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Quality assessment of CIPP lining in sewers: Crucial knowledge acquired by IKT and research gaps identified in Germany

Bert Bosseler[a,*], Dieter Homann[a], Thomas Brüggemann[a], Iain Naismith[a], Matteo Rubinato[b,*]

[a] IKT-Institute for Underground Infrastructure, Exterbruch 1, 45886 Gelsenkirchen, Germany
[b] Centre for Agroecology, Water and Resilience, Coventry University, CV8 3LG Coventry, UK

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ABSTRACT

Deterioration of buried water and sewer pipes is a significant concern among utilities around the world. Cured-In-Place-Pipe (CIPP) is one of the techniques commonly adopted to rehabilitate pipes. The main purpose of this paper is to provide a brief, but comprehensive, summary of information needed by researchers, engineers and municipalities to recognize the barriers and difficulties that may arise during CIPP sewer rehabilitation work. Thus, this paper outlines the issues and challenges associated with CIPP rehabilitation of main and lateral sewers by analyzing a series of projects conducted by IKT-Institute for Underground Infrastructure in Germany over the last two decades. Finally, ideas for further research are then proposed to reduce the obstacles and risks linked with this technique.

1. Introduction

Estimates for Germany indicate that in the federal state of North Rhine-Westphalia (NRW), approx. 20,000 km [approx. 20 %, cf. (Aquabench 2010)] of the 99,172 km of public sewers and pipelines have damage that needs to be repaired in the short to medium-term. A similar picture emerges from the DWA (German Association for Water Management, Wastewater and Waste) survey (Berger et al., 2020) on the condition of the sewer system across Germany in 2020. According to this, 18.7 % of sewers in Germany are in a need of rehabilitation in the short to medium-term. The construction industry of North Rhine-Westphalia estimates the need for rehabilitation of public sewers in NRW to be 1.1 to 1.4 billion euros per year (Bauindustrieverband, 2018). If these estimates are applied to Germany and Europe, then of the total length of the sewer system, which is approx. 600,000 km for Germany (Berger et al., 2020) and 3.2 million km for Europe (Greene, 2021), the rehabilitation requirements are approx. 7.5 billion EUR and approx. 40 billion EUR per year, respectively.

In principle, defective sewers pose a high potential risk for the environment (Wang et al., 2021; Zhou et al., 2020; Hao et al., 2012; Richards, 1998; Allouche et al., 2014; Rubinato et al., 2019, Zhao et al., 2021; Addison-Atkinson et al., 2023). Blocked sewers can release wastewater pollutants to the environment as uncontrolled discharges or leaky sewers can contaminate the soil and groundwater through exfiltration (Beg et al., 2020; Kitsikoudis et al., 2021; Rubinato et al., 2018; Rubinato et al., 2020, Rubinato et al., 2021, Rubinato et al., 2022). The infiltration of groundwater into sewers also poses environmental risks, because this can cause hydraulic overload of the entire sewer system/treatment plant (Liu et al., 2021; Zhao et al., 2020; Su et al., 2020; Fung et al., 2020). As a result, the performance of the sewage treatment plants is impaired (Rödel et al., 2017). Furthermore, in combined systems that convey both foul and surface water, the increased proportion of groundwater can lead to enlarged discharges at sewer overflow structures and thus to additional pollution of water bodies. Both the exfiltration of wastewater and the infiltration of groundwater can impair the stability of the sewer if the surrounding soil is eroded as a result. In extreme cases, not only the collapse of the structure can occur, sink holes can form up to the surface. In such cases, far more damaging consequences for the environment are to be expected, as large quantities of wastewater can then enter the soil, groundwater and surface waters (Indiketiya et al., 2019; Kwak et al., 2020).

Cured in Place Pipe (CIPP) lining methods are commonly used worldwide for the rehabilitation of sewers and other pipes (IKT, 2003; Ji et al., 2018; Ra et al., 2018; Fang et al., 2020; Yang et al., 2021; Kaushal and Najafi, 2020; Hsu and Shou, 2022a,b; Ji et al., 2020) and have become established in the German market as the most frequently used

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* Corresponding authors.
E-mail addresses: bosseler@ikt.de (B. Bosseler), matteo.rubinato@coventry.ac.uk (M. Rubinato).

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method for the renovation of defective sewers and pipes (Abraham & Gillani, 1999; Boot and Gumbel, 1997; Bauindustrieverband, 2018; Sterling, 2020; Fang et al., 2020). The CIPP lining method makes an important contribution to the protection of soil, groundwater and surface water, especially with regard to the water tightness of sewers and pipes (Matthews et al., 2012). For the rehabilitation of public sewers and pipes, the pipe lining method is preferred over conventional excavation and replacement for two main reasons: i) damage can be repaired quickly by this trenchless rehabilitation technique without much interference on the surface (including road traffic, residential buildings); ii) according to (NLBL, 2022), it is more cost-effective than other renovation methods.

According to ISO 11296-4 (+AMD 1:2021) (International Standard, 2018), a CIPP liner is a flexible tube consisting of a carrier material, resin system, and any membrane and/or reinforcement combined prior to insertion in the host pipe to be lined. The CIPP liner can be coated with a thin plastic layer (inside and outside). These foils/coatings serve, among other things, as an installation aid or, depending on the system, are also considered an integral part of the liner's performance over its entire service life (long-term sealing effects) (Insituform Rohrsanierungstechniken, 2008; DIBt, 2020; Norditube Technology, 2008). After curing, a continuous pipe is created. For the planning and execution of rehabilitation measures using CIPP lining, a wide range of standards, regulations and requirements exist at the international and national level such as ISO 11296-4:2018 (+AMD 1:2021) (International Standard, 2018), ISO 11297-4:2018 (Part 4: Lining with cured-in-place pipes, 2018), EN 15885:2018 (DIN 2019), and ASTM F1216 and F2019 (Braun and Macey, 2017) in North America. According to EN 15885, a distinction can be made between liners based on their installation method, by means of inversion of the liner through the pipe (Method A) or installation by pulling the liner through with a winch and subsequent inflation with compressed air or water (Method B). In addition, installation using a combination of both methods is also possible. According to Lorenz et al. (2015), the curing process can be triggered or accelerated either by heat (hot water, steam or electrical heating), UV radiation or by the ambient temperature.

As described, it is clear that sewer CIPP lining has been established across the world for sewer rehabilitation. However, since the final product is only created on the construction site, through the curing of the material and the geometric adaptation to the local conditions, a 100% success rate for installations is required from the point of view of quality assurance. This study aims to present insights identified by the testing of installed liners undertaken by IKT (Institute for Underground Infrastructure) for sewer network owners over the past 25 years. Conclusions on the status of quality assessment and quality assurance of CIPP liners are drawn and areas for future research are suggested.

2. Background

2.1. Benefits of implementing CIPP lining and state of the art

To date, there have been few studies on damage identified in CIPP lining or on their expected service life of CIPP liners (Hudson, et al., 2023; Hsu and Shou, 2022a,b; Yang et al., 2022; Yang et al., 2021; Zhang et al., 2022).

According to UK Water Industry and Research, (2019), in the city of Aarhus in Denmark samples were taken from five CIPP liners at the time of installation in 1991/1992, again in 1999/2000 and then in 2005, for examination and comparison. It was found that the flexural modulus values for all three sets of tests complied with the requirements according to ASTM F1216. No overall trends were observed in flexural modulus, flexural strength and density. Most samples showed an increase of water absorption over the 14-year service period, but all were $< 1.5\%$ by weight. In two projects (Wicke, 2017; Riechel, 2017) in Berlin, the focus was on German and international studies in which laboratory analyses of liner samples were carried out and evaluated after several years in operation. Data and information on liners installed in Berlin was compiled and evaluated (Riechel, 2017), including their age distribution and the materials used. The structural condition of the liners and their influencing factors were analysed. In Wicke (2017) an extensive literature review of international life span studies was conducted. Overall, both studies confirm the good condition of CIPP-liners in operation. But as the examined liners in Berlin (Riechel, 2017) were still quite young (max. 4 years since installation) thus the influence of ageing was not investigated. Trees were identified as one of the main factors influencing the condition of lined sewers (Riechel, 2017). Root growth represented a significant defect with 9% of the inspected liners affected. In addition, positional deviations and drainage obstructions were identified, which were mostly due to errors that occurred during installation or to previous damage to the sewers. Other types of sewer damage, e.g. corrosion, fragmentation or pipe breaks, usually did not affect the liner itself, but mostly affected the areas where lateral sewers connect into a main sewer and where the sewers connect to manholes.

In 2008, IKT tested 18 CIPP samples from liners installed in Switzerland for a variety of parameters (water tightness, short-term modulus of elasticity and short-term flexural stress). These had been in the ground for between 8 and 26 years, and were taken from pipes of various nominal sizes (DN 200 - DN 600) (IKT 2008). The tests conducted on the liners are described in Table 1. For CIPP liners, the inner coating or film usually serves only as an installation aid but it can be damaged by i) operational stresses (sewer cleaning and abrasion) and ii) ageing“ as a result of environmental conditions (temperature stress due to hot wastewater, constant water contact and chemical stress due to wastewater constituents).

The effects of these stresses could clearly be seen in the samples from Switzerland (Table 1). For example, many samples had inner coatings that were discoloured and porous or had been worn away or cut. In some samples, the inner coating was completely missing. The laminates of the samples from Switzerland had numerous, clearly visible defects and leaks through the wall. These were areas with pores and air inclusions or partial areas where the carrier material was visibly exposed. The causes for this could have been:

(a) insufficient impregnation of the liner before installation. If there is too little resin in the liner, there will be areas where the carrier material is not completely enclosed by the cured resin. These imperfections can then cause leaks through the liner wall;
(b) insufficient contact pressure when installing and curing the liner with the result that the resin-carrier material system is not sufficiently compacted and air pockets form, which can lead to leaks though the liner;
(c) when installing the liner without a pre-liner between it and the host pipe, uncured resin can come into contact with water on the outside of the liner. If lower-quality resins are used, “saponification” can occur, the resin foams up. This causes air bubbles in the resin - especially on the outside of the liner - which can lead to leaks;
(d) individual, small pores in the laminate can also be caused by heating up or cooling down the CIPP liner too quickly or by curing temperatures that are too high.

These causes are typical faults linked with installation or preparation of a liner, rather than ageing of the pipe liner material.

IKT found no correlation between the short-term flexural modulus, flexural stress at first break, and the age or type of material used.

As shown in Table 1, four of the liners were needle felt liners with epoxy resin, the other 14 were needle felt liners with unsaturated polyester resin. The specifications required by the client were used as target values for the evaluation of these results. It was found that only three of the 18 liners were able to pass the water tightness test (test results: tight/leaky = passed/failed) according to APS test guideline (APS, 2004). For the short-term flexural modulus, five liners were able to

Table 1
Results of the 18 cipp samples from liners installed in Switzerland.

Sample No.	Nominal diameter of the sewer	Resin	Year of installation	Water tightness	ResultsShort-term flexural modulus [MPa]	Target Short-term flexural Modulus[MPa]	Results Short term flexural stress at first break[MPa]	Target Flexural stress at first break [MPa]	Measured Composit thickness[mm]
L0985-1	DN 300	UP	1990	**Fail**	3,190	2,800	44.52	36.00	4.66
L0985-2	DN 250	UP	1988	**Fail**	2,843	2,800	42.67	36.00	4.20
L0985-3	DN 250	UP	1986	**Fail**	2,976	2,800	42.57	36.00	4.50
L0985-4	DN 400	UP	1987	**Fail**	**2,296**	2,800	44.33	36.00	4.11
L0985-5	DN 300	UP	1988	**Fail**	**2,503**	2,800	43.59	36.00	4.88
L0985-6	DN 250	EP	1988	**Fail**	**2,030**	2,400	65.37	55.00	1.39
L0985-7	DN 250	UP	1988	**Fail**	**2,089**	2,800	41.55	36.00	3.72
L0985-8	DN 300	UP	1988	**Fail**	**2,304**	2,800	**33.88**	36.00	4.61
L0985-9	DN 250	EP	1993	Pass	**1,767**	2,400	**50.77**	55.00	4.97
L0985-10	DN 250	UP	1991	**Fail**	**2,366**	2,800	**34.82**	36.00	5.57
L0985-11	DN 350	UP	1991	**Fail**	3,294	2,800	52.92	36.00	6.07
L0985-12	DN 400	UP	1989	**Fail**	**2,685**	2,800	44.61	36.00	6.43
L0985-13	DN 400	EP	2000	Pass	**1,557**	2,400	**48.53**	55.00	9.12
L0985-14	DN 400	EP	1988	**Fail**	**1,151**	2,400	**52.07**	55.00	2.28
L0985-15	DN 600	UP	1982	**Fail**	**1,924**	2,800	**34.39**	36.00	7.74
L0985-16	DN 200	UP	1991	Pass	**2,730**	2,800	53.49	36.00	6.76
L0985-17	DN 300	UP	1988	**Fail**	**1,684**	2,800	**30.87**	36.00	4.22
L0985-18	DN 250	UP	1988	**Fail**	4,048	2,800	63.80	36.00	3.87

Pass = watertight.
Fail = leaky, water passes through the pipe wall.
In bold text where performance requirements were not fulfilled.
EP: Epoxy.
UP: Unsaturated Polyester.

achieve the required target values as defined in the relevant structural calculation. These were all needles felt liners with unsaturated polyester resin manufactured between 1986 and 1991. Eleven liners met the target values of the short-term flexural stress.

In Canada a traditional WRc/ASCE MOP 62 Risk Model was initially developed to establish the foundation for determining host pipe condition assessment priorities, rehabilitation intervention timing, and policy (Macey and Croft, 2017).

In the USA a database (Selvakumar et al., 2012) was set up to serve as a basis for an evaluation of rehabilitation techniques for water supply and wastewater networks, particularly with regard to the evaluation of the long-term behavior of installed CIPP liners. This study covered findings from samples obtained from 13 CIPP liners that had been installed between 4 and 34 years prior to sampling. The project (Selvakumar et al., 2012) was conducted by the Trenchless Technology Center at Louisiana Tech University. Initially, four liner samples were taken from operating sewers in two US cities (25 years, 23 years, 21 years, 5 years post-installation) and investigated for their mechanical properties. In addition, the existing environmental influences (including soil characteristics and pH value of the wastewater) were evaluated. All liner samples were rated as being “in excellent condition”. Samples were tested for wall thickness, annular gap, ovality, density, specific gravity, porosity, flexural strength, flexural modulus, tensile strength tensile modulus, surface hardness, glass transition temperature and Raman spectroscopy. Where the physical requirements were not met, this was not attributed to material deterioration, but as a quality variation within the liner section itself.

2.2. *Potential gaps*

Further information on studies on the performance of CIPP Liners can also be found as a chapter of the UKWIR Report CB/01/A/201 Sewer Rehabilitation Techniques (IKT for WRc 2020) (UK Water Industry and Research, 2019).

Results from investigations into the quality assurance of rehabilitation procedures of lateral sewer pipes can be found in Bosseler et al. (2001) and Bosseler and Schlüter (2003). As part of those studies, the quality of pipes rehabilitated using lining methods was also examined by taking liner samples and checking the mechanical parameters in the laboratory. The results of the investigation of Bosseler et al. (2001), and in particular the material and system tests, show that functional and watertight CIPP liners may not achieve the material characteristics parameters, which are required. There are indications that these deficiencies can be traced back to the installation.

Basic quality requirements for CIPP liner products and sound quality assurance on the construction site are of great importance when using this method to avoid mistakes at installation and to permanently ensure the success of a rehabilitation project and to fulfil the performance requirements for the sewer with regard to its stability, operation and water tightness over the planned service life of the installed liner. However, research also shows that defects can occur for a variety of reasons, such as ineffective sealing in the proximity of junctions and local features (e.g. lateral connection, manhole entry, manhole exit), where there are poorly cured areas or there are excessive geometrical imperfections (Pinnekamp et al., 2014; Bosseler and Beck, 2009; Bosseler et al., 2010; Bosseler et al., 2009).

In Germany, current post-installation inspection of liners by the supply chain and network owners is heavily biased towards CCTV inspection and to a much lesser extent determining material characteristics of samples. Whilst CCTV will confirm the positioning of a liner and will show up geometrical imperfections such as wrinkles that could affect serviceability of the sewer, it does not provide any information on the physical properties of a liner. Sampling of installed liners for laboratory testing is usually undertaken by cutting a sample from the end of a liner within a manhole not from within the lined pipe.

3. IKT's knowledge acquired to date

As an engineering research institute, IKT examines practical issues concerning the underground pipe and sewer infrastructure on behalf of the network operators and owners. The main testing and research projects on sewer rehabilitation undertaken by IKT are described and summarised below.

3.1. *Short term testing of liner samples by the IKT test Centre for CIPP liners (2003–2020)*

The IKT's Test Centre for Construction Products is a testing centre for CIPP liners and short liners that is recognised by the German Institute for Construction Technology (DIBt). It is accredited according to DIN EN ISO/IEC 17025 for selected mechanical-technological tests on polymer components of pipe and CIPP liner systems as well as GRP laminate cutouts. Since 2004, the IKT Test Centre has reported annually on the results of its CIPP liner tests in a series of publicly available 'IKT LinerReports' (Waniek and Homann, 2004; Waniek and Homann, 2009; Waniek and Homann, 2020). The main aim is to provide a transparent quality assessment for the clients involved in CIPP rehabilitation projects to enable a competitive market. To achieve this, samples of CIPP liners from installation sites are regularly sent to the IKT laboratory for modulus of elasticity, flexural strength, wall thickness and water tightness testing (Table 2). To be included in the IKT LinerReport, a rehabilitation company must have submitted for testing at least 25 samples of a type of liner from at least five different construction sites. The test results analysed to date have come from more than 70 rehabilitation companies from construction sites in Germany, Austria, Switzerland, The Netherlands, Belgium, Great Britain, France and Czech Republic, and a total of 22 different liner systems are listed in the IKT LinerReports. IKT produces this document to summarise the individual results and ranks them in order of performance to create transparency. The tests are analysed in terms of the variables described in Table 2. Between 2003 and 2020, a total of 30,000 samples taken from construction sites have been examined.

Fig. 1 shows the number of liner samples tested at IKT in each year from 2003 to 2020, which has shown a continuous upwards trend.

In 2020, only 87.5% of the CIPP liner samples passed all four test criteria (Fig. 2), while in the previous year, the comparative value was 93.1% and in 2016 it was 94.8%, indicating a recent lowering of the overall performance attained. The causes for this development cannot be attributed to individual influencing factors, even though the possible influences have already been presented in Bosseler et al., 2001 and Bosseler & Schlüter, 2003.

Table 2
Parameters investigated to assess the quality of the samples provided to IKT.

Short-term flexural modulus E_0	**Wall thickness** (average composite thickness)
• Short-term flexural modulus is used to determine the required linear thickness to resist to external pressure and to prevent a buckling failure. • Test method: Three-point bending test according to DIN EN ISO 178 and DIN EN ISO 11296-4.	• The required minimum wall thickness depends on the specific site related structural calculation. • Test method: mean composite thickness is measured with precision callipers according to DIN EN ISO 11296-4.
Flexural stress at first break σ_{fb}	**Water tightness**
• Definition according to ISO 11296, Annex B, Figure B.4 • Test method: Load increase in three-point bending test until failure; according to DIN EN ISO 178 and DIN EN ISO 11296-4.	• Examines whether water can pass through the liner wall under vacuum. • Test method: German Standard DWA-A 143-3, Section 7.2.9*.

*Reference DWA => DWA-A 143-3 Sanierung von Entwässerungssystemen außerhalb von Gebäuden. Teil 3: Vor Ort härtender Schlauchliner. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (German Association for Water, Wastewater and Waste), May 2014.

All the details of the tests conducted between 2015 and 2020 and the corresponding results can be found in English, German, Dutch, Japanese, Polish and Chinese within the annual reports shared by IKT (https://www.ikt.de/downloads/ikt-linerreport/).

3.2. *Projects on CIPP in sewer mains*

Two initial research projects were undertaken in 2001 (Bosseler et al., 2001) and 2003 (Bosseler & Schlüter, 2003) to carry out the first detailed condition assessment of in-service main sewers that had previously been rehabilitated using CIPP methods.

3.2.1. *Assessing the condition of previously rehabilitated sewers*

The condition of rehabilitated sewers was initially assessed using visual inspection and leakage testing on 15 sewer systems. To gain further knowledge for the operators of the sewer systems, material tests and tests of the static load-bearing capacity were carried out on excavated samples from rehabilitation sites. Since the majority of the rehabilitation installations were on non-man entry nominal diameter sewers, the removal of entire rehabilitated pipe sections of at least 2 m in length was necessary.

The focus of the first study (Bosseler et al., 2001) was to identify typical anomalies on 15 sections of liner (DN 250-DN 500) in six different cities in North Rhine-Westphalia, Germany. Anything that fundamentally deviated from the client's expectations of an "impeccable liner" (in accordance with the highest standards therefore faultless) was recorded as an anomaly. Based on extent of failure to the stability, water tightness or operational safety, these can also constitute a defect. So, an anomaly may or may not be a defect. This had to be evaluated separately in each individual case. Fig. 3 shows an overview of the anomalies investigated and identified.

With regard to wrinkling, a distinction must be made as to whether it is merely an accumulation of resin under the inner foil or if the wrinkling affects the entire wall thickness. In the latter case, the CIPP liner is no longer in contact with the wall of the host pipe. An example of this is shown in Fig. 4. Overlapping of the liner in the wrinkles increases the risk of insufficient curing of the resin. This means that the required material properties were not achieved, which poses a risk to the structural strength of the liner (Luimes/Scheperboer, 2022). In this example, a single wrinkle of 50 mm leads to instability of the CIPP liner, which cannot withstand groundwater pressure.

The overall condition of the 15 lined sewer sections was assessed using CCTV inspections and leak tests, and anomalies were found in all of the inspected sewers. These were generally localized and, in most cases (e.g., wrinkling in the longitudinal and annular directions and faulty integration of laterals), could be clearly traced back to individual installation errors. For eight of the fifteen sewer pipes inspected, an acceptance video had been made at the time of rehabilitation, on which the majority of these anomalies were already recognized. In the comparison with inspection data from the project (up to 5 years later), no noteworthy changes in the liner due to operational influences (after 2 to 5 years) could be detected.

3.2.2. *Criteria for quality assessment and life cycle assessment*

As part of the project, three "new" CIPP liners were installed within the IKT facility in specially constructed pipe runs in accordance with normal installation practice. In total, eleven different liner samples were examined. These included liners that had been cured using water, steam and UV, from concrete and clay host pipes with dimensions between DN 250 and DN 900. As a result of their examination, a test programme (Table 3) was developed to assess the quality of CIPP liners during their service life. The individual elements of the test concept can be used on a

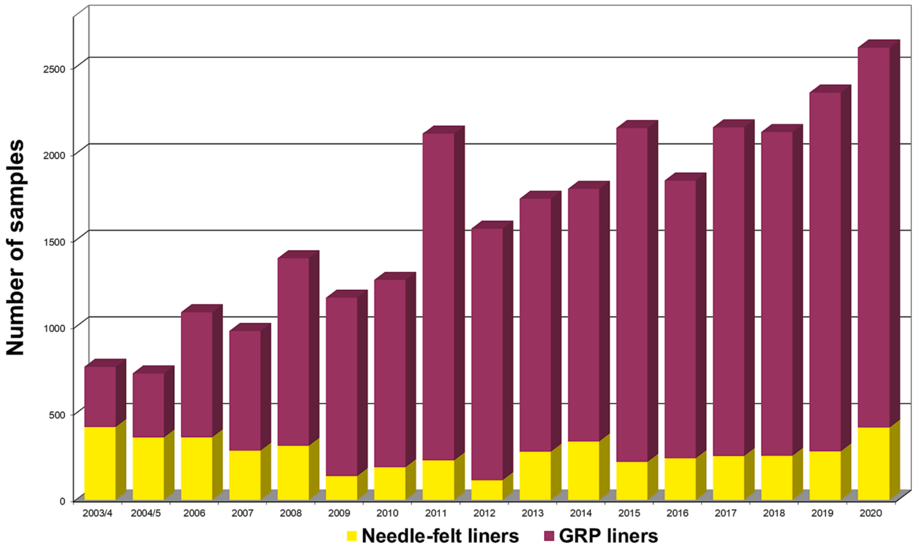


Fig. 1. Number of GRP and Needle-felt CIPP liner samples tested each year at IKT (IKT-Liner Reports from 2003 to 2020).

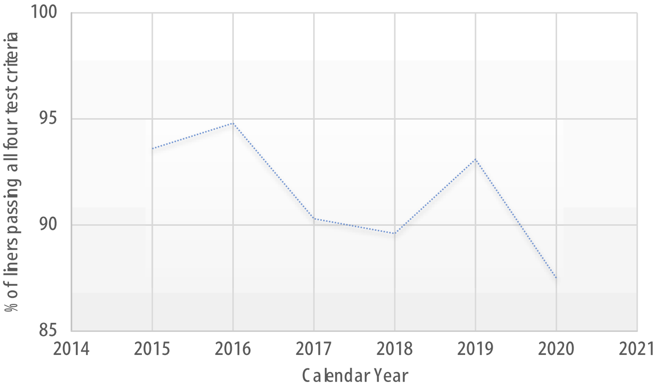


Fig. 2. Percentage of CIPP liner samples that passed all four test criteria at the same time at IKT Test Centre from 2015 to 2020.

case-by-case basis to support an adapted service life assessment, especially in the case of significant deviations from the contractually agreed quality requirements.

Three main points are important in this context:

(1) To date, the geometry of the CIPP liner had not been considered during monitoring on the construction side and in particular its influence on the stability. The test programme now took this into account.
(2) Test methods for the quality control are basically available and known. In particular, instructions for their application were further developed in the project.
(3) A further conclusion from the project was to carry out a warranty acceptance and observe the liner performance over time.

The test programme for life cycle quality assessment of CIPP liners developed from IKT research (modified from Bosseler et al., 2001; Bosseler & Schlüter, 2003) provides for an inspection period of 10 years because it was found that negative changes in CIPP liner material are in the majority of cases due to installation errors. Since it was not possible to examine the entire service life of 50 years of the pipe liner, it was recommended that the material properties of a pipe liner should be checked periodically at intervals of 10 years over the service life. This was a purely qualitative assessment made in consultation with the 10 sewer network operators involved in the project.

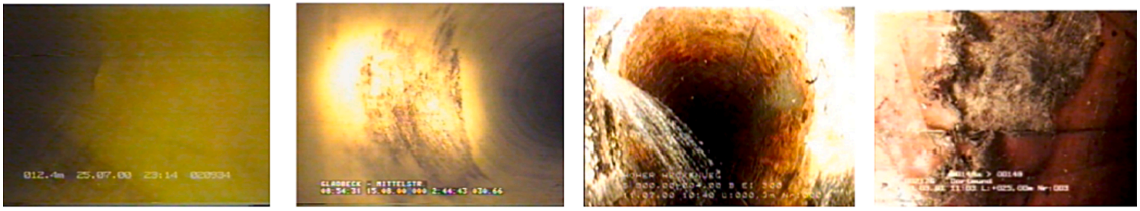
3.2.3. *Addressing the needs of drainage sewer operators*

Based on the experience gained from these two studies, IKT was asked to undertake a project called “Warranty acceptance of CIPP lining” (Bosseler and Beck, 2009) on behalf of five German sewer network operators. During the project, a total of about 40 samples of installed CIPP liners were taken. The influence of anomalies on the stability, operational safety, leak tightness and durability of the renovation was defined as an essential evaluation criterion for the study. Case-specific, detailed suggestions for dealing with anomalies were presented in an evaluation catalogue (Annex to Bosseler and Beck, 2009).

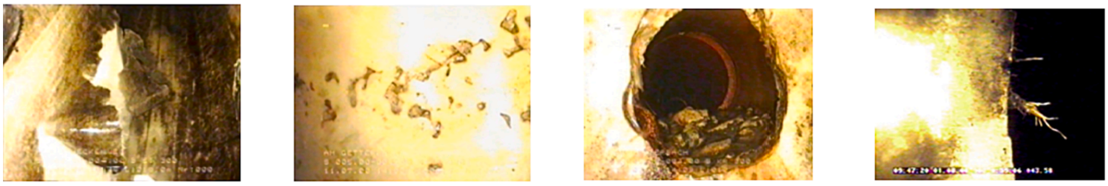
Subsequently, a project “*Acceptance of liner installations - material evidence and assessment of liner quality*” (Bosseler et al., 2009) was initiated to provide network operators with further information on the evaluation of results from the acceptance testing of CIPP liners. It built on the earlier research (Bosseler and Schlüter, 2003) and examined samples from 19 CIPP liners that had been installed for 4 to 14 years and a further 19 newly installed liners from 11 locations in North Rhine-Westphalia, Germany. Visual inspection (e.g., CCTV) was used to identify anomalies and deviations in the geometry and material properties and samples were taken to examine their possible effects on the stability, functionality, water tightness and durability of installed liners. 52 samples were examined from liners that had been installed for 4 to 14 years in circular (DN250 to 500) and egg shaped (DN 400/600 to 1000/1500) sewers, and once again this included water, steam and UV cured products. The new installations were used to examine how representative the samples taken in a manhole are of the condition of the liner within the host pipe. A total of 70 samples were taken in-situ from the 19 new lining installations from 2008 from both circular (DN200 – DN600) and egg shaped (DN 275/375 to 900/1350) host pipes. Furthermore, the project also investigated the extent to which innovative test methods could be used for the acceptance of lining measures.

In detail, this research (Bosseler et al., 2009) considered whether a correlation between the optical assessment of a liner sample and the achieved liner quality could be proven. For this purpose, test specimens of visually inconspicuous and visually conspicuous anomalies in liner samples – observed before the laboratory tests - were used and the test results for water tightness and mechanical characteristics were compared. It was shown that the results from the visual inspection alone were not sufficient to evaluate the quality of a CIPP lining performance measure in the course of the acceptance test. Particularly, many anomalies cannot be detected in the sewer during a purely visual inspection; they only become apparent under laboratory conditions, e.g., by inspecting the liner’s outer surface and wall structure. To provide

Transverse wrinkles Longitudinal wrinkles



Bulge Discolouration Leak at manhole (water entry) Exposed fibres



Inner foil/coating detached Air inclusion Improper connection Root penetration

Fig. 3. Documented anomalies from examinations on 15 liner sections (Bosseler et al., 2001).

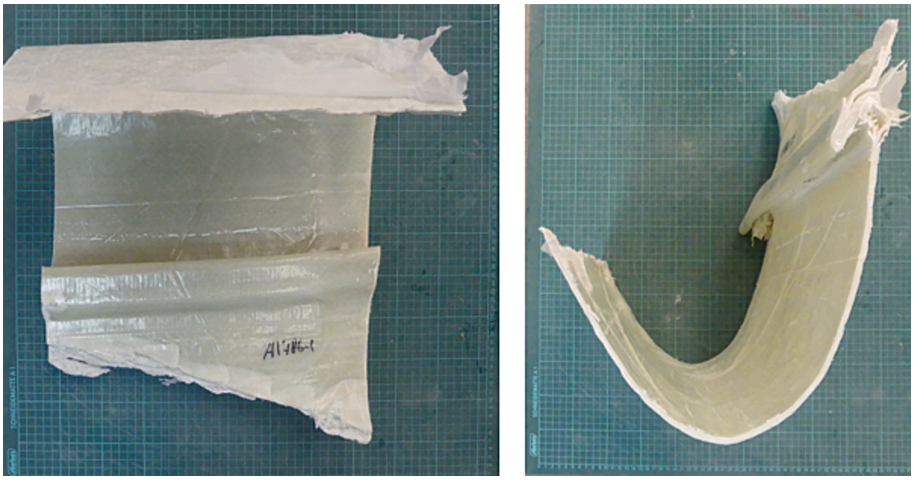


Fig. 4. CIPP liner with wrinkling that affects the entire wall thickness (Luimes/Scheperboer, 2022).

guidance on possible anomalies and their description for condition assessment, a condition catalogue of liner anomalies was compiled (Bosseler et al., 2009). This catalogue includes anomalies in the pipeline, as well as in the connection areas where lateral pipes join and where liners end in manholes and is based on a comprehensive survey that includes even extremely rare anomalies.

Within the framework of the monitoring of CIPP installations, the common practice of taking samples was questioned. For example, it had to be clarified whether the taking of a sample from the end of a liner in the manhole is representative for the entire length of the rehabilitated pipe section. To clarify this question, the sampling locations were varied, and samples were taken from the manhole, as well as, from within the pipe at different cross-section locations (crown, 90°, invert). Furthermore, it was randomly examined whether the time that had elapsed between cutting a sample from an installed liner to the time it was tested could have a significant influence on the test results of the mechanical short-term properties.

The results showed that nine out of 15 liners sampled demonstrated at least one shortfall against the expected values (for water tightness, wall thickness (composite wall thickness), modulus of elasticity or flexural stress at the first break), although in some cases only to a minor extent. These effects were already taken into account by using 5% fractile values as target values and using the mean value from the samples (usually 5 individual test specimens cut per sample). For the evaluation of a sample, the binary decision rule according ILAC-G8 (Global Association for the Accreditation of Laboratories, Inspection

Table 3
Test programme and correspondent parameters selected for life cycle quality assessment of CIPP liners developed from IKT research (modified from Bosseler et al., 2001; Bosseler & Schlüter, 2003).

Test	Achievable benefit	Taking CIPP liner samples during construction and operation		
		Time interval	Sampling location	Quantity/ Dimensions
Qualitative and quantitative status documentation				
Site protocol/sampling	Substantial benefit, cause of installation errors can be determined	Installation, ten years	Selection during inspection	2× Dug up
TV inspection	Substantial, most installation errors are visible, material changes detectable by before/after comparisons	Acceptance,2-yearly after cleaning	Section	6×
Water tightness test (according to legal requirement in Germany)*	Substantial, tightness cannot be determined otherwise	Acceptance, ten years	Sewer section	2×
Anular gap measurement	Substantial, non-visible, statically relevant defects	Acceptance, ten years	Proximity to manhole shaft	2×
Liner measurement	High benefit, statically relevant deficiencies	see above	see above	2×
High pressure cleaning	High benefit, relevant operational stress, no expense	See TV inspection	Section	6×
System properties				
Wall thickness	High benefit, very low effort, but statements on ageing processes not to be expected	see above	see above	6×, 15 pcs. from above samples
Three point bending test	Substantial, change due to ageing possible	see above	see above	see above
Chemical resistance**	Low benefit, low effort	see above	see above	see above
Water tightness (of samples)	see above	see above	see above	see above
Creep ratio (24 h)***	Substantial, possible influence of ageing	see above	see above	see above
Short-term parallel plate loading test	high benefit	Acceptance, ten years	2 m pipe	2×, 1 pc.
Long-term parallel plate loading test (10,000 h)	Substantial, ageing influence possible	see above	see above	see above same tube
Material properties				
IR spectroscopy, Density, loss on ignition	Identification of the materials used, indicative of cure and that the liner is wet out as it was supposed to be	Acceptance	Crown	3 pcs. 50x50 mm
DMA **Dynamic mechanical properties**	Detectable effects of material ageing, curing of resin can be checked	Acceptance, thereafter 2-yearly	Bottom, 90°, Crown	Each 3 pcs. 50x50 mm

[*] The water tightness test was developed in Germany (and formalised in a testing standard by DWA (DWA, 2014) or in the APS test guideline (APS, 2004)) in response to a national focus on avoiding groundwater pollution caused by exfiltration from sewers. If water can pass through the wall of a liner, it indicates that either the liner material was not fully impregnated with resin or that the curing process was incomplete. Hence results from this test also serve as a very useful performance monitoring measure as part of an installation quality assurance system. If samples fail on water tightness, then investigation of the installation process can identify and address the cause.

[**] Chemical resistance according to ISO 175 (BS EN ISO 175, 2010): This test can be used to check very easily and quickly on construction site samples whether a corrosion-resistant glass material has been used.

[***] Creep ratio (24 h) according to ISO 899-2 (ISO 899-2, 2003): This is about the 24-hour creep tendency and not about the 10,000-hour test. With the result of this 24-hour creep tendency, the long-term creep behaviour can be estimated on a construction site sample.

Bodies, Proficiency Testing) providers and reference material producers is applied, (Ilac, 2015).

Furthermore, counter examples were found for the hypothesis propagated on the market by the rehabilitation companies that manhole samples generally provide worse material characteristics than samples from within the pipe run. Liners sampled several times showed in some cases considerable scatter (of more than 20% of mechanical characteristic values and also different results in the water tightness test) both according to the location (manhole, beginning of liner, middle of liner, end of liner) and the cross-sectional position (invert, 90°, crown). The results of the testing of different test pieces cut from within a single sample also showed significant scatter (Table 4).

The results thus indicate that the standard sampling in the manhole only represents a random single value. No changes in properties were recorded between the time elapsed between cutting out of a sample from an installed liner to time when it was tested on the mechanical short-term properties originally.

Overall, it could be seen that the material properties of individual CIPP liners can vary greatly (up to 43 %, see Table 4). This concerns both the position along the length of a liner and over the cross-sectional circumference. Furthermore, strong scattering in test specimens cut from a sample was detected, so that even within the same test specimen significantly different test results were obtained (deviation from at least 10 to 20% were found almost on every test series).

3.2.4. Evaluation of other testing methods

The project also evaluated six non-destructive testing methods for quality control of the liners both in the laboratory and in-situ: 3D Laser Scanning, Temperature Measurement, Heat Flow Thermography, Local Resonance Spectroscopy, Ultrasonic Echo Method, and Impact Echo Method. It was shown that these methods have a high potential for application on CIPP liner systems, but that the state of the art of equipment technology does not (yet) offer an alternative to taking physical samples to check the achieved quality of rehabilitation. In particular, the equipment technology needs to be downsized or automated so that these test methods represent a meaningful supplement to the current quality assurance and acceptance by optical inspection and laboratory testing of liner samples.

3.3. Comparative tests of CIPP lining in lateral sewers

In a separate series of projects, various methods for the rehabilitation of lateral sewers (those connecting properties to main sewers) were comparatively examined in the large 1:1-scale test facility at IKT. In the first project (Kaltenhäuser, 2005) eight different lateral sewer lining products were subjected to comprehensive testing. An examination of quality assurance measures used by liner suppliers was undertaken to show the extent to which they supported high-quality rehabilitation when using their products. The product tests served to examine the limits of application of the products and the quality of rehabilitation that could be achieved. The products were installed in a total of 36 sections of sewer pipe in the IKT underground test facility. In addition, evaluations were undertaken at five installation sites in the field to verify the accuracy of the installation procedures witnessed in the laboratory and to record the practicability of installation of the systems under construction site conditions. As a result of these product tests which were

Table 4
Sampling on site, results of lab tests.

CIPP-Liner No.	Target Value	Test results mean values (except leak tightness) (values in bold where performance requirements were not fulfilled)	Coefficient of variation of the test results
No. 1	Tightness: pass	2 x pass	
DN 300	Short-term flexural modulus [MPa]: 9,500	12,510; 13,246; 13,258; 11,607	8%
GRP-UP	Short term flexural stress at first break [MPa]: 220	250.92; 266.72; 286.12; 255.04	7.7%
UV-curing	Composit thickness [mm]: 2.45 mm	4.78; 4.68; 4.64; 5.10	5.6%
No. 2	Tightness: pass	2 x pass	
DN 300	Short-term flexural modulus [MPa]: 9,500	11,950; 12,117; 15,177; 12,471; 13,499; 14,098	8.8%
GRP-UP	Short term flexural stress at first break [MPa]: 220	**156.45**; 236.53; 298.85; 224.10; 293.69; 246.77	19.6%
UV-curing	Composit thickness [mm]: 2,45	4.40; 4.87; 4.57; 4.86; 4.68; 4.09	6%
No. 3	Tightness: pass	2 x pass	
DN 250	Short-term flexural modulus [MPa]: 9,500	12,013; 13,525; 12,258; 11,219	10.1%
GRP-UP	Short term flexural stress at first break [MPa]: 220	221.26; 235.12; 245.40; 225.23	6.1%
UV-curing	Composit thickness [mm]: 3.5	4.15; 4.00; 4.19; 4.39	5%
No. 4	Tightness: pass	2 x pass	
DN 300	Short-term flexural modulus [MPa]: 9,500	10,722; 12,054; 12,491; 13,142	11%
GRP-UP	Short term flexural stress at first break [MPa]: 220	**183.50**; **202.59**; 225.69; 229.72	13.3%
UV-curing	Composit thickness [mm]: 3.5	4.35; 4.24; 4.19; 4.04	4%
No. 5	Tightness: pass	2 x pass	
DN 400	Short-term flexural modulus [MPa]: 9,500	10,128; 11,731; 11,467: 11,798	9%
GRP-UP	Short term flexural stress at first break [MPa]: 220	**125.13**; **169.89**; **142.89**; **172.43**	19.3%
UV-curing	Composit thickness [mm]: 4.2	6.04; 6.04; 5.92; 5.90	1.6%
No. 6	Tightness: pass	3 x pass	
DN 300	Short-term flexural modulus [MPa]: 9,500	10,098; **8,943**; 10,267; 11,007; 15,237; 15,229	21.2%
GRP-UP	Short term flexural stress at first break [MPa]: 220	**146.48**; **118.91**; **158.50**; **146.70**; 324.61; 334.91	43.4%
UV-curing	Composit thickness [mm]: 4.00	4.78; 4.83; 4.74; 4.53; 4.48; 4.26	4.3%
No. 7	Tightness: pass	Pass	
DN 400	Short-term flexural modulus [MPa]: 9,500	15,847	
GRP-UP	Short term flexural stress at first break [MPa]: 220	342.65	
UV-curing	Composit thickness [mm]: 5.6	5.74	
No. 8	Tightness: pass	**Fail**	
DN 300	Short-term flexural modulus [MPa]: 9,500	13,595;	
GRP-UP	Short term flexural stress at first break [MPa]: 220	303.27	
UV-curing	Composit thickness [mm]: 5.6	**4.94**	
No. 9	Tightness: pass	1 x pass / **1 x fail**	
Egg-shaped 400/600	Short-term flexural modulus [MPa]: 2,800	3,284; 3,251	1.5%
NF-UP	Short term flexural stress at first break [MPa]: 28	33.17; 31.82	6.23%
Hot water curing	Composit thickness [mm]: 9.00	11.03; 10.39	9%
No.10	Tightness: pass	5 x pass / **1 x fail**	
DN 500	Short-term flexural modulus [MPa]: 2,400	2,433; 2,591; 2,456; 2,403; **1,839;** 2,641	11%
NF-EP	Short term flexural stress at first break [MPa]: 55	68.79; 76.02; 66.26; 66.53; **46.17**; 78.17	15.5%
Hot water curing	Composit thickness [mm]: 6.00	9.85; 9.73; 9.71; 9.28; 9.76; 9.72	1.9%
No. 11	Tightness: pass	Pass	
DN 400	Short-term flexural modulus [MPa]: 7,985	13,198; 13,545	
GRP-UP	Short term flexural stress at first break [MPa]: 170	319.35; 296.38	
UV-curing	Composit thickness [mm]: 3.32	4.86; 5.18	

(*continued on next page*)

Table 4 (*continued*)

CIPP-Liner No.	Target Value	Test results mean values (except leak tightness) (values in bold where performance requirements were not fulfilled)	Coefficient of variation of the test results
No. 12 DN 250	Tightness: pass	pass	
	Short-term flexural modulus [MPa]: 7,985	11,476	
GRP-UP	Short term flexural stress at first break [MPa]: 170	236.32	
UV-curing	Composit thickness [mm]: 2.07	5.35	
No. 13 DN 500	Tightness: pass	3 x pass / **1 x fail**	
	Short-term flexural modulus [MPa]: 2,800	3,386; 3,603; 3,772; 3,377	7%
NF-UP	Short term flexural stress at first break [MPa]: 28	34.86; 37.29; 34.96; 31.76	8.5%
Hot water curing	Composit thickness [mm]: 7.20	8.25; 7.97; 7.52; 7.87	5%
No. 14 DN 450	Tightness: pass	1 x pass / **1 x fail**	
	Short-term flexural modulus [MPa]: 9,500	12,776	
GRP-UP	Short term flexural stress at first break [MPa]: 180	307.96	
steam curing	Composit thickness [mm]: 4.00	4.36	
No. 15	Tightness: pass	2 x pass	
Egg-shaped 1000/ 1500	Short-term flexural modulus [MPa]: 2,800	3,650; 3,489	6.8%
NF-UP	Short term flexural stress at first break [MPa]: 32	39.00; 37.00	7.9%
Hot water curing	Composit thickness [mm]: 29.10	32.62; 31.95	3.1%

undertaken in 2005 (Kaltenhäuser, 2005), the products included in the evaluation were improved by their suppliers and new CIPP lining systems were subsequently developed. IKT was commissioned in 2010 by a group of network operators for the comparative testing of the quality of CIPP liners for lateral sewers (Bosseler et al., 2010). In addition to the already established requirements from the completed project (Kaltenhäuser, 2005), the effects of external water pressure on the liners installed in lateral sewers were also comprehensively investigated at the 1:1 scale in the laboratory. A total of five products were evaluated in 30 sections of test pipes buried in the IKT test facility.

The results of the first test confirmed that the CIPP liners could in principle also be used for sewer lines with sharp bends and that the functionality of the connecting sewer can be restored. However, the water tightness requirements of the network operators were rarely met by most CIPP liners. The tests carried out also revealed considerable fluctuations in liner quality, both over the circumference and the length of the liners. Many liner manufacturers took these results as an opportunity to further develop their products. Accordingly, the second comparative test (2010) (Bosseler et al., 2010) showed significant improvement in product performance over the earlier project; the products hardly showed any significant wrinkling in bends and at offsets. In addition, all liners proved to be leak-proof in the air pressure test according to DIN EN 1610, even after being high-pressure jetted five times and occasional spinning chain cleaning. It was noted that the properties of laminate performance declared in product DIBt approvals with regard to impermeability and minimum wall thickness were not always achieved. The laminate, which was considered to be waterproof, was permeable to water, and in such cases the installation foil / coating or the bonding to the old pipe was found to have taken over the sealing function. In addition, considerable amounts of the liner resin leaked into the surrounding soil, especially at large damaged areas of the host pipe and leaking joints, so that a weakening of the wall thickness in these areas is to be expected.

When the liner/host pipe was affected by buoyancy uplift due to the formation of cracks, it was obvious that the bonding between liner and host pipe had stiffened the pipe-liner system excessively, inducing some systems to fail.

4. Summary of the major outcomes from previous studies

4.1. System behaviour

4.1.1. Scatter and inhomogeneity of material properties in multiple sampled liners

In Bosseler et al., 2009, for example, nine out of 15 CIPP liners sampled from previously rehabilitated sewers were found to fall short of at least one target value for the criteria of water tightness, wall thickness, modulus of elasticity or flexural strength. It was also found that liners can show considerable scattering of the mechanical characteristic values over the entire length of the sewer section and its circumference.

4.1.2. Annular gap between host pipe and liner

According to Bosseler & Schlüter (2003), the load-bearing capacity of the entire system (liner and host pipe) is considerably improved by a positive fit of the liner to the host pipe. However, practical experience shows that an annular gap between liner and host pipe may already be present immediately after installation. However, according to (Falter et al., 2003) an annular gap can also occur after a gap-free installation due to shrinkage of the liner. The formation of a gap between the liner and the host pipe depends on the process technology and the material properties of the liner. In Wagner, 1992, gaps of more than 2 mm were measured between the host pipe and the liner five-years after installation of the liner.

4.1.3. Pre-deformations (geometric imperfections) in installed liners

According to (Falter et al., 2003), pre-deformations - deviating from the ideal circular shape and other boundary conditions significantly reduce the buckling resistance of a liner.

These include local imperfections (e.g., wrinkles and flattening), possibly ovalisation (due to joint deformation in cracked host pipes) and the annular gap between the CIPP liner and the host pipe. These are formally taken into account in the static calculation for the design of CIPP liners. However, the standard values for the ovalisation are usually only 3 % (host pipe condition II) or 6 % (host pipe condition III) (DWA, 2015). However, in Bosseler & Schlüter, 2003 deformations of up to 23 % of the nominal diameter were determined on removed test specimens (Fig. 5a), exceeding the standard value of 3 % used in static calculation many times over. In other cases, wrinkles appeared in the circumferential direction (Fig. 5b).

Possible causes for transverse wrinkles can be, for example, offsets or positional deviations in pipe joints, compression of the liner during installation, particularly in bends, dimensional changes in the sewer,

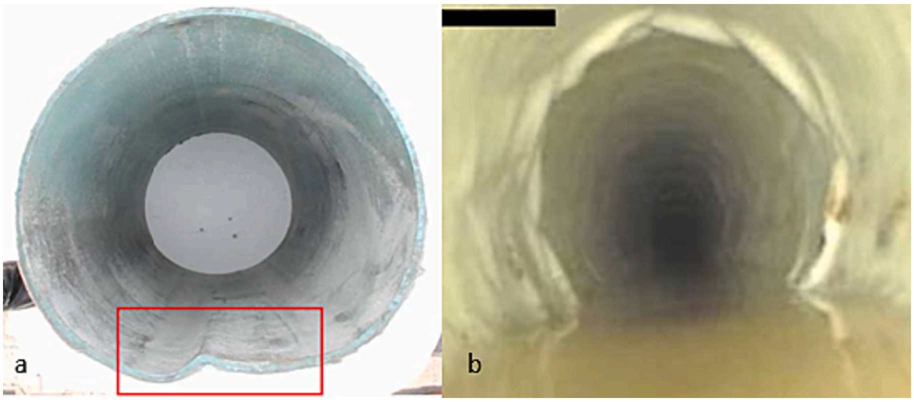


Fig. 5. Examples of imperfections in liners: a) Local pre-deformation at the bottom (Bosseler & Schlüter, 2003); b) wrinkles running in circumferential direction (Bosseler et al., 2009).

curves and other irregularities in the pipe, regularities in the host pipe and problems inserting the liner (Bosseler et al., 2009). As a rule, such wrinkles are statically less critical, but they can be points of attack on the liner when cleaning using high pressure jetting and a cause of sewer blockages forming.

4.1.4. *Operational loads*

Operational loads on an installed liner are essentially caused by the nature of the wastewater (e.g., chemical composition, sediment transport) or by maintenance and cleaning work (e.g. high-pressure cleaning), although these load scenarios are largely covered in approval tests (e.g., high-pressure flushing test according to DIN 19523 (DIN, 2008), abrasion test with the Darmstadt tipping trough based on EN 295-3 (BS EN ISO, 2012), test for chemical resistance based on ISO 175 (BS EN ISO, 2010).

4.1.5. *Behaviour under buoyancy with bonded liners*

In the IKT product test “House connection liner” (Bosseler et al., 2010), water infiltration was found in nine of 30 pipes rehabilitated using the CIPP lining method in the course of an external water pressure test in the IKT large-scale test facility. The infiltration points were located in the area of pipe joints in front of bends or lateral connections and examples are shown in Fig. 6. The detailed analysis after the excavation of the rehabilitated pipes showed that buoyancy effects were mainly responsible for the damage or leaks in the liner. As the groundwater level increased, the soil pressure was relieved and lifted, which in turn led to forced deformations (angling) in some of the host pipe joints. As a result, the liners, which were bonded to the host pipe, were overstretched at the opening pipe joints and eventually cracked.

4.2. *Loading*

In addition to these conclusions concerning the system behavior, the analysis of the research results obtained to date also shows which loading scenarios are of particular importance for product dimensioning and testing as well as for the development of service life-oriented quality assurance guidance.

4.2.1. *Imperfections and root pressure*

When installing the liner, localised imperfections (e.g., wrinkles, dents) cannot be completely avoided. This has to be taken into account when dimensioning the liner (e.g., according to (DWA, 2015) by applying corresponding minimum requirements regarding the local pre-deformation. However, it would have to be questioned whether the liner can actually fulfil these minimum requirements after installation.

Roots that have grown into the host pipe can grow again into the annular space between the host pipe and the liner (Fig. 7).

On one hand, there is a risk that the roots will emerge again at weak points (e.g., liner tie-in points in the area of the manhole or in the area of lateral connections). The roots can also exert a point pressure on the liner, which according to Stützel, 2004, can be up to 5 bar over a longer period of time. The deformation of the liner then depends essentially on the extent to which the host pipe represents an abutment for the root pressure.

4.2.2. *Production process*

In addition to these findings on the system behavior and the relevant load scenarios of CIPP liners, the research projects and testing activities evaluated also provide further interesting conclusions with regard to the actual CIPP production on site. The intensive site monitoring of twelve CIPP lining measures in (Bosseler et al., 2009) confirmed that the production of a CIPP liner for use in main sewers generally consists of two

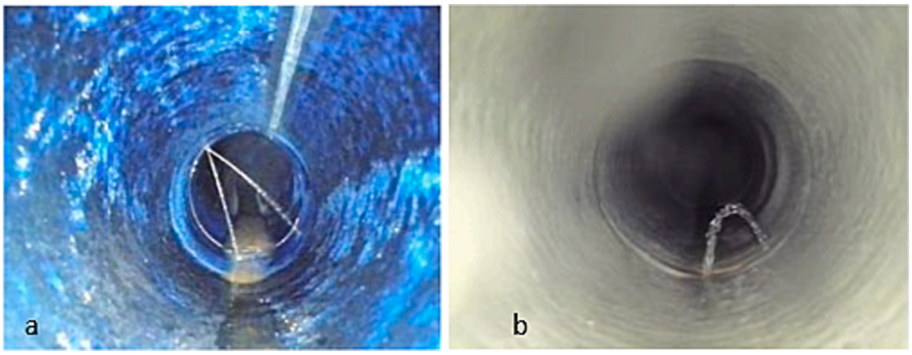


Fig. 6. Damaged areas with infiltration after groundwater level was raised in testing (Bosseler et al., 2010) for two different products.

Fig. 7. Root ingrowth between liner and host pipe.

essential, almost independent, production steps. Firstly, the CIPP liner is manufactured in the factory as a prefabricated, resin-impregnated carrier material in hose form and delivered to the construction site. In the second step, the CIPP liner is inserted into the old pipe, placed there under water or air pressure and cured into a pipe, if necessary also using hot water steam or UV radiation. Only in the course of curing does the CIPP liner obtain its final geometric and material properties as a new pipe in the old pipe-soil system. Accordingly, quality deviations or anomalies that only occur in the second process phase can only be detected in the installed state of the finished product.

However, a completely defect-free production ("zero rejects") of a CIPP liner in industrial production cannot be expected, if only for reasons of economy. Major fluctuations in the manufacturing process are to be expected in particular due to the locally fluctuating production conditions and here in particular the uneven old pipe conditions. Thus, the detection and elimination of defects in CIPP liner production must also include the second part of pipe production, the installation process on site, if possible already within the framework of the internal quality assurance of the executing companies. In addition to the actual prevention or elimination of defects, this also applies to the repair of any affected liner sections with the aim of achieving consistent new pipe quality.

5. Unified research ideas

When using CIPP liners, the resulting renovation can be strongly influenced by external factors, as the finished product is only created at the installation site on the day of installation. However, the current standard for quality assurance of this widespread renovation method is only aimed at the pure material characteristics of the liner. Sampling of the CIPP liner is usually only carried out in the manhole structure, therefore, to better deal with this aspect in the future, there are significant needs that should be researched in the future as follows.

5.1. Investigation of the quality of the overall system CIPP liner - host pipe over the complete length

Previous research projects (Riechel, 2017; Selvakumar et al., 2012; Bosseler et al., 2001; Bosseler and Schlüter, 2003; Pinnekamp et al., 2014; Bosseler and Beck, 2009; Bosseler et al., 2009) are essentially based only on material samples from in-situ installations, which were taken in the manhole or in isolated cases in the sewer section, as continuous sampling along the entire length of a complete sewer section was not possible. However, when using the CIPP liner process there can be a scattering of material quality within a lined section of sewer. According to (Bosseler et al., 2009), this can be caused, for example, by variations in the curing process, variations in the quality of the starting materials and the sensitivity of the process and material to fluctuating environmental conditions during installation. A systematic investigation of the overall system "host pipe - liner", in which not only the material characteristics at one or two sampling points are of interest, but also the material quality, the geometry and stability over the entire sewer section, has yet to be carried out. There is a lack of a non-destructive in-situ testing method with which the stability of the system can be checked with reasonable effort. Furthermore, the connections of the CIPP liners at laterals and at manholes often show quality deficiencies, as corresponding investigations confirmed (Vogel, 2018). Therefore, the complete system of liner – lateral connections – end connections should also be investigated further.

5.2. Investigation of performance in egg-shaped profiles

CIPP liners are also increasingly used in non-circular, egg-shaped profiles. This raises questions about the performance spectrum and the rehabilitation quality, as an ovalised shape of the liner has a less favorable stress distribution than that of the ideal shape of the circle. As a result, a considerably lower buckling resistance is to be expected in the flatter areas (lateral surfaces). Furthermore, according to Vogel, 2018, egg-shaped profiles can hinder the inflation (expansion with compressed air or water) of the liners in the host pipe prior to curing, e.g., due to increased frictional forces along the steep side surfaces. As a result, geometric imperfections and larger gaps between the host pipe and the liner can occur. Here, too, the question arises as to what the current systems actually achieve. The load-bearing behavior of egg-shaped profiles should be further investigated in 1:1 scale laboratory test to get reproducible results under definable boundary conditions.

5.3. Investigation of life cycle influences

Since in the CIPP lining process, the finished product is only created underground on the construction site, the pipe production is exposed to many external influences, such as qualification of the personnel, accessibility, and host pipe damage pattern and condition. The longer life cycle of a CIPP liner is also characterised by many external and operational influences (e.g., external water pressure, high-pressure cleaning, earth and traffic loads), which can influence the material properties (e.g., creep, abrasion). However, previous research projects do not represent the complete life cycle, as sampling was usually only carried out at a certain point in time. Furthermore, when sampling liners in operation within the scope of these projects, information on the boundary conditions and influencing factors found during installation was often missing. This is where further investigations should start and the typical load scenarios for a life cycle should be applied in laboratory tests, e.g., high-pressure cleaning, abrasion, external water pressure and earth and traffic loads.

By applying a corresponding number of load changes, for example, a time-lapse can be generated that depicts the actual service life. The exact load scenarios should be agreed with practitioners of sewer operation.

6. Conclusions

This study has confirmed that quality assurance within CIPP liners, in terms of products and activities on the construction site, is fundamental and required at all stages, not only when the materials are produced but also when they are fitted to rehabilitate existing sewer systems. More in detail, this manuscript has summarized quality assurance issues that are linked with installation or preparation of a liner that could be causing faults that may interfere with the stability, operation and water tightness over the planned service life of the installed liner, such as:

- insufficient impregnation of the liner before installation. Insufficient resin in the liner could expose areas where the carrier material is not completely enclosed, generating leaks through the liner wall;

- insufficient contact pressure when installing and curing the liner. In this case, the resin-carrier material system is not sufficiently compacted, generating air pockets that can lead to leaks though the liner;
- when installing the liner without a pre-liner between it and the host pipe, uncured resin can come into contact with water on the outside of the liner. If lower-quality resins are used, "saponification" can occur, the resin foams up, producing air bubbles in the resin that can lead to leaks;
- individual, small pores in the laminate can also be caused by heating up or cooling down the CIPP liner too quickly or by curing temperatures that are too high.

Furthermore, research presented in this paper (Bosseler and Beck, 2009; Bosseler et al., 2010; Bosseler et al., 2009) also showed that defects can occur for ineffective sealing in the proximity of junctions and local features (e.g. lateral connection, manhole entry, manhole exit), where there are poorly cured areas or there are excessive geometrical imperfections.

Being this study mainly focused on Germany, it was noted that the current post-installation inspection of liners by the supply chain and network owners is heavily biased towards CCTV inspection and to a much lesser extent determining material characteristics of samples. However, this study confirmed that whilst CCTV can confirm the positioning of a liner and can show up geometrical imperfections such as wrinkles that could affect serviceability of the sewer, it does not provide any information on the physical properties of a liner. Thus, in order to support stakeholders, another main goal of this study was also to highlight the IKT laboratory developed to test modulus of elasticity, flexural strength, wall thickness and water tightness of CIPP liners samples. Results obtained from this facility confirmed that water tightness requirements of the network operators involved were rarely met by most CIPP liners and the tests carried out also revealed considerable fluctuations in liner quality, both over the circumference and the length of the liners. These results were extremely important because they gave an opportunity to many liner manufacturers to further develop their products.

Furthermore, this study has identified crucial research gaps that need to be investigated in the future to support decision makers and engineers in stipulating evaluation procedures, degradation mechanisms and deterioration rates to be considered for CIPP liners at installation and in-service. The key gaps can be summarized as follows:

- Taking in consideration the material quality, the geometry and stability properties, there is the need to develop a non-destructive in-situ testing method with which the stability of the system can be checked, plus there should also be a focus on lateral connections – end connections and their implications.
- Considering dissimilar load-bearing reserves, it is important to examine to what extent weakening effects arise when liners are not installed perfectly.
- The load-bearing behavior of egg-shaped profiles should be further investigated in 1:1 scale laboratory test to get reproducible results under definable boundary conditions.
- Life cycle scenarios should be applied with laboratory tests in order to provide further insights associated with high-pressure cleaning, abrasion, external water pressure and earth and traffic loads.
- Bendability, annular gap dimension, pre-deformation, wrinkling, resistance to external water pressure, homogeneity of the material properties and geometry factors are also decisive for the quality of a CIPP liner rehabilitation, thus, there is a need to conduct further investigations that would allow a real product comparison that is not only based on the material quality of individual test pieces.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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