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Sustainable Rehabilitation of Urban Sewers Using In-Situ Lining Techniques

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Abstract. This article investigates the impact of service-induced imperfections in underground pipelines on the structural performance of pipelines rehabilitated using Cured-In-Place Pipe (CIPP) technology. The novelty of the implemented research program is the expansion of knowledge regarding the safe use of pipelines, which in turn has a direct impact on the reduction of the number of failures of transport infrastructure. These irregularities in pipelines directly contribute to increased energy consumption in sewage treatment operations, higher exhaust emissions due to reduced vehicle speeds that are caused by infrastructure failures, and the elevated operational costs associated with road traffic disruptions. Therefore, maintaining underground pipelines in a proper technical condition is an extremely important issue that directly affects energy consumption. CIPP technology, which is the subject of this paper, can be classified as an eco-friendly urban solution that can reduce this consumption. Thanks to the data collected during the implementation of the laboratory tests described in this paper, it will be possible to precisely determine the effect of the geometric changes in the cross-section and the linear damage of the conduit undergoing renovation on the strength parameters of the combined "pipeline - CIPP lining" structure. The author's previous observations and experience gained during the design and implementation of repairs using sleeve technologies confirm the need for a thorough individual analysis of damage and changes in a pipeline's geometry before it undergoes renovation. The results of the conducted original research contribute to the current understanding of the load-bearing capacity of pipes with deformed cross-sections that have been reconstructed using CIPP technology, which in turn has a fundamental impact on the safety of the operation of sewers.

Key words: pipeline rehabilitation, trenchless technologies, cured in place pipe, CIPP, ring stiffness

1. INTRODUCTION

The length of the sewage network in Poland increases year by year by about 2-3% [1], and is currently over 185 thousand km long. Most of it is over 70 years old. In many cities there are still sewage systems that were built at the end of the 19th century and at the beginning of the 20th century [2]. Despite ongoing investments, which involve the repair and restoration of sewage networks, a huge number of them remain damaged and require renovation in a short period of time. Such sewage systems pose a significant threat to the natural environment, e.g. groundwater and soil [3]. Blocked and leaky sewage systems can release sewage pollutants into the environment in the form of uncontrolled discharges or exfiltration [4].

Conversely, the infiltration of groundwater into sewage systems also poses a threat to the environment. It may cause hydraulic overload of the entire sewage system, and in particular of sewage treatment plants, which then results in increased network operating costs and a deterioration of the quality of sewage treatment. [5].

It is also worth mentioning combined sewage systems. In such systems, emergency discharges in overflow facilities may be necessary due to the infiltration of groundwater and an increase in the amount of sewage. This can cause the additional contamination of water reservoirs.

The basic types of irregularities and damage that can be seen in sewage networks, which result from their technical wear and tear, are as follows:

- deformations of the cross-sections of conduits, which are due to structural cracks (Fig. 1),
- reductions in the diameter of conduits, which result from the accumulation of hard sediments (Fig. 2). This in turn has an influence on the deterioration of hydraulic parameters,
- longitudinal and transverse crumbling of conduit walls. In the case of conduits made of brittle materials, this may lead to the failure of both the network and the surrounding infrastructure (Fig. 3).

Some of the most popular methods of repairing network infrastructure are trenchless technologies, which involve the installation of linings made of technical fabrics that are cured on site (CIPP) in conduits under renovation. These techniques are used all over the world for the renovation of sewage systems and other pipelines [6]. They have become the most used group of methods for renovating damaged sewage conduits and pipes in Poland [7]. The CIPP method has become the basic solution for repairing sewage networks, and has a significant impact on the protection of soil, groundwater and surface water [8].

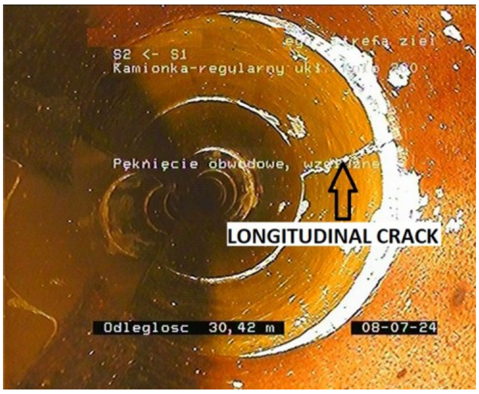

Fig.1. Example of a longitudinal crack

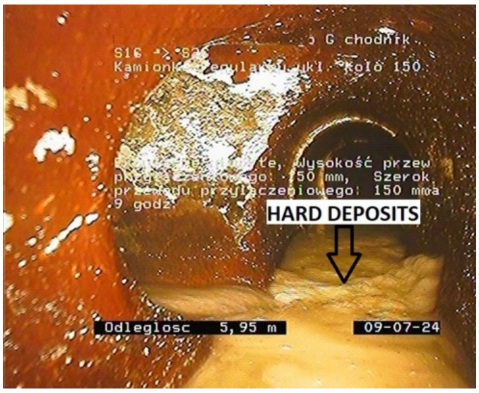

Fig.2. Example of hard deposits

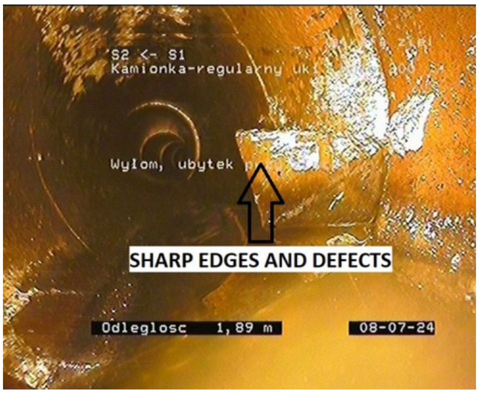

Fig.3. Example of sharp edges and defects

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It should also be noted that in the case of renovating municipal sewage networks, trenchless repairs are used due to the ease and speed of their application. They allow for the minimization of difficulties in the functioning of a city. Moreover, energy consumption resulting from traffic disruptions is also limited to a minimum. The short times of repair conducted with the use of CIPP technology lead to an optimization in energy consumption.

The technical conditions to be met by CIPP linings, the guidelines for assembly procedures, and the production of lining components are regulated by standards and regulations resulting from many years of experience, research and the application of linings. Such standards and technical regulations include, among others:

- ISO 11296-4:2018 - Plastics piping systems for renovation of underground non-pressure drainage and sewerage networks Part 4: Lining with cured-in-place pipes [9],
- ISO 11297-4:2018 - Plastics piping systems for renovation of underground drainage and sewerage networks under pressure Part 4: Lining with cured-in-place pipes [10],
- EN 15885:2018 - Classification and characteristics of techniques for renovation, repair and replacement of drains and sewers [11],
- ASTM F1216 - Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube [12],
- ASTM F2019 - Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass Reinforced Plastic Cured-in-Place Pipe (GRP-CIPP) Using the UV-Light Curing Method [13],
- PN-EN 1228:1999 - Plastic piping systems - Glass fibre pipes reinforced with thermosetting plastics (GRP) - Determination of the initial specific ring stiffness [14]
- ISO 7685:1998 - Plastics piping systems — Glass-reinforced thermosetting plastics (GRP) pipes — Determination of initial specific ring stiffness [15]
- ISO 10466 - Plastics piping systems — Glass-reinforced thermosetting plastics (GRP) pipes — Test method to prove the resistance to initial ring deflection [16]
- PN-EN ISO 178:2019-06 Plastics - Determination of bending properties [17]

The process of installing a CIPP lining in a host pipeline has been described extensively in literature [18]. The installation procedure includes two basic stages: the stage of inserting the lining into the existing pipeline, and the stage of curing the introduced lining. The first stage, i.e. the installation, can be carried out by inverting the liner, or by pulling it with a winch. Such a liner is then inflated with water or compressed air. In addition, it is possible to install such a lining using a combination of both methods. The second stage is the curing process, which can be triggered or accelerated by heat (hot water, steam or electric heating), UV radiation, or the ambient temperature.

2. RESEARCH SIGNIFICANCE

Despite extensive knowledge and the many established conditions and guidelines that aim to ensure the required quality of an installed lining, and due to the fact that the finished lining is always created on site, it is difficult to always achieve identical, standard parameters. Therefore, it is necessary to conduct research that involves models with properties that differ from the parameters of the reference samples (without imperfections).

Many studies concerning damage that can be identified in CIPP linings, or the expected service life of these structures [19], have been conducted. Research on CIPP linings takes into account various parameters that affect the durability of renovation work.

Knowledge about the parameters of CIPP linings, their cooperation with the repaired pipeline, and the impact they may have on the functioning of the network and road infrastructure is constantly being deepened. Many scientists around the world are involved in expanding knowledge in this area, which effectively contributes to the optimization of CIPP technology. The conducted research has led to the improvement of the quality of design work, which in turn has resulted in a better technical condition of pipelines.

Paper [20] describes tests of damaged connections between concrete pipes reinforced with CIPP lining. The aim of the tests was to determine the actual value of the load-bearing capacity of a composite system (a concrete pipe and CIPP lining) in the place of the damaged connection between the concrete pipes. The tests were performed in two directions – longitudinal and transverse. The conclusions from the performed analysis indicate the need for an individual approach to this type of damage.

In turn, the authors of paper [21] described tests performed on a liner with a diameter of 600 mm. The analyzed problem concerned the effect of the buckling of a CIPP liner, which resulted from the irregularities in the pipe's connections. The research involved the assessment of the effect of the size of ovalization on the value of permissible external loads. The obtained results are important for the process of designing CIPP liners, and the scope of the research described in the paper closely refers to the problems explored by the author of the current article.

The authors of paper [22] conducted full-scale tests of models of pipes reinforced with CIPP lining, and also performed simulations using the FEM method. The analysis was carried out for pipes with a diameter of 600 mm and 1000 mm. The influence of ovalization, the annular gap, and lining deformations on the change in the value of loads that can affect a pipeline reinforced with CIPP lining was studied. The authors of paper [23] analyzed the issue of the cooperation between the soil medium surrounding an existing damaged pipeline and CIPP lining. The aim of their scientific work was to propose a numerical model that takes into account the mutual cooperation between the lining, pipe and soil. Their research resulted in the determination of modelling guidelines that allow for the optimization of the designed solution and the obtaining of economic benefits.

In turn, the author's current research covers two areas:

- nano-scale CIPP lining sample analyses [24] that cover the following issues:
  - the insufficient impregnation of lining before its installation. If there is too little resin in the lining, there will be areas where the carrier material is not completely surrounded by the cured resin. These imperfections can then cause leaks through the lining wall;
  - the presence of individual small pores in the lining, which can be caused by heating or cooling it too quickly, or by curing temperatures that are too high,
- macroscopic examination of CIPP lining samples, including:
  - imperfections that occur in conduits: solid deposits and geometry disturbances (Fig. 4a, b),
  - the scale of damage – the number of cracks in the cross-section of a conduit.

The author's research on CIPP linings, which has been conducted over many years, has recently been supplemented with nano-scale analysis. An important parameter that is responsible for the durability of CIPP linings is the porosity of the material's structure. Therefore, in addition to strength tests, research using computed tomography was also conducted. Its aim was to determine the porosity of the CIPP lining material, and to conduct analysis of the effect of the porosity on the durability of the CIPP lining.

Thanks to the research conducted by the author, optimization regarding the appropriate selection of the type of CIPP lining is possible. Knowledge gathered during the research work enables the design process to be based on the actual technical condition of pipelines (determined during diagnostic investigations using e.g. CCTV inspections). In addition, the results of the conducted research allow for the extension of analyses with regards to the forecasting of the durability of repairs using CIPP technology. The previous research, conducted by other researchers and described in the above-mentioned articles, did not cover the subject of the author's scientific work.

In the case of CIPP linings, no research has been conducted on full-scale models with regards to the verification of the change in strength parameters as a result of irregularities such as cracks, cross-sectional deformations, and the accumulation of sediment in existing pipelines.

The obtained results constitute a new set of data, which, in connection with the information gathered by other researchers, expands the knowledge that is necessary for the correct design of pipeline repairs.

3. LABORATORY TESTS

3.1. Preparation of the research samples

The paper focuses on the initial stage of laboratory testing, which involves the evaluation of lining samples that are installed in conduits with a circular cross-section.

Within the scope of this stage of the research, reference tests were carried out on a model of a pipeline without any damage.

Individual elements of the pipe-lining system were tested separately in order to determine their actual strength parameters and the change in these parameters, which results from the cooperation of both structures, i.e. the host pipe and the CIPP lining.

The tests were carried out on two medium pipes, i.e. pipes with a diameter of 200 mm and pipes with a diameter of 300 mm. PVC pipes with a declared circumferential stiffness of 4 and 8 kN/m^2 were used as the host pipes. The basic parameters and selected mechanical properties are indicated in Tables No. 1. and No. 2. A liner made of technical fabric was used as the CIPP lining. The fabric was polyester felt covered with a 0.56 mm thick layer of polypropylene. The edges of this lining were sewn in order to obtain a sleeve with dimensions adapted to the repaired conduit, and the stitching was then additionally sealed. The roughness coefficient of the inner side of the sleeve was 0.01 mm. The used epoxy resin was a solvent-free, two-component resin that provides excellent adhesion to all sewage materials, even in conditions of high humidity and a high water content. Both materials (polyester felt and resin) are resistant to chemicals and gases that are present in sewage. They are also chemically resistant to the impact of deposited sediments. Their chemical resistance is maintained at temperatures of up to 60°C and within the pH range of 4-9.

TABLE 1. Basic parameters of the host PVC pipe

Diameter [mm]	200		300	
Declared circumferential stiffness [kN/m^2]	4.0	8.0	4.0	8.0
Wall thickness [mm]	4.9	5.9	7.7	9.2

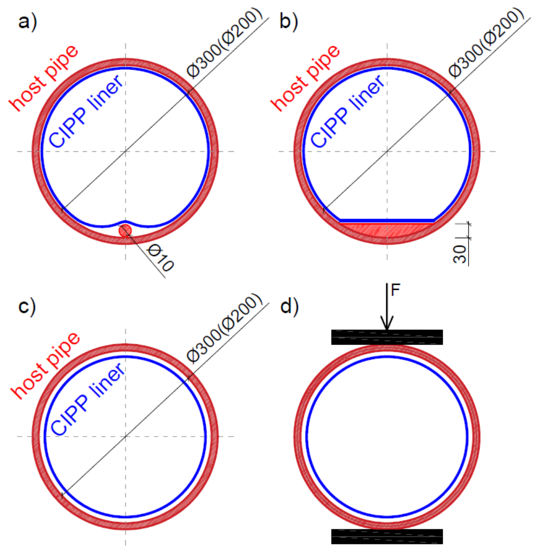

Fig.4. Schematic diagrams of laboratory models: a - model with a fold, b - model with deposits, c - reference model, d - research scheme

TABLE 2. Selected mechanical properties of the used CIPP lining

Bending strength	Young's modulus E	Young's modulus E	Elongation
Short-term	Short-term	Long-term	Short-term
MPa	MPa	MPa	%
30	2400	1200	0.75

Test samples were made in field conditions using tools and machines that are used in real conditions during the application of CIPP linings in conduits. The installation of the lining was carried out by a specialized team with appropriate qualifications and experience, which was confirmed by the supplier of the CIPP lining. The installation process consisted of:

- laying and stabilizing the model host pipeline (DN200 and DN300 PVC pipes) that had a length of 9 m,
- setting up an inversion tower to enable the insertion of the CIPP lining inside the host pipe,
- impregnating the CIPP lining with resin – performed in a mobile impregnation plant,
- inserting the lining inside the pipe's section using the pressure of a water column; the inversion was performed using a water column pressure of 5 mH20, i.e. a hydrostatic water column pressure equal to 0.5 bar,
- pressing the lining to the host pipe's wall by applying the required value of internal pressure,
- carrying out the heating process of the lining, which in turn led to its hardening,
- completing the renovation process.

The production process of the samples is shown in Figure 5.

Fig.5. Inversion tower and the insertion of the CIPP lining into the PVC pipe

3.2. Testing of the lining sections and the conducting of verification calculations.

In the case of real implementation conditions, it is difficult to obtain full fragments of the lining for testing due to the fact that it is not possible to cut out the entire cross-section of the made lining from the host pipe. Therefore, a three-point bending test is often performed as part of the acceptance tests. This involves the determination of bending properties, which is performed in accordance with the PN-EN ISO 14125:2001 [25] or PN-EN ISO 178:2011 [17] standards. The test samples are most often sections of a hardened CIPP lining that are taken in the circumferential direction in accordance with PN-EN ISO 11296-4:2018-03 [9].

Moreover, at the stage of designing the renovation, the required parameters of the CIPP lining are selected on the basis of conducted calculations. The determination of the thickness, and the circumferential stiffness or bending strength directly related to it, is crucial [26].

$$S_o = \frac{E_R * J}{d_m^3} = \frac{E_R}{12}\left(\frac{s}{d_m}\right)^3 \quad [1]$$

Ring stiffness S_o, as a derivative of the CIPP lining's thickness, was calculated using Formula [1]:

where:

E_R – the modulus of elasticity of the lining [N/mm^2],

J – the unit moment of inertia of the lining's wall [N/mm^2],

s – the lining's thickness [mm],

d_m - the average diameter of the lining [mm].

In the case of short-term conditions, the value of the short-term modulus of elasticity E_{RK} should be used in the above formula. In the case of long-term conditions, the value of the long-term modulus of elasticity E_{RL} should be used. The samples of the hardened resin lining, which were taken after the completion of the rehabilitation of the conduit, were checked in laboratory conditions in order to see if they achieved the circumferential stiffness calculated from the above formula for the short-term modulus of elasticity.

3.3. Laboratory tests of the reference samples.

The series of tests of the reference samples allowed for the determination of the ring stiffness of the:

- PVC pipe - Figure 6,

Fig.6. PVC pipe

- CIPP lining – Figure 7,

Fig.7. CIPP liner

Fig.8. Composite structure –PVC pipe + CIPP liner

- Composite structure – Figure 8.

Laboratory tests of the full-size samples were based on the method of testing the initial specific ring stiffness according to PN-EN 1228:1999 [14] and ISO 7685 [15], as well as the method of testing the resistance to initial annular deflections according to ISO 10466 [16]. As mentioned in the "Research significance" section, the tests were divided into two stages:

- stage I – testing of the reference samples in order to determine the actual stiffness of the host pipe model, CIPP lining model, and the combined pipe-CIPP lining model,
- stage II - these tests included, among others, samples with modeled damage according to state III (two and four longitudinal linear cuts that weaken the host pipe), and also samples with changes in the cross-section geometry in the form of deposits and sharp edges.

Moreover, during the tests, in addition to the parameters required by the standards (a loading force and the deflection of a sample's diameter), the following values were recorded:

- transverse deflections of the material of the inner surface of the CIPP lining at the four most stressed points, i.e. at the top, bottom and in the groins. The tests were conducted using electro-resistance strain gauges,

- changes in the shape of the cross-section of the CIPP lining in the plane perpendicular to the pipe's axis. The tests were conducted using a laser scanner.

During the tests performed for stage I (Figs. 9, 10, 11), the change in the real ring stiffness of the tested models, which was occurred as a result of installing the CIPP lining inside the host pipeline, was determined. The obtained results are presented in the tables below. The research results are presented in Tables 3, 4, 5 and 6.

TABLE 3. Results of the simulations for sample DN200 SN4

Model No.	Existing pipe	CIPP lining	Existing pipe + CIPP lining
	Ring stiffness [kN/m^2]		
1-DN200-SN4	6.224	5.668	12.522
2-DN200-SN4	6.209	5.685	12.775
3-DN200-SN4	6.286	5.664	13.298
Average value	*6.239*	*5.672*	*12.865*

TABLE 4. Results of the simulations for sample DN200 SN8

Model No.	Existing pipe	CIPP lining	Existing pipe + CIPP lining
	Ring stiffness [kN/m^2]		
1-DN200-SN8	11.248	5.840	18.998
2-DN200-SN8	11.683	5.479	18.865
3-DN200-SN8	10.559	6.097	18.395
Average value	*11.163*	*5.805*	*18.752*

TABLE 5. Results of the simulations for sample DN300 SN4

Model No.	Existing pipe	CIPP lining	Existing pipe + CIPP lining
	Ring stiffness [kN/m^2]		
1-DN300-SN4	5.705	4.613	10.648
2-DN300-SN4	5.586	4.804	10.718
3-DN300-SN4	5.683	4.220	10.322
Average value	*5.658*	*4.545*	*10.562*

TABLE 6. Results of the simulations for sample DN300 SN8

Model No.	Existing pipe	CIPP lining	Existing pipe + CIPP lining
	Ring stiffness [kN/m^2]		
1-DN300-SN8	10.062	4.416	14.525
2-DN300-SN8	10.070	4.516	14.256
3-DN300-SN8	9.981	4.707	14.703
Average value	*10.037*	*4.546*	*14.494*

Fig.10. Testing of the reference sample

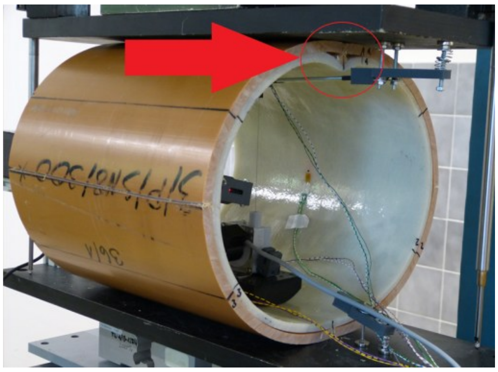

Fig.11. Testing of a sample with a fold

In order to obtain additional data for comparative analyses, and to be able to verify the correctness of the results for the used CIPP linings, verification calculations and stiffness tests were performed according to ISO 178:2019 [17]. The obtained results are summarized in Table 7.

TABLE 7. Results of the simulations and analytical calculations

E_R [MPa]	s [mm]	dm [mm]	$S_o(1)$	$S_o(2)$	$S_o(3)$
			[kN/m^2]		
2400	5.80	184.4	6.2235	6.1160	5.6720
	5.80	181.7	6.2498	6.1410	5.8050
	7.80	291.0	4.8515	4.8170	4.5450
	7.80	288.3	4.9608	4.9330	4.5460

where:
$S_o(1)$ – the value of the ring stiffness obtained during the analytical calculations in accordance with the guidelines included in [26].
$S_o(2)$ – the value of the ring stiffness obtained during the tests of the sections of the lining, which were made in accordance with ISO 178:2019 [17].
$S_o(3)$ – the value of the ring stiffness obtained during the tests of the full-size samples – scale 1-1 – the tests were carried out using loading plates and method B according to PN-EN 1228:1999 [14] and ISO 7685:1998 [15].

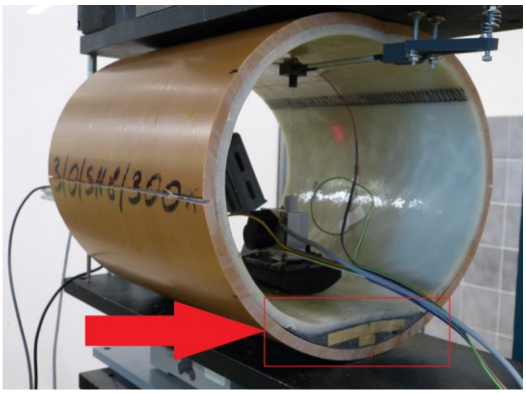

Fig.9. Testing of a sample with sediments

3.4. Analysis of the obtained results.

The conducted tests showed a high convergence between the obtained results when testing the lining sections (Table 7) and the analytical calculations based on the calculation algorithm included in standards [14 and 15]. The computational model is shown in Figure 12. The obtained values for diameters of 200 mm and 300 mm were approximately 6.18 kN/m^2 and 4.88 kN/m^2, respectively. They are lower than the values obtained during the tests of the full-section samples by 6–8%. The differences in the results are in favour for the tests of lining sections and for the obtained values of analytical calculations because they are lower than the actual values.

The values of ring stiffness obtained as a result of the laboratory

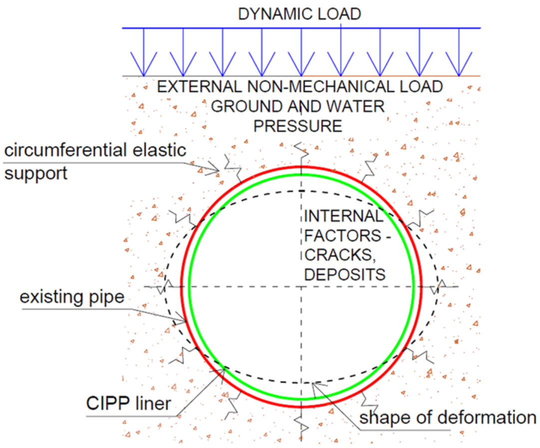

Fig.12. Computational model.

tests of the full-scale models with a diameter of 200 mm were 5.672 kN/m^2 and 5.805 kN/m^2. For the models with a diameter of 300 mm, the values obtained were 4.545 kN/m^2 and 4.546 kN/m^2.

The obtained results exceeded the value declared by the manufacturer (4.000 kN/m^2). For the tested lining with a thickness of 5.80 mm, which was installed in a pipe with a diameter of 200 mm, the actual value of the ring stiffness of the CIPP lining obtained during the laboratory tests was 42% and 45% higher than that declared by the manufacturer (see Tables 3 and 4). For the tested lining with a thickness of 7.80 mm, which was installed in a pipe with a 300 mm diameter, the actual value of the ring stiffness obtained during the laboratory tests was 13% higher than that declared by the manufacturer (see Tables 5 and 6). This guarantees the safety of the reinforced underground structure.

The first stage of the above-described research, which aimed to determine the initial parameters of the CIPP lining and the level of increase in the ring stiffness of the combined pipe-lining system, will enable the real impact of damage, and its scale on the deterioration of strength parameters, to be specified. Based on the many years of experience [27] in the implementation, design and diagnostics of pipelines, two common groups of irregularities were assumed as representative for most conduits. The first group involves the weakening of the conduit's wall – damage in the form of longitudinal cracks occurring at the top and bottom of the conduit and in its groins (Fig. 10). This group of damage is particularly dangerous because it can lead to rapid damage propagation, infiltration of groundwater inside the conduit, and exfiltration of sewage into the ground in a short time. This in turn can cause biological hazards to the natural environment. The simultaneous occurrence of the above-described phenomena can lead to the loss of the conduit's stability and then to its failure. This, in the case of locating underground network infrastructure in the ground space of road areas, is an extremely dangerous situation that has a direct impact on the safety of use and the safety of the road surface infrastructure. Such a situation poses a direct threat to road users and contributes to numerous breakdowns of vehicles moving on the damaged surface. In connection with the above, it is necessary to carry out renovations using CIPP linings that guarantee the obtaining of appropriately high strength parameters, which are verified by laboratory tests.

The second group of irregularities that often appear in gravity sewer networks involves changes in hydraulic parameters that result from the occurrence of solid deposits at the bottom of the conduit, and also other geometric disorders that contribute to the deterioration of the hydraulic parameters.

These irregularities, unlike the previously described cracks, do not pose a direct threat to the stability of the conduit, but instead have a negative impact on the efficiency of the network and its hydraulic parameters. This in turn may cause many local irregularities, such as: slower outflow, blockages, and local flooding (in the case of storm sewer networks). This directly affects energy use and consumption.

The synergy of damage requires the constant expansion of knowledge concerning the nature of the operation of the host pipe-CIPP lining system and its real strength parameters. The presented material refers to the research works shown in [28], which have been conducted since 2019 in order to deepen the knowledge regarding the design and implementation of renovations using CIPP technology.

4. CONCLUSIONS

The conducted research allowed for the collection of data that enables the correctness of the parameterization of initial boundary conditions to be verified within the scope of the load-bearing capacity of a conduit reinforced with CIPP lining.

The scope of the research described in the article, together with the obtained results, constitutes a set of data that enables the author to conduct further studies. The results of the tested samples provide a basis for the analysis of the changes in the strength parameters of composite structures (a pipeline with lining), which were caused by damage to a host pipeline. The possibility of comparing the results obtained for the models without geometric changes with the results of the deformed samples will allow for the construction of an analytical model and the determination of the actual changes in the parameters of the reinforced pipelines. Most pipes that undergo repair are conduits with a big amount of damage, and therefore knowledge in the field of designing the reinforcements of such objects is particularly desirable.

The performed tests were conducted on pipes with two diameters, i.e. DN 200 and DN300, which were assumed by the author of the article as representative of the majority of sanitary sewer networks located in areas designated for residential development. Despite the limitations that result from the study of the two selected diameters, the results can be considered representative for sewage pipelines located in urban areas. The modelled types of damage are the most common irregularities in pipelines.

The next stage of the research will allow for the determination of the extent of the influence of the above-described geometric irregularities on the deterioration of the strength parameters of a composite system consisting of the host pipe and a CIPP lining. Such irregularities should include longitudinal corrugations of the CIPP lining, changes in the geometry of the cross-section caused by pipe cracks (in the case of brittle materials) and the occurrence of solid sediments deposited on the bottom of the conduit. The laboratory tests carried out on full-scale models of pipelines without damage, based on standard algorithms, validated the correctness of the ring stiffness parameters that were assumed according to available calculation methods. The ring stiffness values were slightly higher than declared, which is beneficial from the point of view of the safety of structures. The second part of the laboratory tests will include the determination of the strength parameters of models with imperfections, i.e.:

- the modeled pipe wall's weakening (crack),
- the fold effect – the possibility of testing in 3 different locations in a conduit (bottom/top/groins) + the modeled pipe wall's weakening (crack),
- hard deposits in the bottom + the modeled pipe wall's weakening (crack).

Conducting full-scale model tests on pipelines reinforced with CIPP linings expands the knowledge that is necessary when designing repairs and when forecasting the durability of applied solutions. Maintaining pipelines in a proper technical condition ensures the minimization of:

• the risk of failures involving the release of sewage into the environment, as well as the resulting threats and costs of their elimination,

• damage to road infrastructure that can lead to traffic disruptions, and which requires repair work – economic consequences,

• operating costs of sewage treatment plants – a lack of groundwater infiltration into sewers.

The above-mentioned aspects constitute a set of factors that are directly related to the implementation of the goals of sustainable urban development, and also contribute to minimizing energy losses.

These considerations clearly confirm the need to deepen knowledge regarding CIPP technology applications for pipeline renovations. The correct design and implementation of repairs are factors that enable the operating costs of urbanized areas to be maintained at a level that guarantees a sustainable economy. The results of the conducted research are essential for creating accurate digital models that simulate the behaviour of pipelines after renovation. The precise determination of the strength parameters and durability of linings allows for the prediction of when degradation or damage may occur. Such information is crucial for predictive maintenance systems that use historical and current data in order to predict failures and plan pipeline repairs.

The collected data can be analysed by Artificial Intelligence (AI) algorithms to detect anomalies, cracks or leaks in pipelines. AI can also integrate this data with digital models, which in turn enables a comprehensive assessment of the technical condition of pipelines.

To sum up, research on CIPP linings provides key data and knowledge, which are the foundation for advanced digital modelling, predictive maintenance systems, and AI-assisted urban infrastructure diagnostics. This in turn translates into the effective long-term management of sewage networks, the increased safety of their use, and a reduction in the number of failures.

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