 0.219 N/mm².

The design code ATV-M 127-2 is based on the theory of a perfect circular ring in a rigid cavity (Glock, 1977) enhanced by an imperfection reduction factor $\kappa_{v,s}$ (Falter, 2008).

$$\text{crit}\,p_a = \kappa_{v,s} \cdot 2.62 \cdot \frac{E_L}{12 \cdot (1-\nu^2)}\left(\frac{s_L}{r_L}\right)^{2.2} \quad [8]$$

For the example above, take $\kappa_{v,s}$ = 0.68 for state I (see Figure 4), E_L / (1-ν^2) = 1000 N/mm², s_L/r_L = 20: The result is crit p_a = 0.68 · 0.2998 = 0.204 N/mm² which is close to code F 1216.

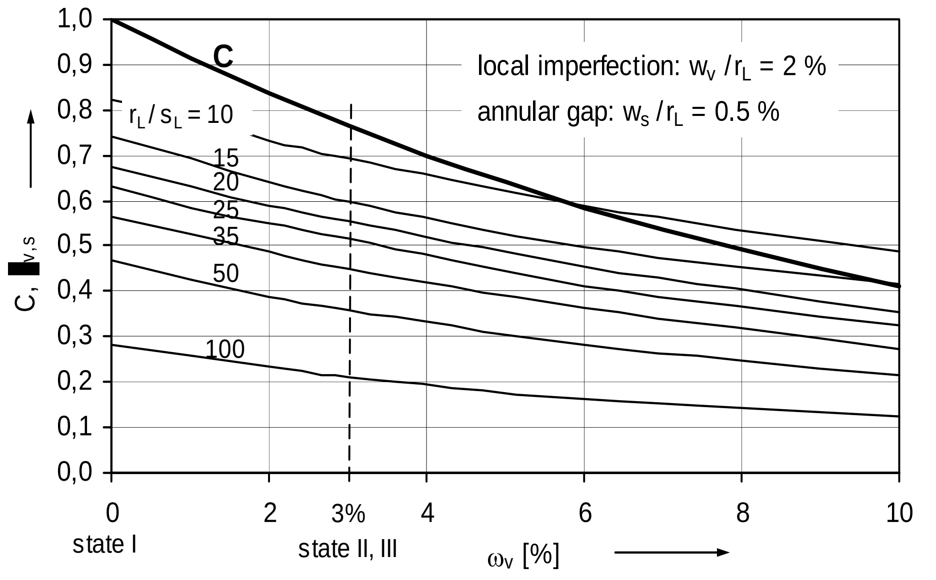

Fig. 4. Imperfections reduction factors for ovality according to F 1216, local imperfection, ovality and annular gap according to ATV-M 127-2

However, this comparison is not generally valid, as the Eqs. 5 and 8 are quite different from their theoretical origin (Thépot, 2004).

Figure 4 shows the reduction factors C and $\kappa_{v,s}$ used in the different models to describe linings in deformed host pipes. As the factor $\kappa_{v,s}$ includes a local imperfection (index v) and an annular gap between lining and host pipe (index s), C is bigger than $\kappa_{v,s}$ for nearly all values of slenderness (r_L/s_L) and ovalization. That is easily seen for a zero ovalization where $\kappa_{v,s}$ is 0.68 for a typical CIPP with a slenderness ratio of 20, in which case C is 1.

For very slender linings like GRP or even thinner constructions (e. g. stainless steel sleeves), the reductions are even more severe.

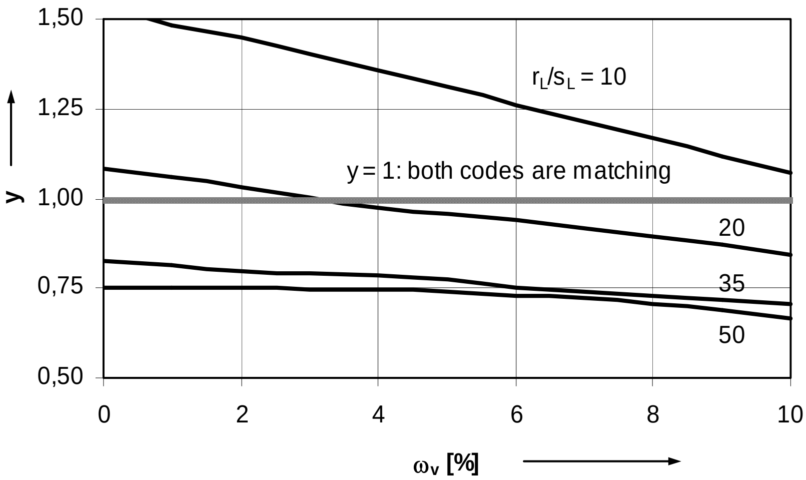

Fig. 5. Ratio between crit P according to ASTM F 1216 and crit p_a according to ATV-M 127-2

The ratio between Eq. 7 and 8 is shown in Figure 5 for variable ovality and slenderness.

$$y = \frac{C}{\kappa_{v,s}} \cdot \frac{12 \cdot 1.75}{2.62} \cdot \left(\frac{s_L}{r_L}\right)^{0.8}$$

In case of a slenderness r_L/s_L = 20, the difference is acceptable; however, for 35 or 50 it is too big. In rehabilitations with CIPP reinforced by fiberglass, these relations are met more often.

4. INTERACTION

In the US standard F 1216, all loads (soil, traffic and water) are summarized as the total load on pipe q_t, cf. Eq. 1b.

If both soil load combined with traffic load and water table are relevant for design (e. g. an analysis for flooded sewers next to rivers), the interaction has to be regarded by a special procedure in ATV-M 127-2. It is not allowed to add single solutions, since the mathematical problem is non-linear. One possible way to solve the problem is to use a computer program for frameworks (Linerb, 2008).

Figure 6 shows the load-deformation curves of a liner ND 300 and increasing water table. If the water level exceeds $h_W > h$ + OD (flood), the live load is removed and the curve has a discontinuity. The critical value for interacting loads is significantly less than the critical loads for each single case.

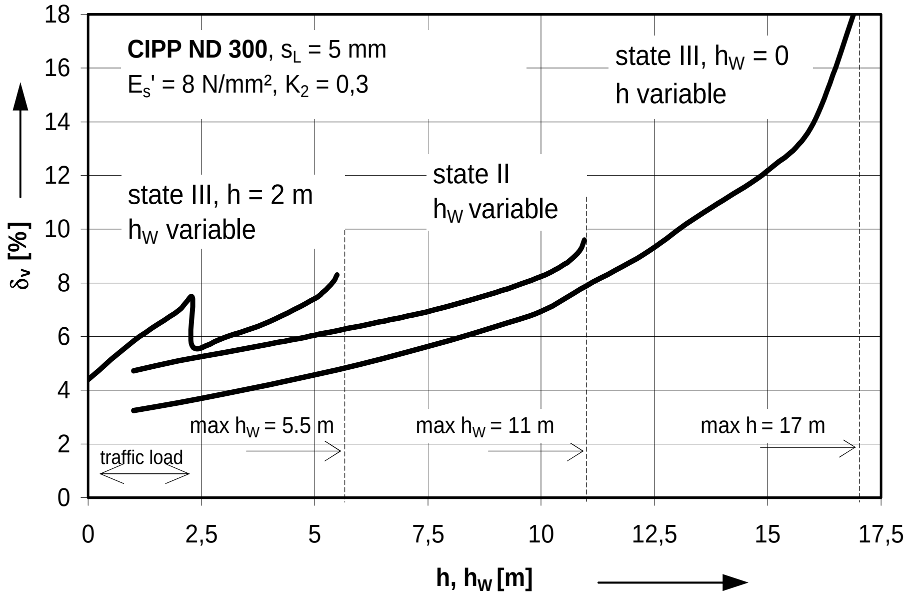

Fig. 6. Interaction of water pressure (water table h_W, state II) and soil load (cover h, state III)

5. HOST PIPE PRESSURE ZONES (STEFFENS ET AL. 2002)

The transfer of pressure in the springlines was tested experimentally on specimen cut out of a new concrete pipe ND 500 and an old one from a 100-year-old sewer in Muenster, cf. Fig. 7 to 8.

Fig. 7. New concrete pipe specimen, 9% ovality

Fig. 8. Old concrete pipe specimen, close to failure

The load capability of the host pipe springlines can be proved numerically by a simple formula. First, the normal force in the springlines is calculated by equilibrium condition:
$N_S = q_v \cdot OD \cdot (1 + \omega_v) / 2$, where OD is the outer diameter of the host pipe. [9]

Assuming a contact zone of 20% from the host pipe wall thickness, the compression stress is
$\sigma = 2N_S / (0.2 \cdot s) = 10N_S / s$. [10a]

If the ultimate stress σ_u of the pipe wall is known, the safety factor yields
$\gamma = \sigma_u / \sigma$. [10b]

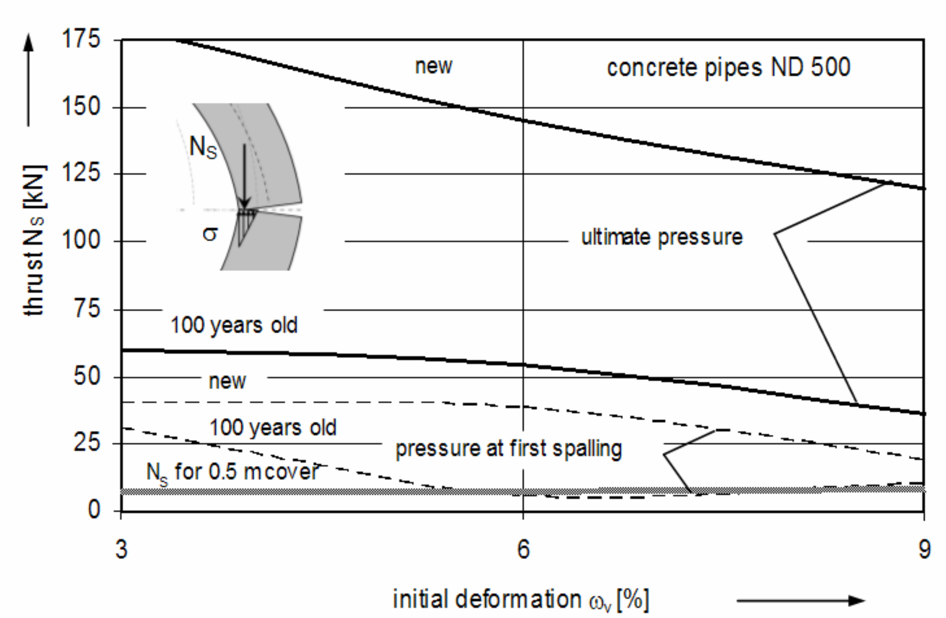

Fig. 9. Ultimate pressure subjected to concrete pipe segments arranged with 3, 6 and 9% ovality

A state III condition may be assumed if $\gamma \geq 2$, and a state IIIa condition if $\gamma < 2$. In the state III condition the host pipe is able to bear the main part of the normal forces N_S caused by the overburden, but in the state IIIa condition the liner must bear this burden. The numerical models for both states show significantly different normal forces in the liner wall.

6. CASE STUDIES

6.1 Airport Dresden (2008)

An Airport sewer ND 700 mm in Dresden, Germany, made of concrete was found to be heavily damaged, cf. Figure 10. The cover height is 3.8 m, the airplane weight 750t. For safety the GRP lining was calculated for state III (host pipe transferring pressure) and IIIa (granular host pipe).


Fig. 10. Video print of the airport sewer DN 700

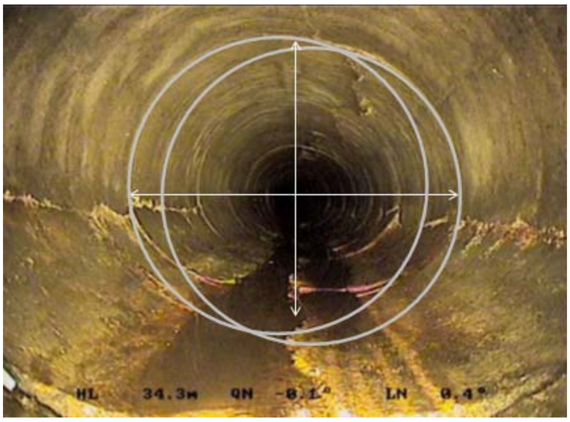
Fig. 11. Circles fitted to the upper pipe quarters

The initial deformation is calculated from the difference of the mean circle diameter and the extension max ID of the two circles in Figure 11:

Mean ID = 4.00 cm, max ID = 4.46 cm, max ID – mean ID = 0.46 cm (measures are taken from the figures) $\rightarrow \omega_v = (0.46 / 4.00) \cdot 100\% = 11.5\ \%$

As the invert is significantly deformed towards the inside, the initial deformation is set at 14%. From the analysis a GRP lining with OD = 616 mm and 34 mm wall thickness results. The lining will be installed by assembling short pipes in the sewer and grouting the annular gap.

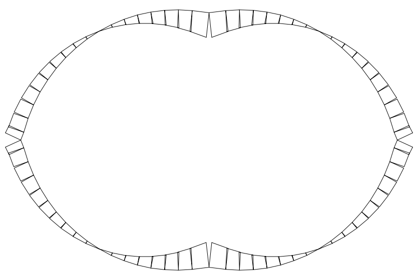

Fig. 12. State III: max M = 10.275 kNm/m

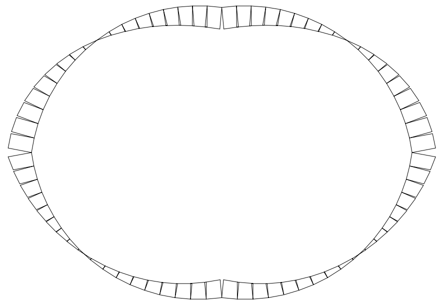

Fig. 13. State IIIa: max M = 7.644 kNm/m

As non-linear calculations must be performed with design loads, all loads are multiplied by the safety factor 2. The deformations in the Figures 12 to 13 are plotted by this enlargement factor. The bending moments calculated by the model for state III are 34% bigger than the bending moments for state IIIa. This relation is not generally valid, since, in some cases, state IIIa might actually be a more unfavorable state.

6.2 Concrete sewer rehabilitation to be designed for flood in Dresden (2008)

The non-circular concrete sewer in Dresden with the dimension B/H = 2300 / 2245 mm is located close to the river Elbe. It was necessary to design the lining for a high water level in case of floods simultaneously with accounting for other loads. From drilling samples analyzed by compression tests, the concrete was found to be very weak, the strength was less than 10 N/mm². Thus, a state IIIa calculation was added to the normal design procedure.

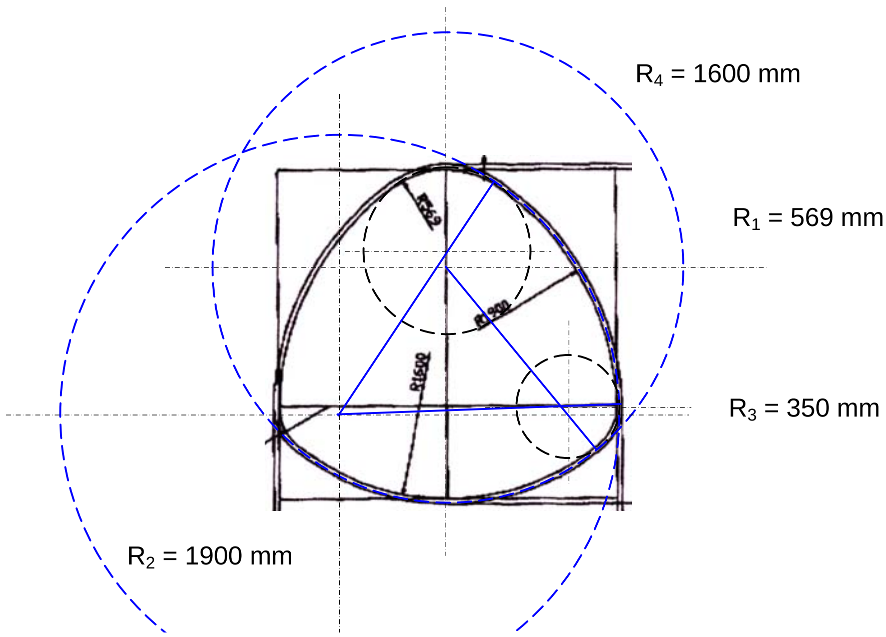

Fig. 14. Profile B/H = 2300/2245 mm described by four arches with different radii R_1 to R_4

The wall thickness of the GRP lining was 51 mm necessary for the combination of a 7.5 m water level above the invert and for the two soil covers min h = 0.85 m and max h = 6.55 m.

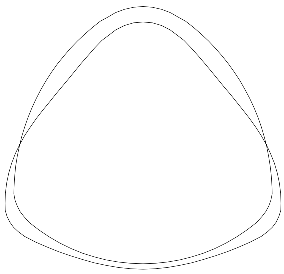

Fig. 15. h = 3.5 m: buckling load for s_L = 32 mm

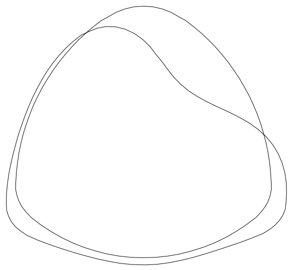

Fig. 16. h = 4.2 m: non symmetric buckling

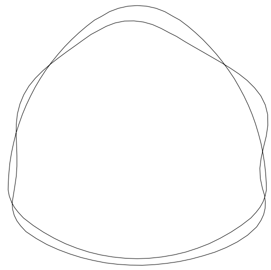

Fig. 17. h = 7 m: multi lobe buckling

The deformations in Figures 15 to 17 result from a smaller wall thickness of 32 mm used for a first attempt by increasing soil cover. Because of the state IIIa condition and poor material properties, an elastic support of granular sewer material and soil was chosen. The calculation of the non-circular lining was performed by a framework program used in Germany for sewers with arbitrary shapes, cf. Figure 14 (Linerb, 2008).

The critical deformations do not differ much from the deformations caused by the loading. Multi-mode buckling is seen only if the critical load is significantly exceeded, Figures 16 to 17. The choice of the local imperfection for non-circular linings must consider the relevant buckling mode (Falter, 2008).

6.3 Masonry sewer crossing a railway in Krefeld, Germany (2007)

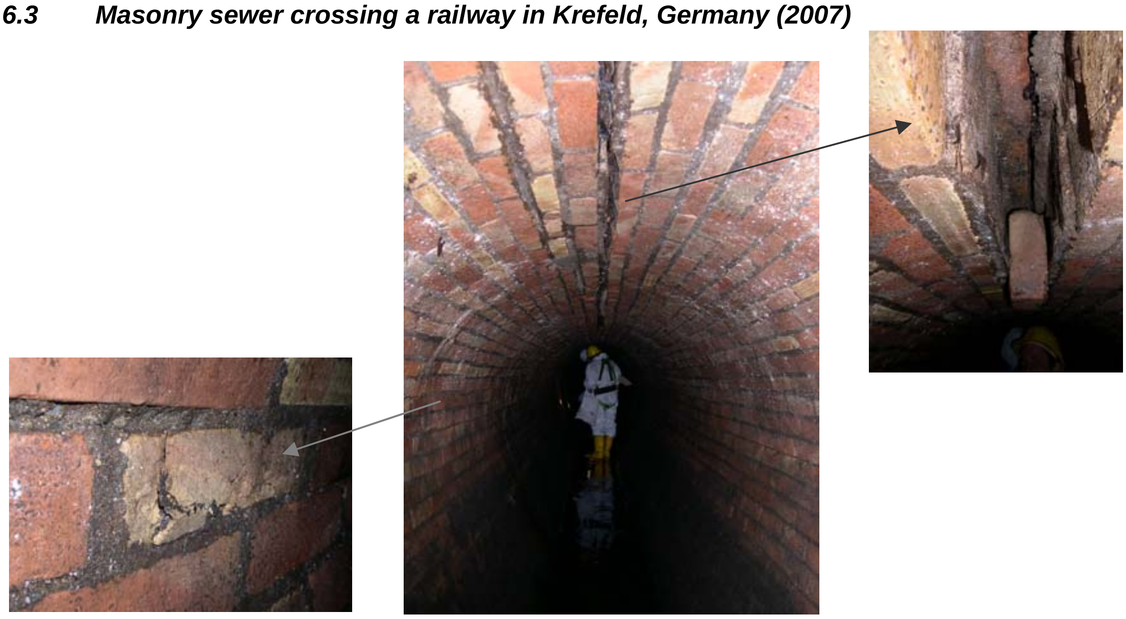

Figure 18. Masonry sewer with longitudinal cracks (crown) and spalling (springlines)

The egg shaped sewer B/H = 1200/1800 mm sewer crossing a railway in Krefeld had to be reinforced by a close-fit lining for two reasons:

- The damage situation and the deformation measurements of 5% (up to 10% in a small area) indicated a state III (fully deteriorated, cf. Figure 18);
- the soil cover of originally 1.7 m was heightened to about 5 m.

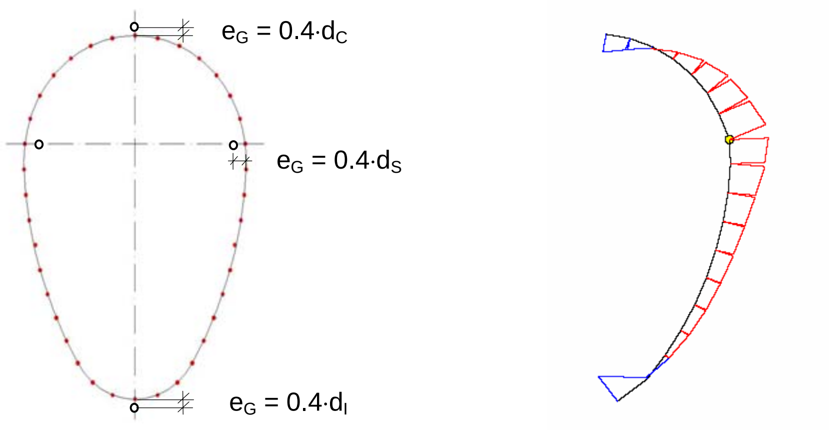

Fig. 19. Numerical model for the masonry sewer, resulting bending moment distribution

An elastically embedded ring with excentric hinges was chosen for the numerical model of the host pipe alone, cf. Figure 19. The safety factor of the system subjected to the planned cover weight yielded 1.7, which is less than the required safety factor.

A CIPP lining with different wall thicknesses was manufactured (23 mm regularly and 30 mm in the largely deformed area) and inverted into the sewer. For more details about the state III calculations and the site work see (Falter, 2008).

6.4 Comparison of the design examples with ASTM F 1216:2005

Table 2. Design steps according to ASTM F 1216 and comparison with ATV-M 127-2 results

Ex.	ND	liner	s_L	OD^A	r_L/s_L	ω_v	h	h_W	p_V	E_s'	E_L or σ_L	γ^E	γ^F
Eq.	B/H		mm	mm	-	%	m	m	kN/m²	N/mm²	N/mm²	-	-
6.1 X1.3	700	GRP	34	616	9.1	14	3.8	-	75.0	5	4000	3.75	2.60
6.2 X1.3	2300/ 2245	GRP	51	2300	45.1	3	6.55	7.5	-^{C}	16^D	5000	*4.96*	*1.82*
X1.1			51	2300	45.1	3	-	7.5	-	-	5000	9.66	6.87
6.3 X1.3	1200/ 1800	CIPP	30	1200	20	10	5	-	28.4	16^D	1400	2.12	3.90
X1.2			30	1800	30^B	10	-	1.9	-	-	18	*3.92*	*2.80*

^{A}Outer diameter of the liner; ^{B}Radius of the flat region in the springlines; ^{C}No live load is applied in the design for a flood situation; ^{D}Assumes a soil modulus including the granular host pipe material; ^{E}ASTM F 1216; ^{F}ATV-M 127-2.

In Table 2 the numerical results for the examples 6.1 to 6.3 are presented. The loads and the diameters of these applications are important, and significant differences between the safety factors of the two design codes are evident. In particular, the design of the non-circular lining in example 6.2 differs by a factor greater than 2. The reason for this difference is likely a result of the allowance for flood conditions by Eq. X1.3; this flood load case is treated by the same theoretical model used for soil loads.

The difference in the safety factors of the egg shaped lining of example 6.3 according to Eq. X1.2 is explained by the uncertainty of the radius, which is necessary for the parameter SDR. In the F 1216 calculation a substitute radius is assumed. The code M 127-2 uses the original shape where the buckling occurs at the flat springline area.

7. CONCLUSIONS

A safe and economic design of linings even in extraordinary situations becomes more and more important. The engineers and customers want to use transparent models both to design and prove the wall thickness and for quality assurance. This paper reports on the background of the design codes ASTM F 1216 and ATV-M 127-2. A few applications taken from actual rehabilitation projects in Germany are presented and the numerical results of these case studies are given.

Both design codes allow for the main load cases like soil, traffic and liquid loads that affect fully deteriorated sewers. There are differences in the underlying theories and models as well as the application of imperfections and the treatment of non-circular linings. E. g. the critical water pressure on the outside of the liner has to be evaluated by the model of a free ring supported by a factor 7 (F 1216) or by a ring in a cavity (M 127-2). The critical pressure from dead and live loads is calculated from the model of a fully embedded liner (F 1216) or from the model of a ring surrounded by four quarters of host pipe embedded in soil.

The calculations of table 2 in detail, the references Falter 2004, Hain & Falter 1977 and details concerning the computer program Linerb 2008 are available at the home page https://www.fh-muenster.de/fb6/personen/lehrende/falter. The authors would be grateful for any collaboration at the subject presented in the paper.

8. REFERENCES

ASTM-Standard F 1216-05. Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube

ATV-M 127-2 (01.2000). Static calculations for the rehabilitation of sewers with lining and assembly procedures. Hennef

Falter, B. (2004). Lining Stability: An Analysis of Damaged Sewers. Proceedings of 2004 NoDig Conference, New Orleans, Louisiana, March 21-24, 2004.

Falter, B. (2008). New developments in liner design due to ATV-M 127-2. Proceedings of 2008 NoDig Conference, Dallas, Texas, April 27-May 2, 2008.

Glock, D. (1977). Ueberkritisches Verhalten eines starr ummantelten Kreisrohres bei Wasser-druck von außen und Temperaturdehnung. Stahlbau 46, pp. 212-217.

Hain, H. and Falter, B. (1977). Zum Stabilitaetsproblem des starr oder elastisch gebetteten Kreisringes infolge gleichmaeßiger Temperaturerhoehung. Pflueger-Festschrift, Leibniz University Hannover.

Linerb (2008). Computer program for the structural analysis of linings. Version 7.2. Interface in German and English language. Univ. of Applied Sciences Muenster.

Steffens, K., Falter, B., Grunwald, G. and Harder, H. (2002). Abwasserkanaele und -leitungen, Statik bei der Substanzerhaltung und Renovierung (ASSUR). Research Project 01RA 9803/8. Supported by the Ministry of Education and Research. Final Report, Univ. of Appl. Sc. Bremen.

Thépot, O. (2004). International Comparison of Methods for the Design of Sewer Linings. 3R international (43) Vol. 8-9

Part 1
Designing of lining projects according to ASTM F 1216–05 [1]

Preliminary remarks

The safety factors γ for three projects in Germany are presented in [4], Table 2. The values of γ^E resulting from ASTM F1216–05 are compared with the values γ^F, which are calculated by a computer program [5] used for ATV-M 127-2 design.

In the meantime the ASTM F 1216–05 has changed to ASTM F 1216–07. The relevant difference is the position of the ovalisation reduction factor C which is now located in the square root of Eq. (X1.3). Thus the critical loads crit q_t and the safety factors calculated increase by the factor $C^{-1/2}$.

In Figure 4 of the conference paper [4] the curve C for the reduction factor crit q_t is now closer to 1.

1. Project 1 - Dresden Airport sewer, Germany

1.1 Assumptions and conditions for calculation

Host pipe geometry, material:	Circular cross section ND 700, concrete
Ovalisation:	q = 14%
Liner material:	GRP
Outer diameter of the liner:	D_{aL} = 616 mm, D = 616 – 34 = 582 mm
Wall thickness of the liner:	s_L = 34 mm
Long-term modulus of elasticity of the liner:	$E_L = 4000\ N/mm^2$
Moment of inertia of the liner:	$I = 34^3 / 12 = 3275\ mm^4/mm$
Cover over pipe crown:	H = 3.8 m
Groundwater level:	$h_{W,Inv} = 3.0$ m → H_W = 3.0 – 0.616 = 2.38 m above crown
Traffic load:	$p_t = 75\ kN/m^2$
Modulus of soil reaction:	$E_S' = 5\ N/mm^2$

1.2 Structural analysis according to [1], X1.2.2 (Fully Deteriorated Gravity Pipe Condition)

Critical total external pressure:

$$\text{crit}\, q_t = \frac{C}{N}\left[32 \cdot R_W \cdot B' \cdot E_S' \left(\frac{E_L \cdot I}{D^3}\right)\right]^{1/2}, \quad \text{cf. Eq. (X1.3)}$$

- $C = \left(\left[1-\frac{14}{100}\right] / \left[1+\frac{14}{100}\right]^2\right)^3 = \mathbf{0.29}$ (see X1.2.1)
- $R_W = 1 - 0{,}33\ (H_W / H)$
  $R_W = 1 - 0{,}33\ (2{,}38 / 3{,}8)$
  $= \mathbf{0{,}79} > 0{,}67 = \min R_W$
- $B' = 1 / (1 + 4 \cdot e^{-0{,}213 \cdot 3{,}8}) = \mathbf{0.360}$
- N = 1 (for critical external pressure)

$$\text{crit}\, q_t = \frac{0.29}{1}\left[32 \cdot 1.0 \cdot 0.36 \cdot 5\left(\frac{4000 \cdot 3275}{582^3}\right)\right]^{1/2} = \mathbf{0.567\ N/mm^2}$$

Existing total external pressure:

q_t = 0 + 20 · 3.8 · 1,0 / 1000 + 75 / 1000

= 0.076 + 0.075 = **0.151 N/mm²**

Proof of safety:

γ = 0.567 / 0.151 = **3.75** > 2.0 = req γ (cf. γ^E in paper D-3-01 [4], Table 2)

2. Project - Dresden main sewer, Germany

2.1 Assumptions and conditions for calculation

Host pipe geometry: material:	Non-circular cross section B/H = 2300/2245 mm concrete with weak compression strength
Ovalisation:	q = 3%
Liner material:	GRP
Outer diameter of the liner:	D_{aL} = 2300 mm, D = 2300 – 51 = 2249 mm
Wall thickness of the liner:	s_L = 51 mm
Long-term modulus of elasticity of the liner:	E_L = 5000 N/mm²
Moment of inertia of the liner:	I = 51^3 / 12 = 11,054 mm⁴/mm
Cover over pipe crown:	H = 6.55 m
Groundwater level:	$h_{W,Inv}$ = 7.5 m → H_W = 7.5 – 2.3 = 5.2 m above crown
Traffic load:	p_t = 0 kN/m² (interaction without traffic load)
Modulus of soil reaction:	E_S' = 16 N/mm²

2.2 Structural analysis according to [1], X1.2.2 (Fully Deteriorated Gravity Pipe Condition)

Critical total external pressure:

$$\text{crit}\, q_t = \frac{C}{N}\left[32 \cdot R_W \cdot B' \cdot E_S'\left(\frac{E_L \cdot I}{D^3}\right)\right]^{1/2}, \quad \text{cf. Eq. (X1.3)}$$

- $C = \left(\left[1-\frac{3}{100}\right] / \left[1+\frac{3}{100}\right]^2\right)^3$ = **0.764**, (see X1.2.1)
- R_W = 1 – 0.33 (H_W / H)
  R_W = 1 – 0.33 (5.2 / 6.55)
  = **0.738** > 0.67 = min R_W
- B' = 1 / (1 + 4 · $e^{-0,213 \cdot 6.55}$) = **0.502**
- N = 1 (for critical external pressure)

$$\text{crit}\, q_t = \frac{0{,}764}{1}\left[32 \cdot 0{,}738 \cdot 0{,}502 \cdot 16\left(\frac{5000 \cdot 11.054}{2249^3}\right)\right]^{1/2} = \mathbf{0.733\ N/mm^2}$$

Existing total external pressure:

q_t = 0.00981 · 5.2 + 20 · 6.55 · 0.738 / 1000 + 0

= 0.051 + 0.0967 + 0 = **0.148 N/mm²**

Proof of safety:

γ = 0,733 / 0.148 = **4.96** > 2.0 = req γ (cf. γ^E in paper D-3-01 [4], Table 2)

2.3 Structural analysis according to [1], X1.2.1 (Partially Deteriorated Gravity Pipe Condition)

Critical groundwater load:

$$\text{crit } p = \frac{2 \cdot 7 \cdot 5000}{1 - 0.35^2} \cdot \frac{1}{(2300/51-1))^3} \cdot \frac{0.764}{1} = \mathbf{0.711\ N/mm^2}$$

Existing total external pressure:

q_t = 0.00981 · 7.5 = 0.0736 N/mm²

Proof of safety:

γ = 0.711 / 0.0736 = **9.66** > 2.0 = req γ (cf. γ^E in paper D-3-01 [4], Table 2)

3. Project 3 – Sewer below railway in Krefeld, Germany

3.1 Assumptions and conditions for calculation

Host pipe geometry: material:	Egg shaped cross section B/H = 1200/1800 mm masonry
Ovalisation:	q = 10%
Liner material:	UP-SF (resin impregnated felt)
Outer diameter of the liner:	D_{aL} = 1200 mm, D = 1200 – 30 = 1170 mm
Wall thickness of the liner:	s_L = 30 mm
Long-term modulus of elasticity of the liner:	E_L = 1400 N/mm²
Moment of inertia of the liner:	I = 30^3 / 12 = 2250 mm⁴/mm
Cover over pipe crown:	H = 5.0 m
Groundwater level:	$h_{W,Inv}$ = 1.9 m → H_W = 1.9 – 1.8 = 0.1 m, chosen H_W = 0
Traffic load:	p_t = 28.4 kN/m²
Modulus of soil reaction:	E_S' = 16 N/mm²

3.2 Structural analysis according to [1], X1.2.2 (Fully Deteriorated Gravity Pipe Condition)

Critical total external pressure:

$$\text{crit}\, q_t = \frac{C}{N}\left[32 \cdot R_W \cdot B' \cdot E'_S \left(\frac{E_L \cdot I}{D^3}\right)\right]^{1/2}, \quad \text{cf. Eq. (X1.3)}$$

- $C = \left(\left[1 - \frac{10}{100}\right] / \left[1 + \frac{10}{100}\right]^2\right)^3$ = **0.41**, (see X1.2.1)
- $R_W = 1$
- B' = 1 / (1 + 4 · $e^{-0,213 \cdot 5}$) = **0,42**
- N = 1 (for critical external pressure)

$$\text{crit}\, q_t = \frac{0.41}{1}\left[32 \cdot 1 \cdot 0.42 \cdot 16 \left(\frac{1400 \cdot 2250}{1170^3}\right)\right]^{1/2}$$ = **0.267 N/mm²**

Existing total external pressure:

q_t = 0 + 20 · 5.0 · 1 / 1000 + 28.4 / 1000

= 0.1 + 0.0284 + 0 = **0.128 N/mm²**

Proof of safety:

γ = 0.267 / 0.128 = **2.12** > 2.0 = req γ (cf. γ^E in paper D-3-01 [4], Table 2)

3.3 Structural analysis according to [1], X1.2.1.1 (for oval original pipe)

Critical groundwater load:

$$1.5 \cdot \frac{q}{100}\left(1 + \frac{q}{100}\right) \cdot SDR^2 - 0.5 \cdot \left(1 + \frac{q}{100}\right) \cdot SDR = \frac{\sigma_L}{P \cdot N}, \quad \text{cf. Eq. (X1.2)}$$

Using the safety factor N = 1 the critical external pressure yields.

$$1.5 \cdot \frac{10}{100}\left(1 + \frac{10}{100}\right) \cdot 40^2 - 0.5 \cdot \left(1 + \frac{10}{100}\right) \cdot 40 = \frac{18}{\text{crit}\, P}$$

$\rightarrow$ crit P = $\frac{18}{242}$ = 0.0744 N/mm²

Existing total external pressure:

q_t = 0.00981 · 1.9 = 0.019 N/mm²

Proof of safety:

γ = 0.0744 / 0.019 = **3.92** > 2.0 = req γ (cf. γ^E in paper D-3-01 [4], Table 2)

Part 2
Designing of lining projects according to ATV-M 127-2 [3]

Preliminary remarks

The safety factors γ for three liner projects in Germany are presented in [4], Table 2. The values of γ^F have been calculated by a computer program used for liner design according to ATV-M 127-2 [5].

The computer program [5] is applicable to any material, circular and arbitrary cross sections (like egg shapes, hood shape etc) and the host pipe states I, II and III as defined in ATV-M 127-2. The host pipe wall thickness and the material properties are regarded by the design method.

The computer output for the three projects is presented in the files:

1. Project1_DresdenAirport_ND700.pdf
2. Project2_Dresden_MainSewer_2300_2245.pdf
3. Project3_Krefeld_eggshape1200_1800.pdf

Literature

[1] ASTM F 1216 – 05 (2008): Standard Practice for Rehabilitation of Existing Pipelines by the Inversion and Curing of a Resin-Impregnated Tube

[2] ASTM F 1216 – 07b (2008): Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube

[3] ATV-M 127-2 (01.2000). Static calculations for the rehabilitation of sewers with lining and assembly procedures. Hennef, Germany

[4] Falter, B., Hildebrandt, S. and Wolters, M.: Designing liners for fully deteriorated sewers. Contribution to the NoDig Conference March 29 – April 3, 2009 in Toronto, Ontario

[5] Falter, B.: LINERB Version 7.2 (2009) – Computer program for the structural analysis of linings according to Design Code ATV-M 127-2. In German and English language